Fingerprint Recognition
Biometric Systems (DTU 02238)

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Session 4, 5 and 6

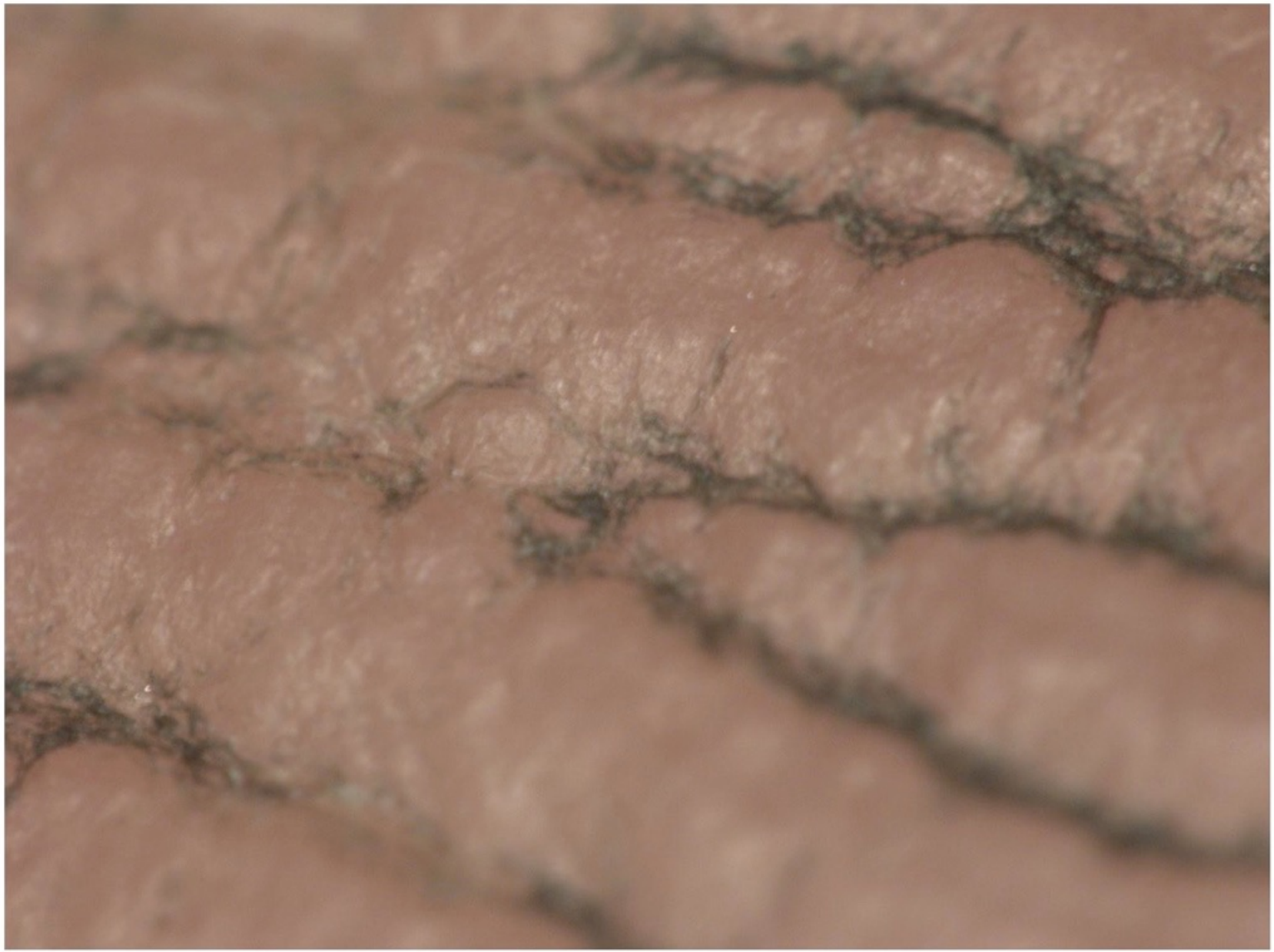
Overview Fingerprint Recognition

Structure of this session

- Anatomical foundations
- Fingerprint capture device technology
- Usability and aging
  - challenges at image acquisition
- Image preprocessing and enhancement
- Feature extractor
  - 1. Level - Global pattern configuration
  - 2. Level - Types of Minutiae
  - 3. Level - Poroscopy
- Comparison subsystem
- Applications

The Finger as a Biometric Characteristic

Fingerprint Recognition



Source: Keyence / Fraunhofer IGD 2012

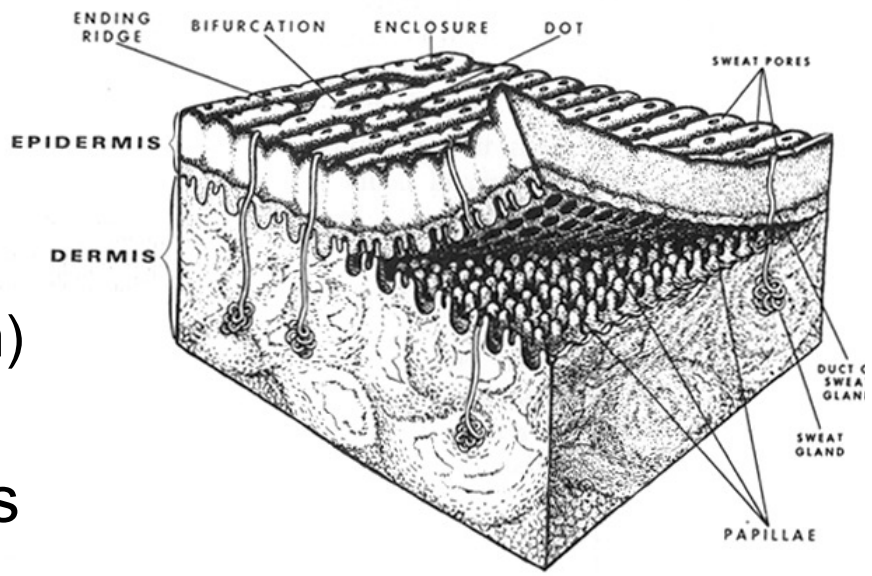
Fingerprint Recognition

Source: Keyence / Fraunhofer IGD 2012

Fingerprint Recognition

Structure of the skin

- Fingerprints are formed during early foetal life
  - between the third and fifth month of pregnancy (foetus is approx. 10 cm)
- Remain constant and are one of the last recognizable characteristics to disappear after death
- Built at random
  - monozygotic twins have different fingerprints
- Identical reproduction of pattern
  - the ridges on the epidermis grow from the underlying dermis and are steadily reproduced
  - minor cuts, burns and injuries will only alter the fingerprint appearance for a limited time period

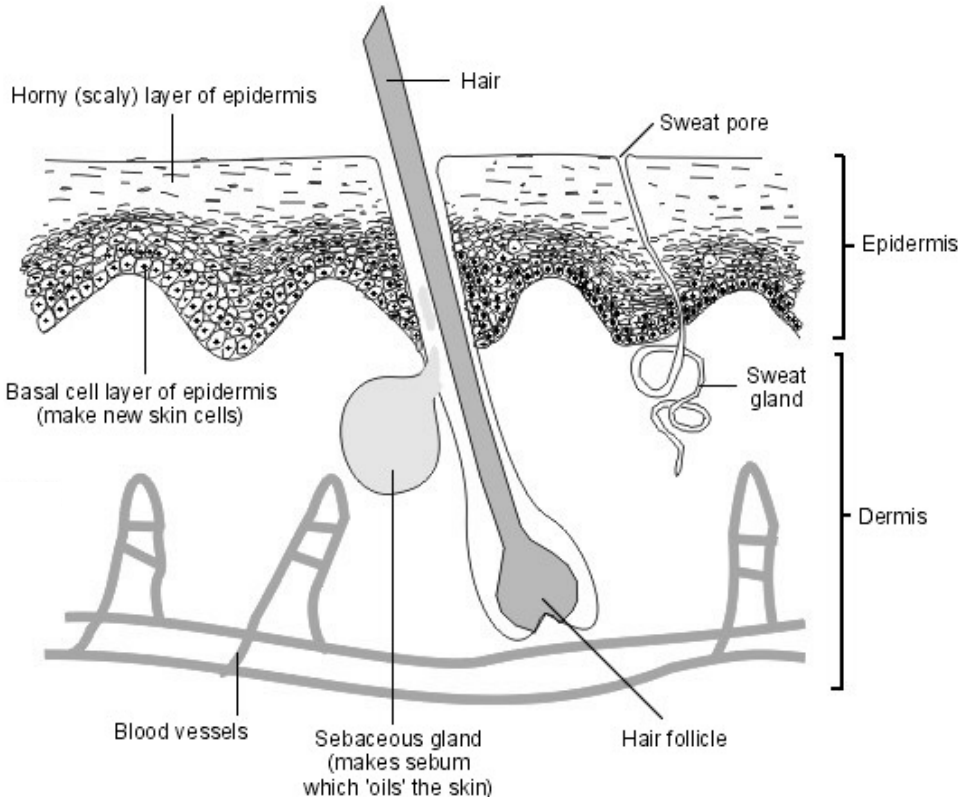


Source: FBI 1984

Fingerprint Recognition

Cross-Sectional diagram of the skin

- Two layers:
  epidermis and dermis
- The epidermis is the thinner of the two layers and serves as a protective covering
- The dermis is the thicker layer of skin which lies protected under the epidermis, and contains glands:
  - sweat glands -
    releases sweat consisting of water, salt and urea
  - sebaceous glands -
    releases oils



Source: SWP 2007

Fingerprint Recognition

Release of sweat to the skin surface

Source: Keyence / Fraunhofer IGD 2012

Fingerprint Recognition

From ridges to fingerprint lines:

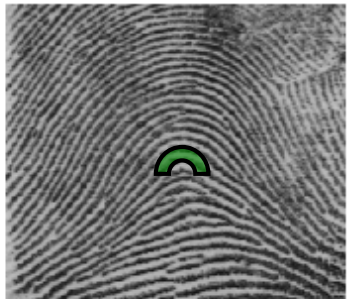
- Latent Fingerprints are generated without intention,
  - when fingers are dirty or oily ...
  - ... then we deal with a latent print
    that is generated by the sweat
    that is always present on finger ridges
- Techniques to make latent prints visible:
  - lasers, powders (and tape) and alternate light sources

Source: Knox Forensics 2012

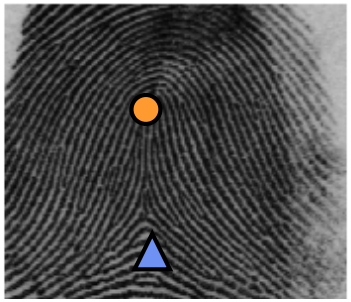
History of Fingerprint Recognition
Classification Schemes

1st level Classification of Fingerprints

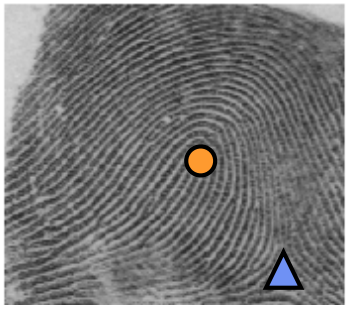
Classification of prints according to global patterns



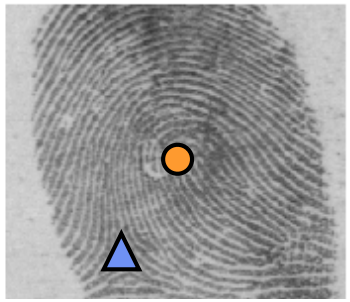
Arch



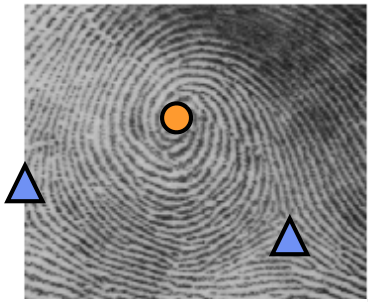
Tented Arch



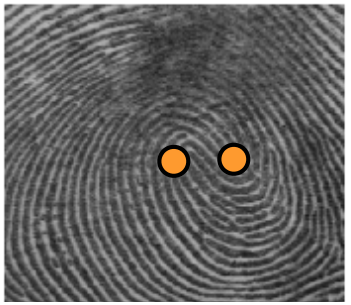
Left Loop



Right Loop



Whorl



Twin Loop

Singularities: Definitions

Core (Definition in ISO/IEC 19794-8)
"A singular point in the fingerprint, where the curvature of the ridges reaches a maximum"

- Can be considered as an U-turn that includes a number of ridges
- Approximation for the centre of the pattern

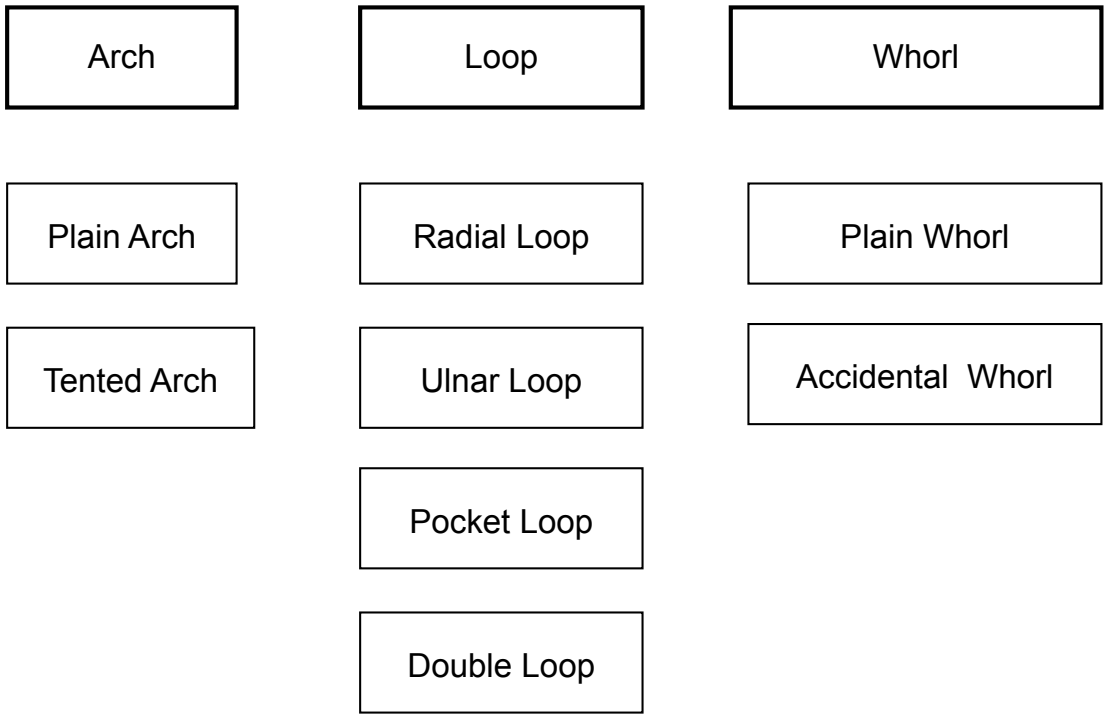
Delta (Definition in ISO/IEC 19794-8)
"structure where three fields of parallel ridge lines meet"

- Two parallel lines that divert

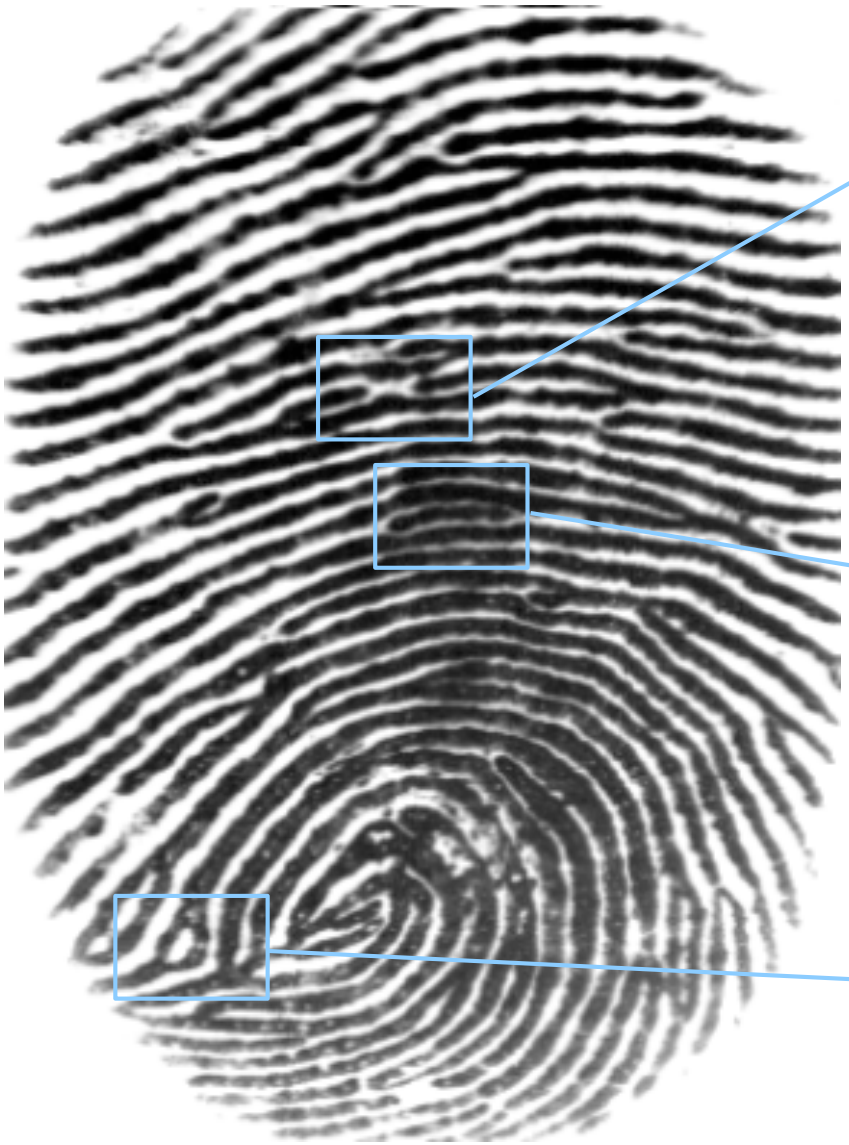
1st level Classification of Fingerprints

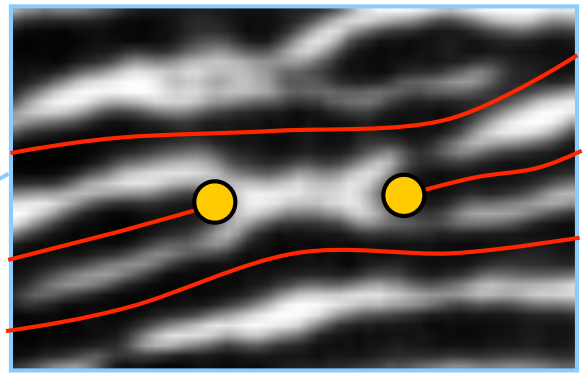
Classification of fingerprints according to basic dactyloscopic patterns (global patterns)

- Henry System: arches, loops, whorls and compounds
- FBI System: arches, loops and whorls
  - sub classes:
- Statistics
  - Arch 5%
  - Loops 60-65%
  - Whorl 30-35%

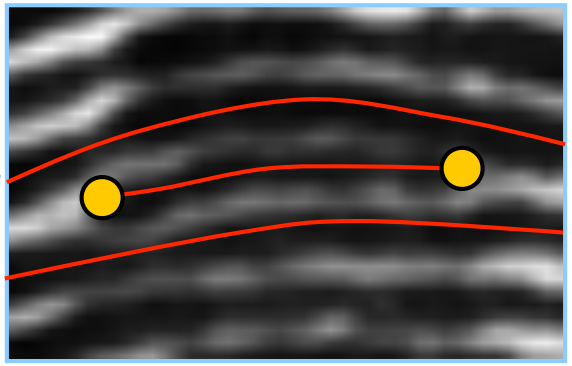


Galton Details

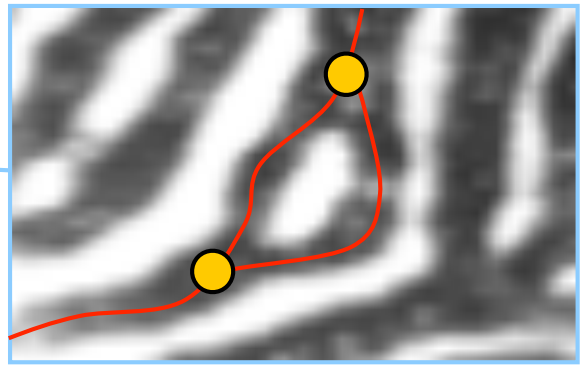




Line Break



Independent
Ridge
(Short Line)

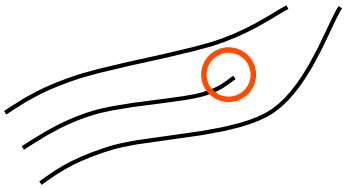


Island / Lake
(Enclosing)

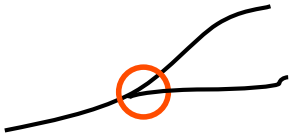
Image Source: FVC2005

Galton Details

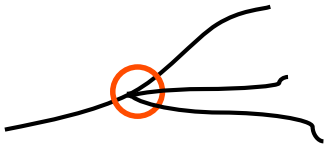
Minutia types



ridge ending

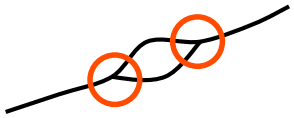


bifurcation

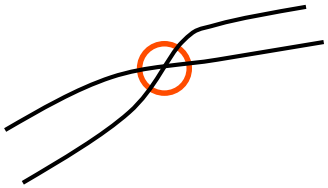


trifurcation

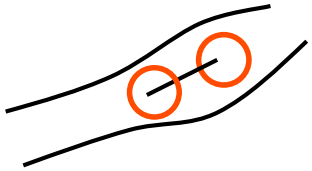
Galton Details: Compositions of ridge endings / bifurcations:



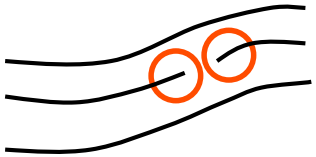
lake (enclosing)



line crossing



independent ridge
(short line)



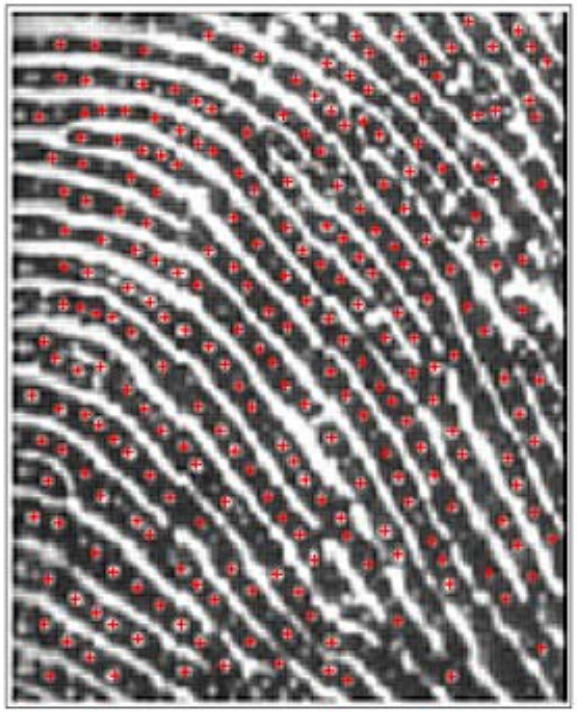
line break

crossover

Poroscopy

Fingerprint analysis (ridgeology) can be subdivided:

- Edgeoscopy - analysis of minutia points
- Poroscopy - analysis of sweat pores (up to 2700 pores)
  - Small pores in the size range of 60µm
  - Rarely used -
    as capture devices with 800 dpi or more would be required



Fingerprint Capture Devices

Fingerprinting

Biometric Capture Process

- Off-line (Traditionally)
  - With ink and paper (rolled)

Image Source: BKA

- Live-scan (Present)
  - Direct scanning of finger tips using electronic sensors
  - Digitally captured biometric sample

- Off-line
  - Latent fingerprints at crime scenes

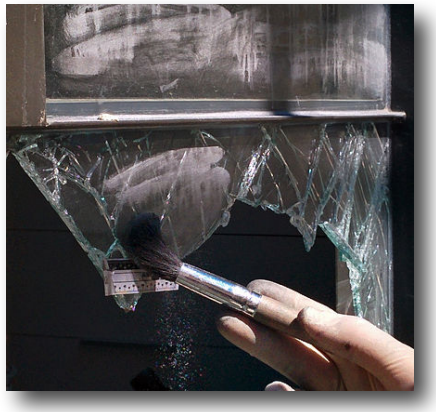
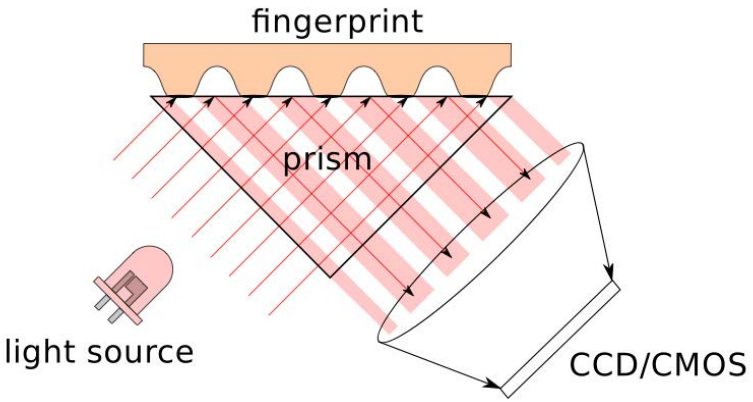


Image Source: Wikipedia 2016

Fingerprint Capture Devices

Optical Sensor

- Finger is placed on the surface of an optical prism and illuminated with monochrome light
- High image quality, extensive size (construction)
  - Resolution 256 dpi up to 1000 dpi
- Total Internal Reflection (TIR)
  - Reflection of light is suppressed, where the skin contacts the surface

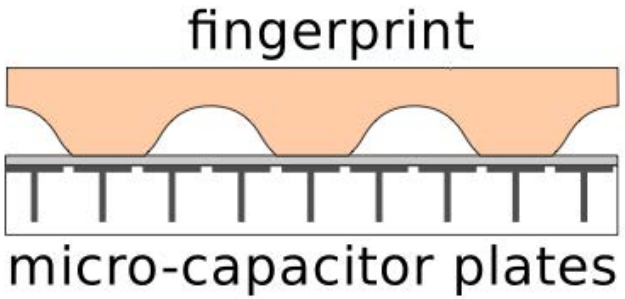


Optical Sensor

Source: Cross Match

Fingerprint Capture Devices

Capacitive sensor chips



- Contacting skin acts as the opposite plate of a capacitor
- Chip configured as an array of capacitor plates
- The capacity for every cell is measured via the conductance and corresponds to the skin distance
- Small and integrate-able (e.g. in mobile phones)
- Can suffer from electrostatic discharge and mechanic stress

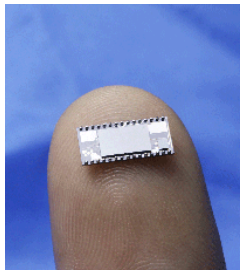
Capacitive sensor
Image size: 224 x 288 Pixel
Image resolution:
513 dpi - 8 bit/pixel
Sensor: 11,3 mm x 14,3 mm

Source: Infineon

Fingerprint Capture Devices

Further sensors

- Line sensor chips - swiped method
  - IDEX, Atmel, Kinetic Sciences



Capacitive line sensor

Source: Idex

- Ultra sound
  - Good image quality
  - UltraScan

Ultrasound Quality

Optical Quality

- Multispectral Imaging (MSI)
  - Looks at and beneath the skin surface
  - Lumidigm, (TST)

MSI Quality

Optical Quality

Source: Lumidigm

Fingerprint Capture Devices

Source: Qualcomm 2015

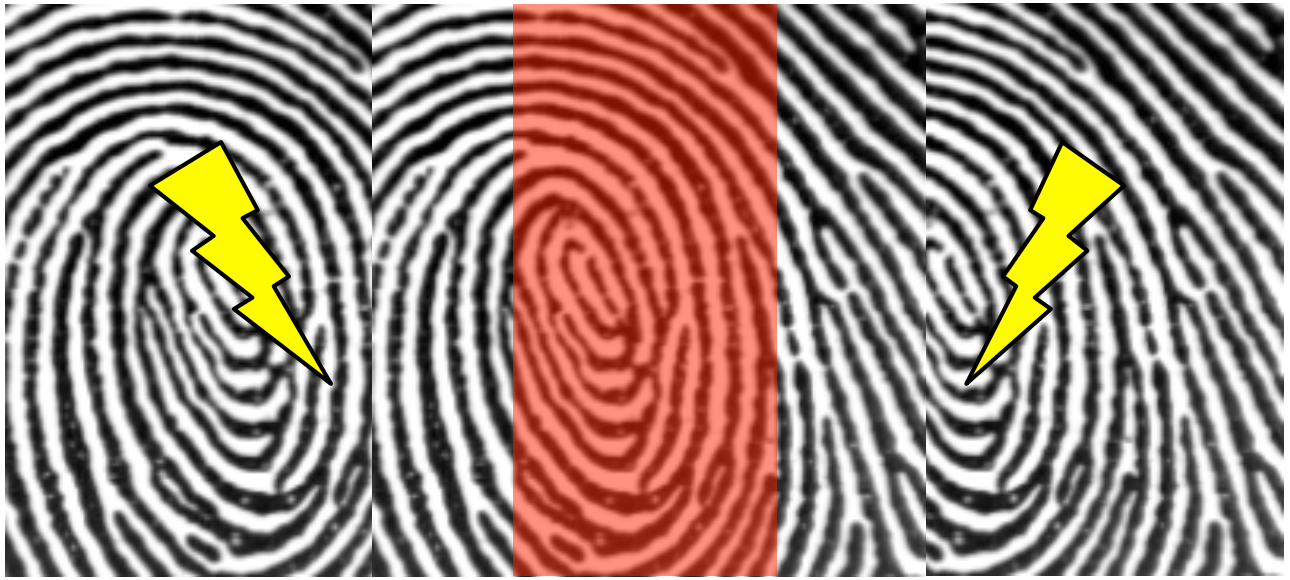
Challenges - Image Capturing and Processing

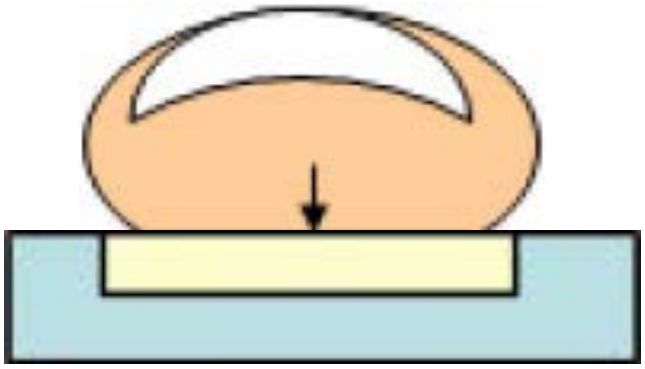
Challenge: User Interaction

Centered finger

Displaced finger

Limited overlapping fingerprint area!





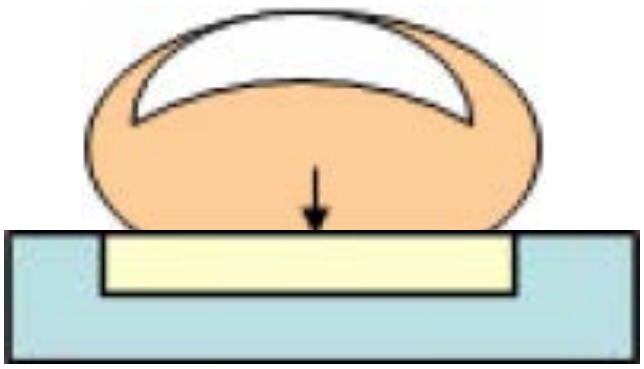
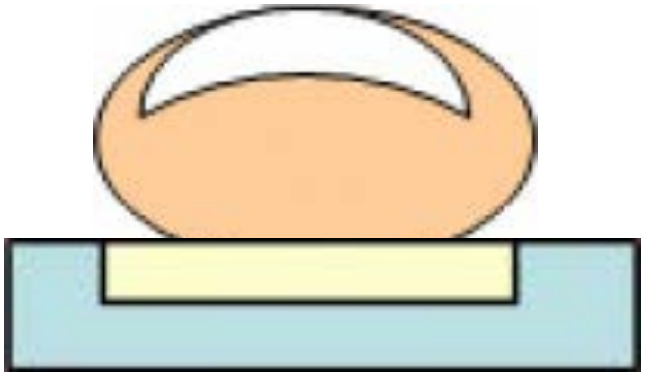


Image Source: ISO/IEC 19794-4:2011

Challenge: User Interaction

Finger is placed at an angle to the sensor

Limited overlapping fingerprint area!



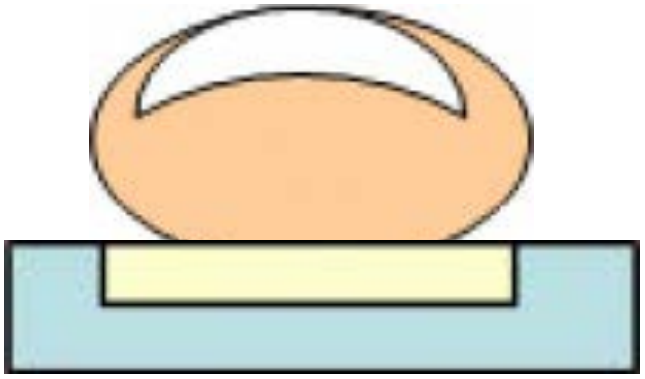


Image Source: ISO/IEC 19794-4:2011

Challenges with Fingerimage Capture

Translation:

- Limited overlapping area due to varying positions of the finger on the sensor or angle of finger placement

Challenges at Image Capturing

Translation:

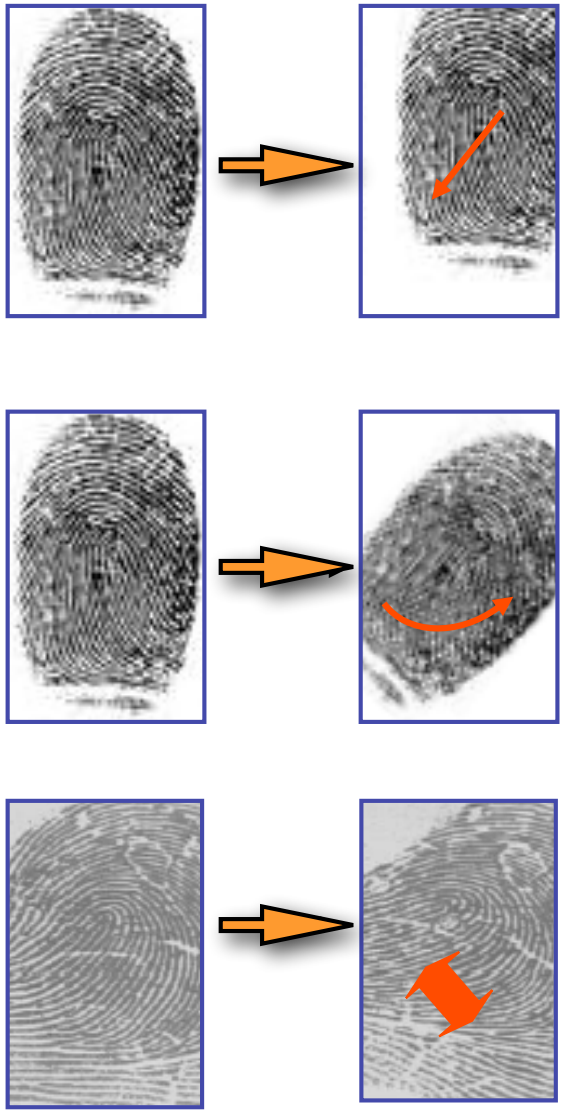
- Limited overlapping area due to varying positions of the finger on the sensor or angle of finger placement

Rotation:

- Varying orientation of the finger on the sensor

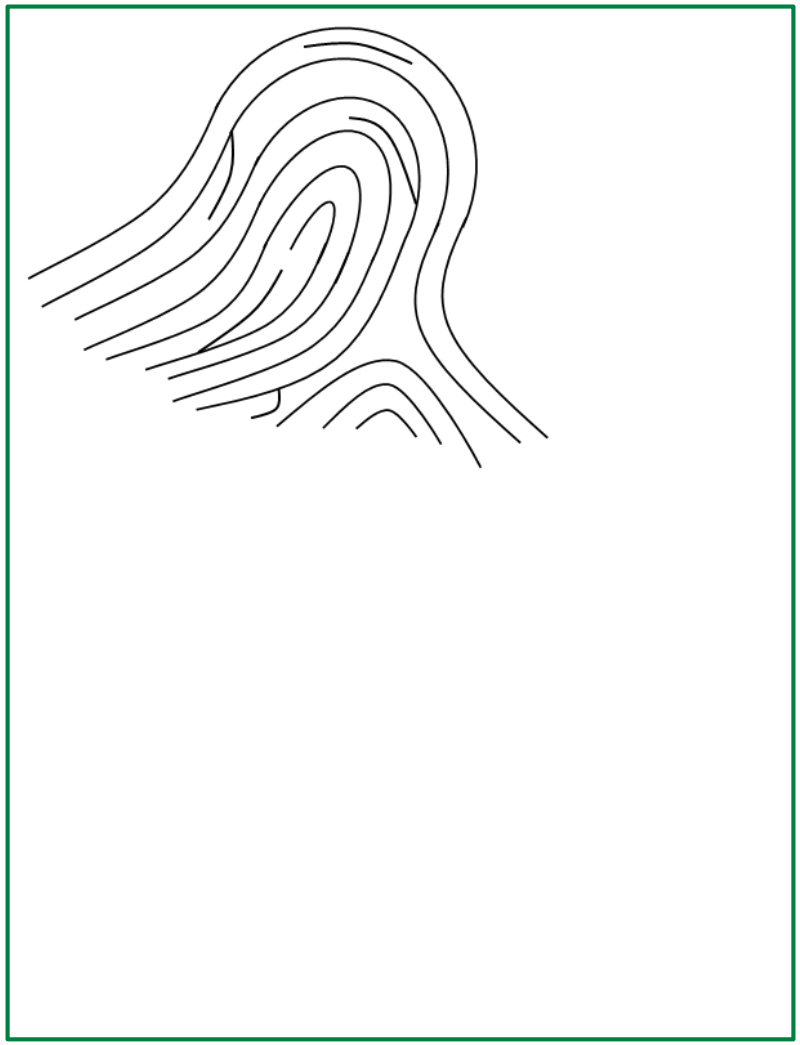
Scaling:

- Non-linear deformation of the fingerprint



Alignment of Fingerprints (1)

Reference

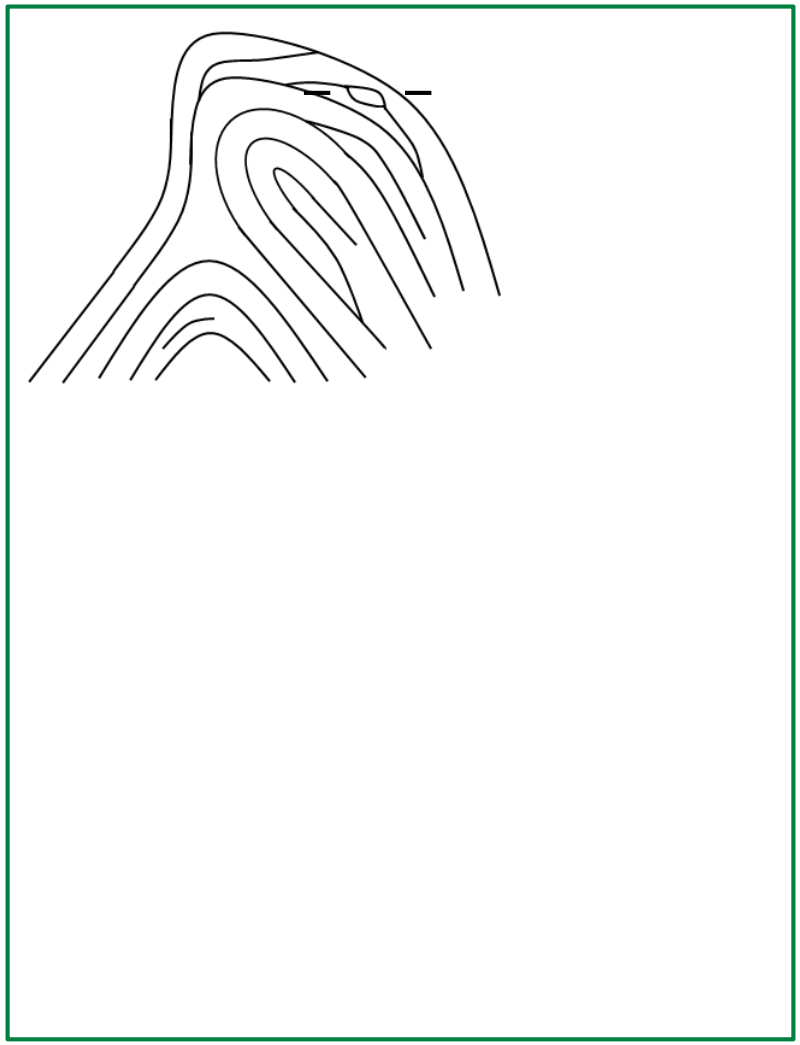


Probe / Query

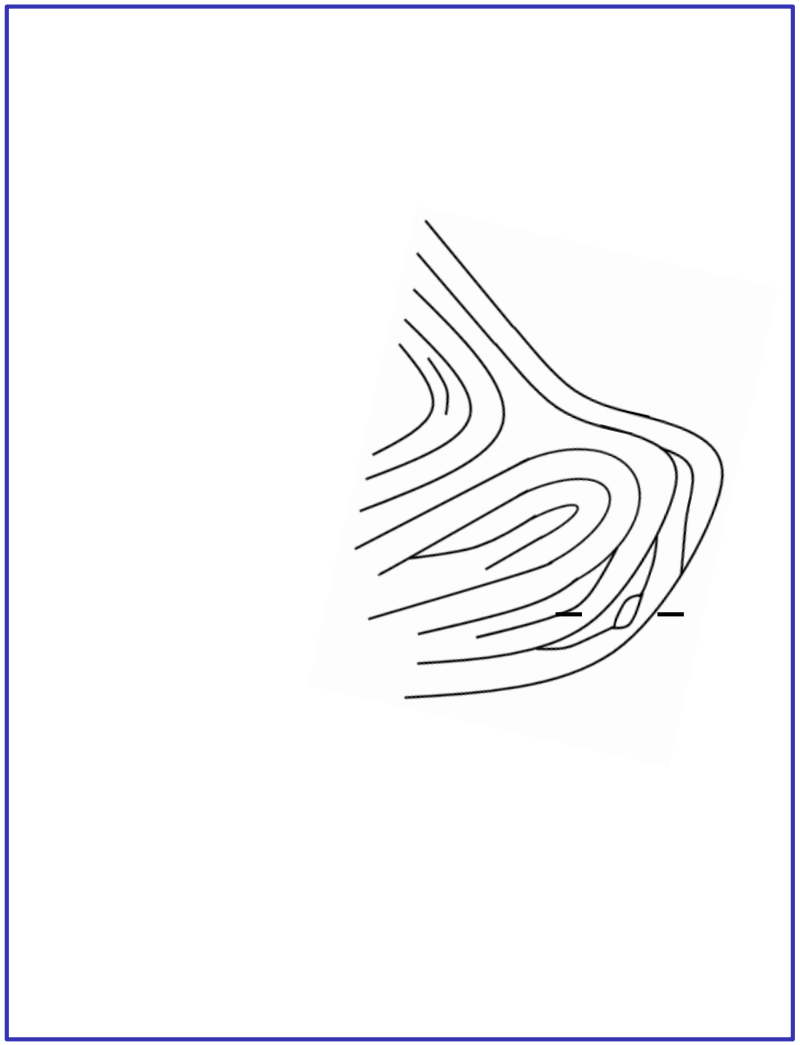
Alignment of Fingerprints (2)

- Relative alignment via Galton Details (lake, island)

Reference

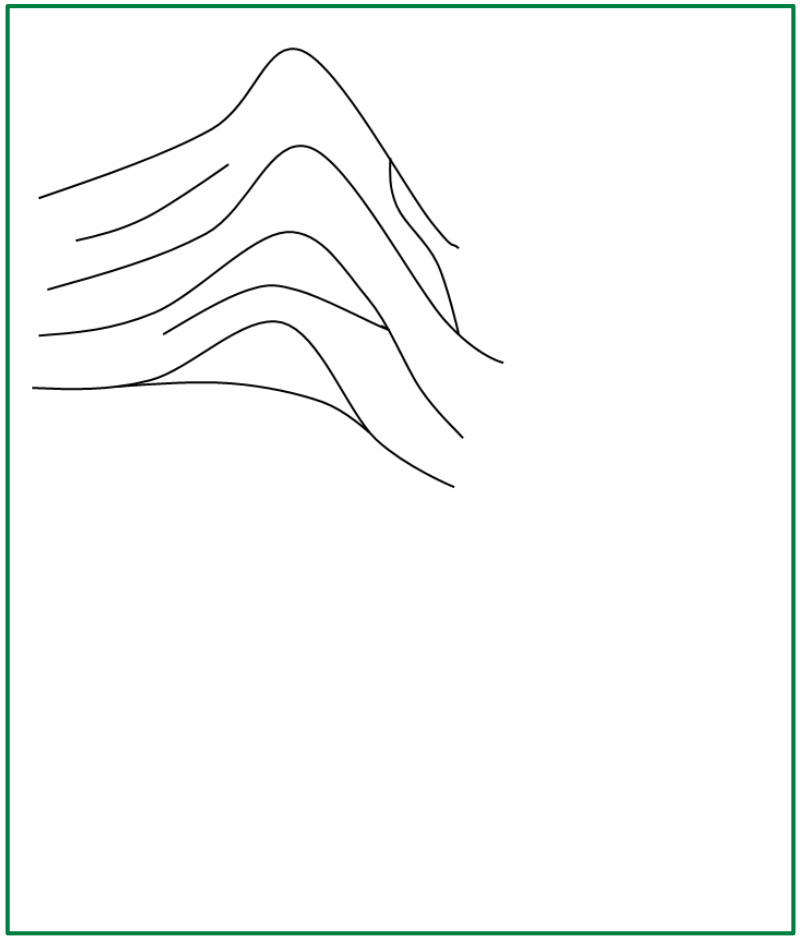


Probe / Query



Alignment of Fingerprints (3)

Reference

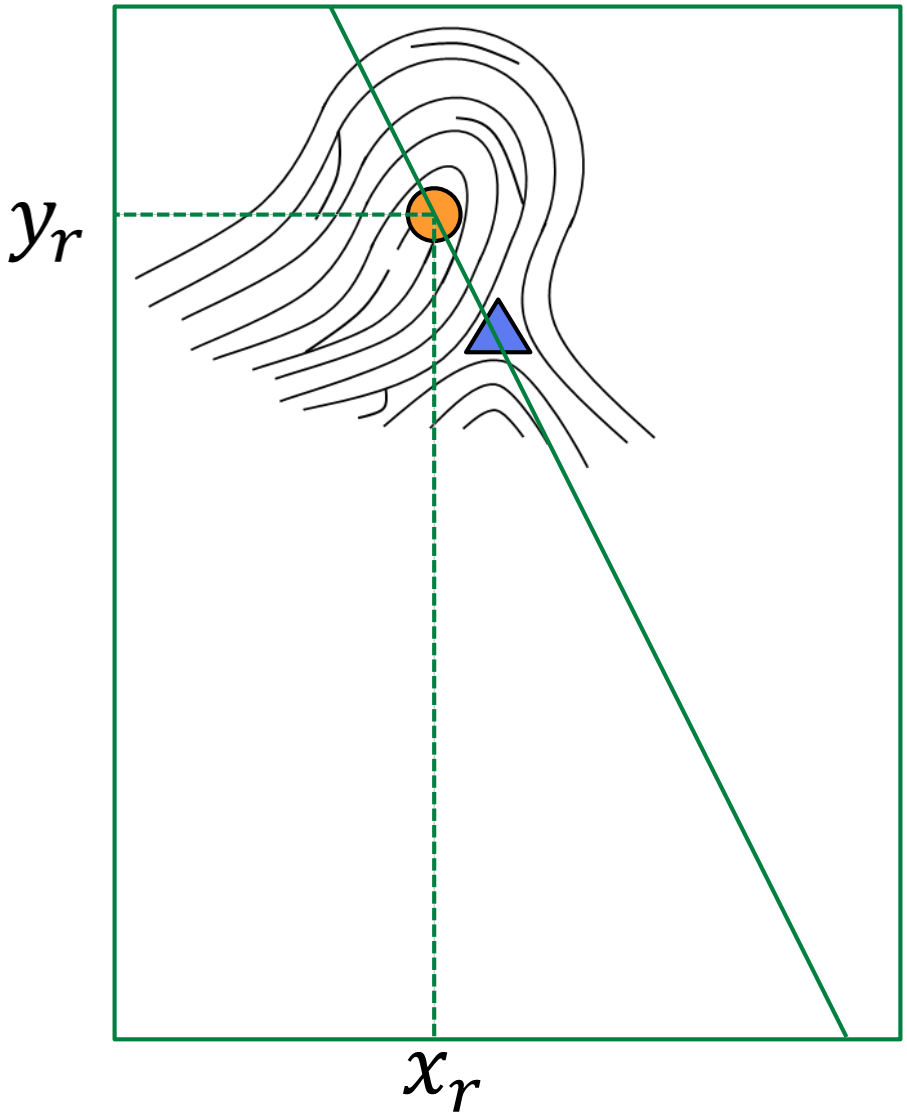


Probe / Query

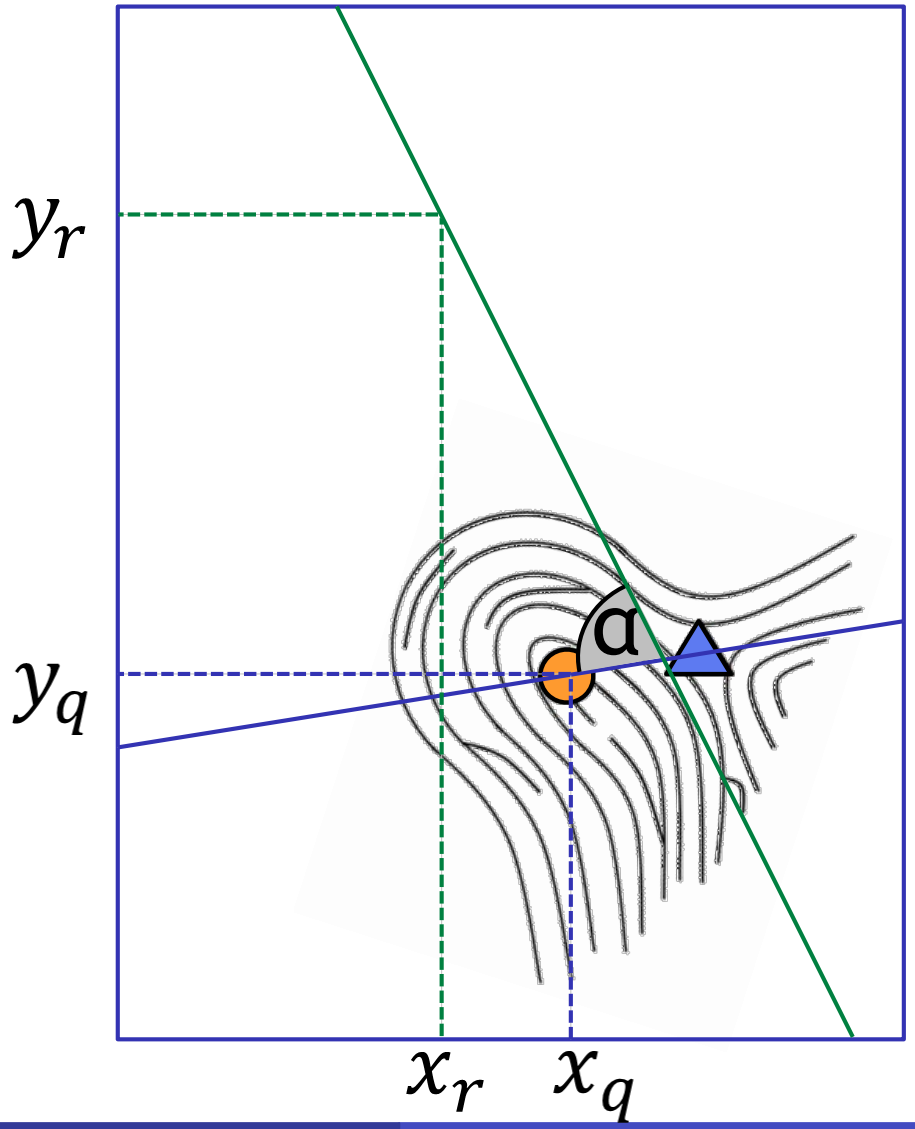
Alignment of Fingerprints (1)

- Relative alignment via Core and Delta

Reference



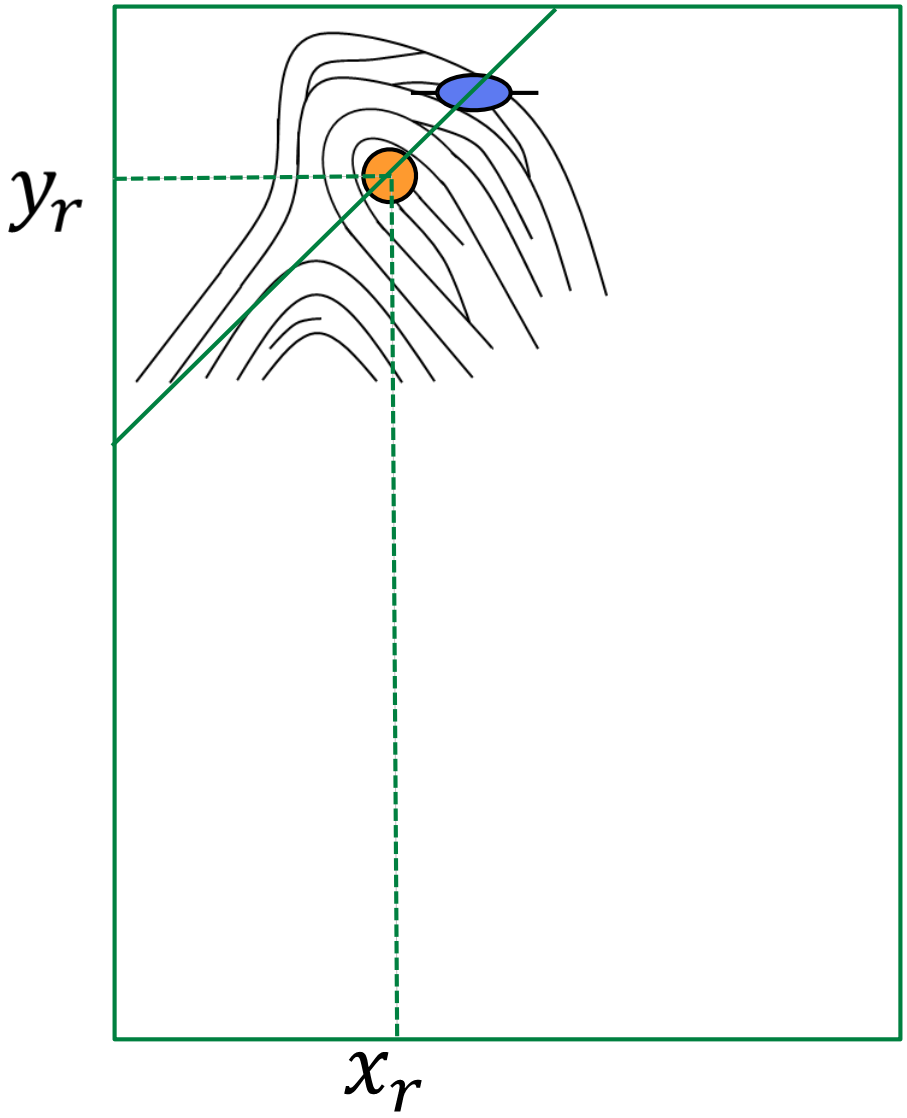
Probe / Query



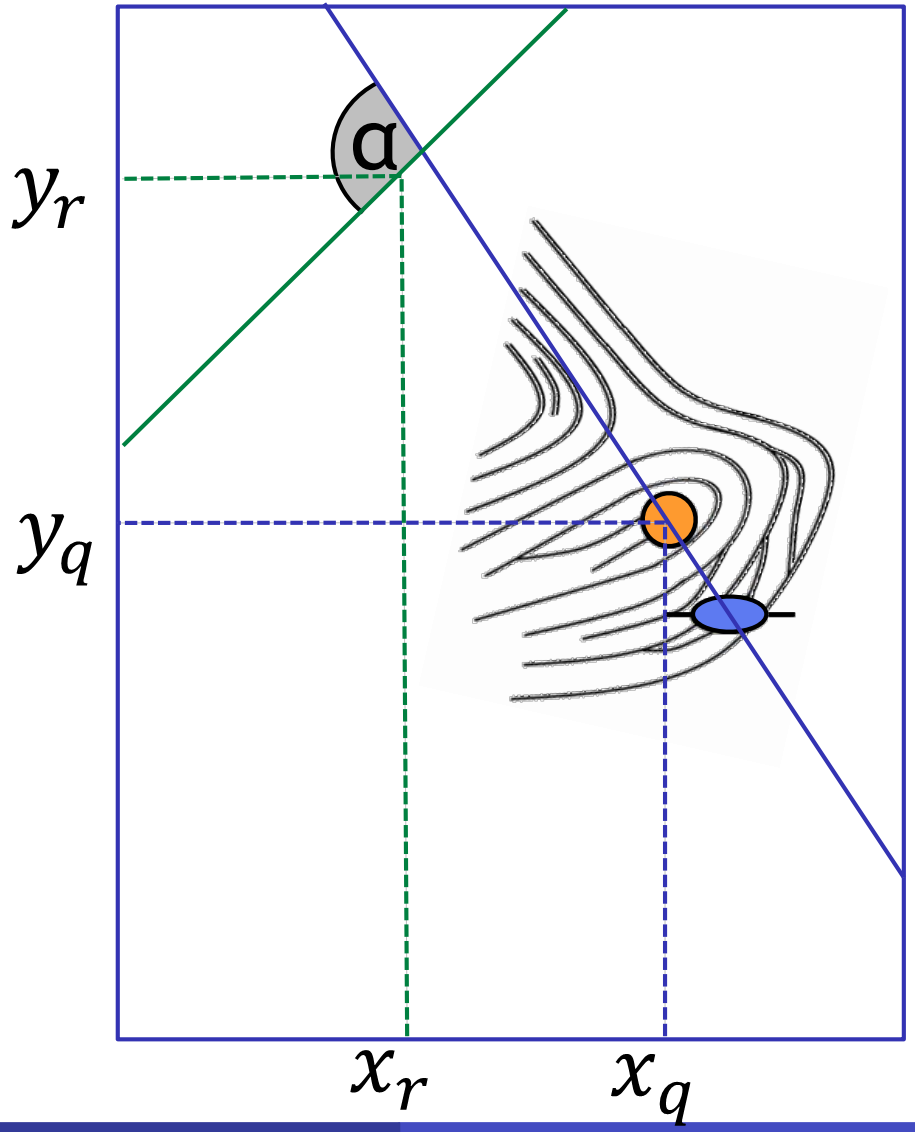
Alignment of Fingerprints (2)

- Relative alignment via Galton Details (lake, island)

Reference



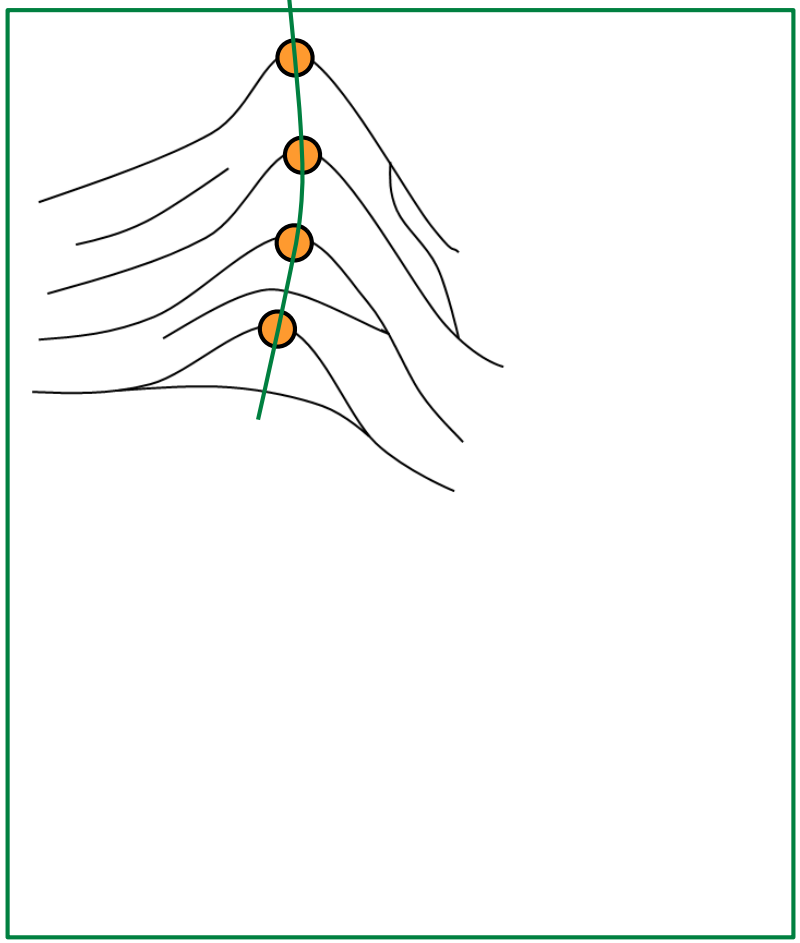
Probe / Query



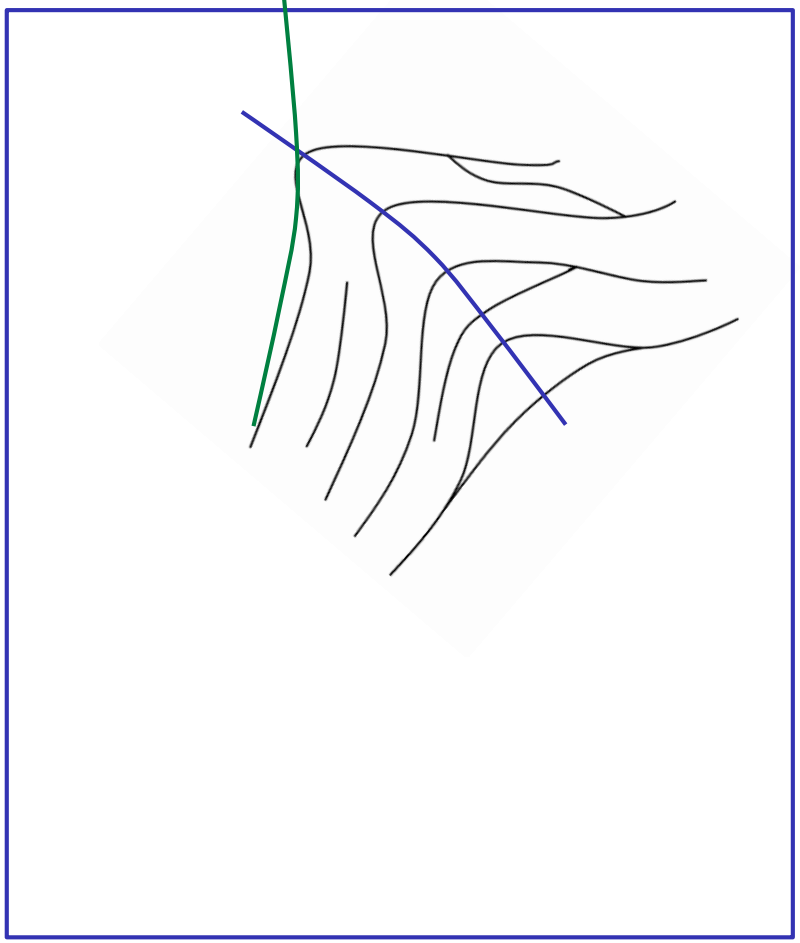
Alignment of Fingerprints (3)

- Relative alignment via the connecting line along multiple max-curvature points

Reference



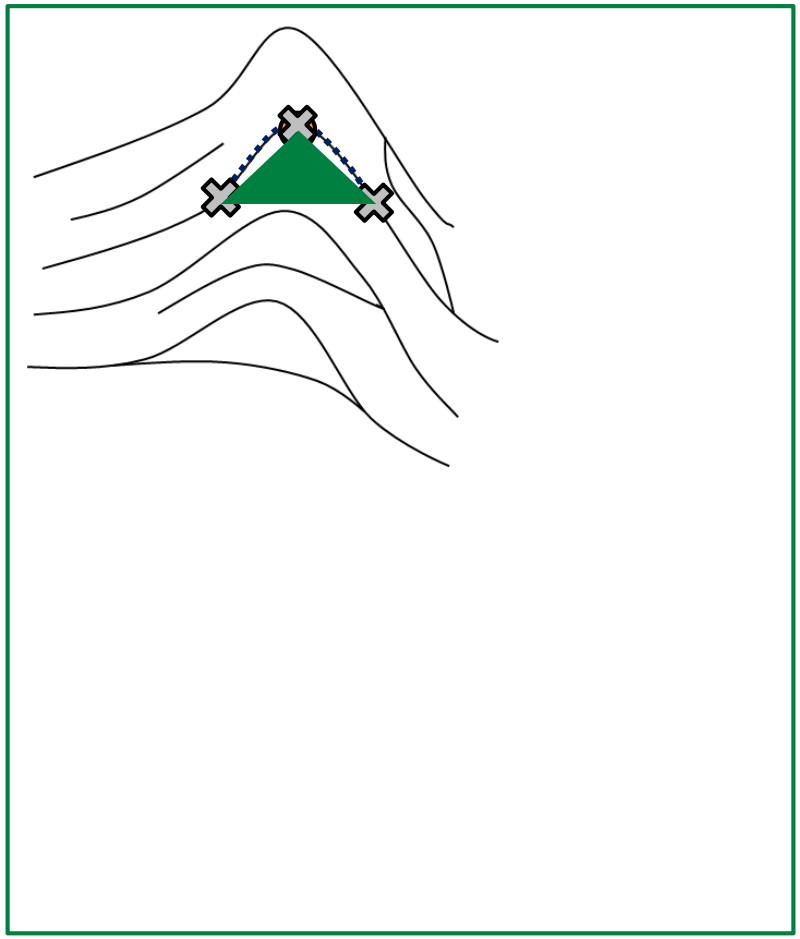
Probe / Query



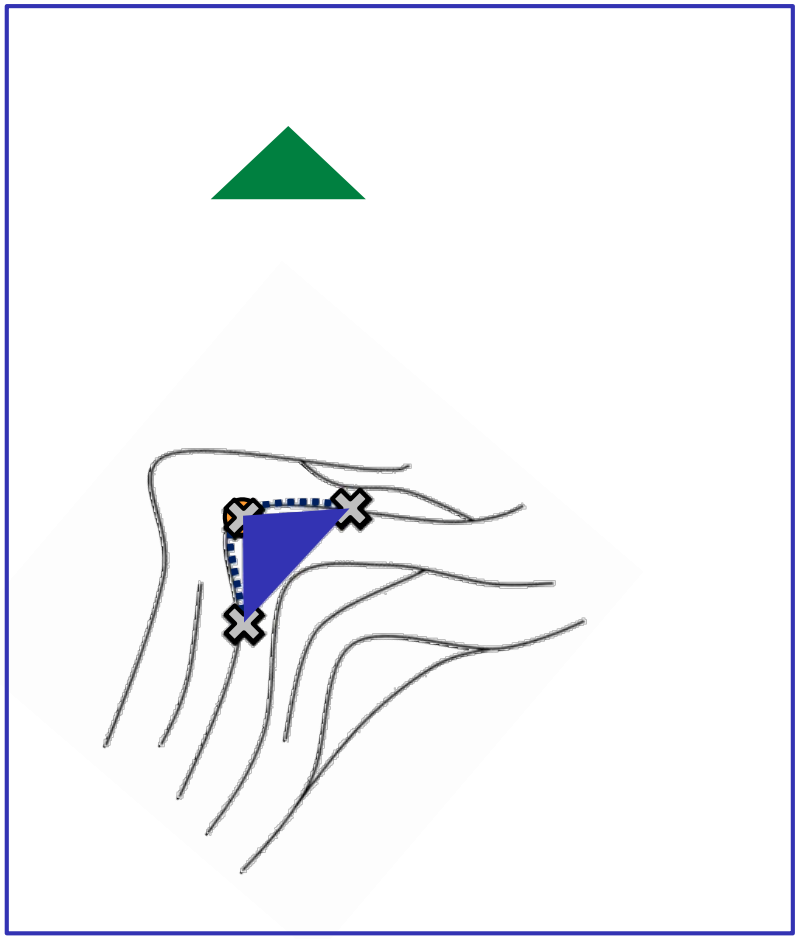
Alignment of Fingerprints (4)

- Relative alignment with a triangle on the ridge with max-curvature

Reference

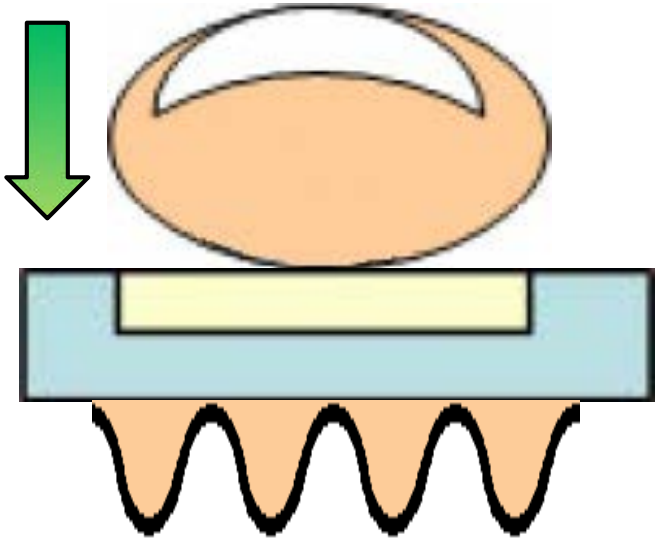


Probe / Query

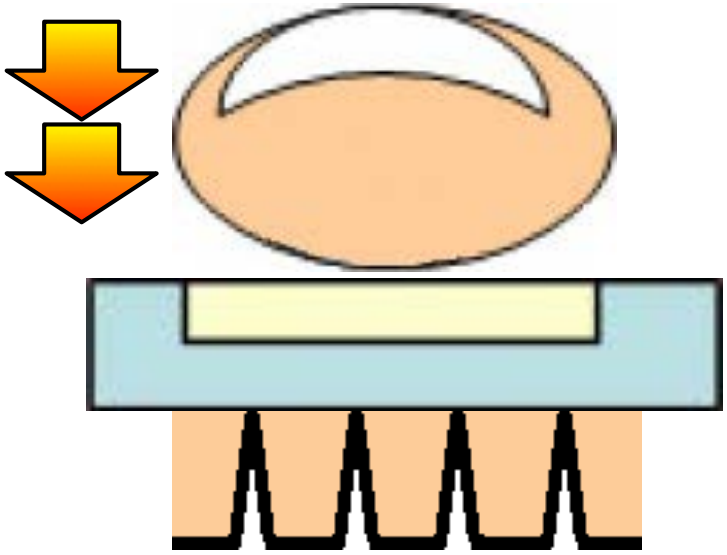


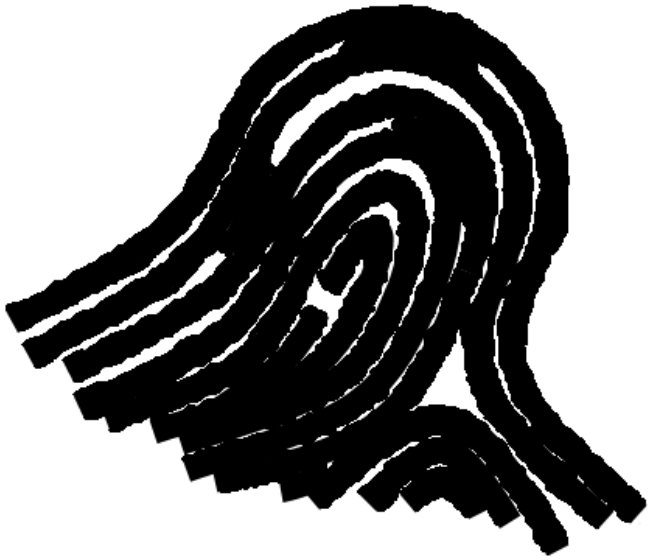
Challenge: Pressure / Force

Normal pressure



Strong pressure





Contactless Image Capturing

Capture finger photos with a smartphone camera

Advantages

- No deformations of the fingerprint
- No finger contact is required:

  No latent fingerprint resides on the surface of the capture device.

  No COVID-19 infection risk

Contactless Image Capturing

Fingerprint capture device “Fingerprint on the Fly”

- Mitigates hygienic concerns
- No latent print
- 4 fingers in < 1 second

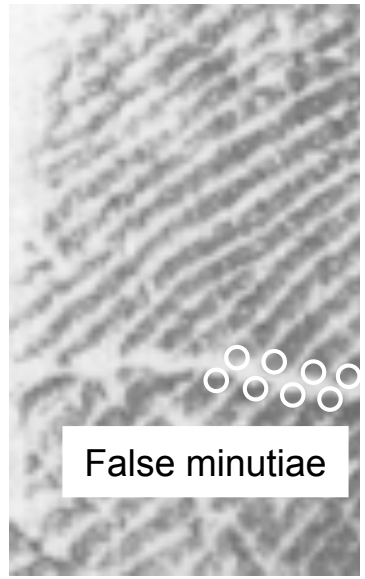
Image Source: Morpho

http://www.morpho.com/identification/border-control-242/semi-automated-control/finger-on-the-fly-r-946/?lang=en

Challenges at Image Capturing

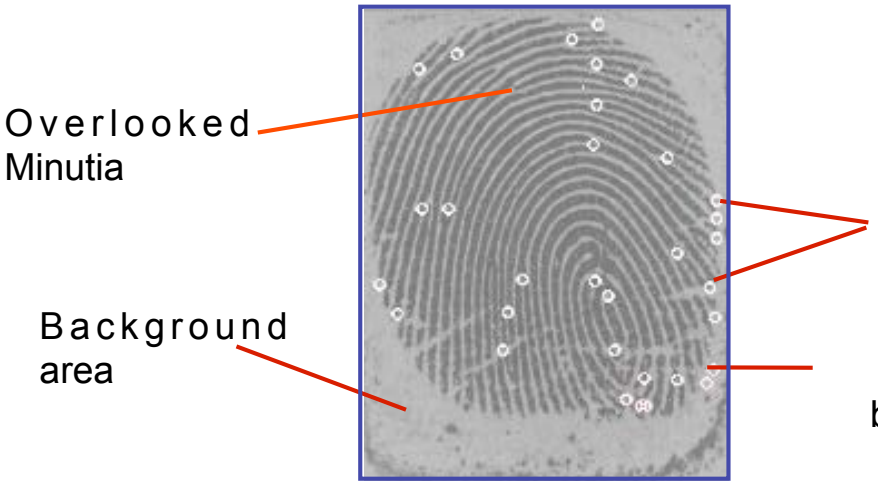
Poor image quality might be due to the following:

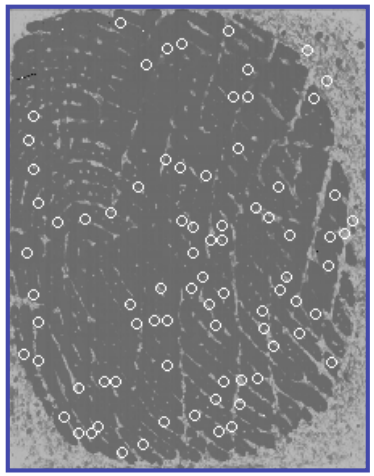
- Finger too dry, wet, worn-out, dirty
- Pressure too high or too low
- Scratches (temporarily interruption of ridges)



False minutia appear

- False minutia (also called spurious minutia) - often exist at the borderline of the fingerprint area
- False minutia are added, when scratches interrupt the ridge





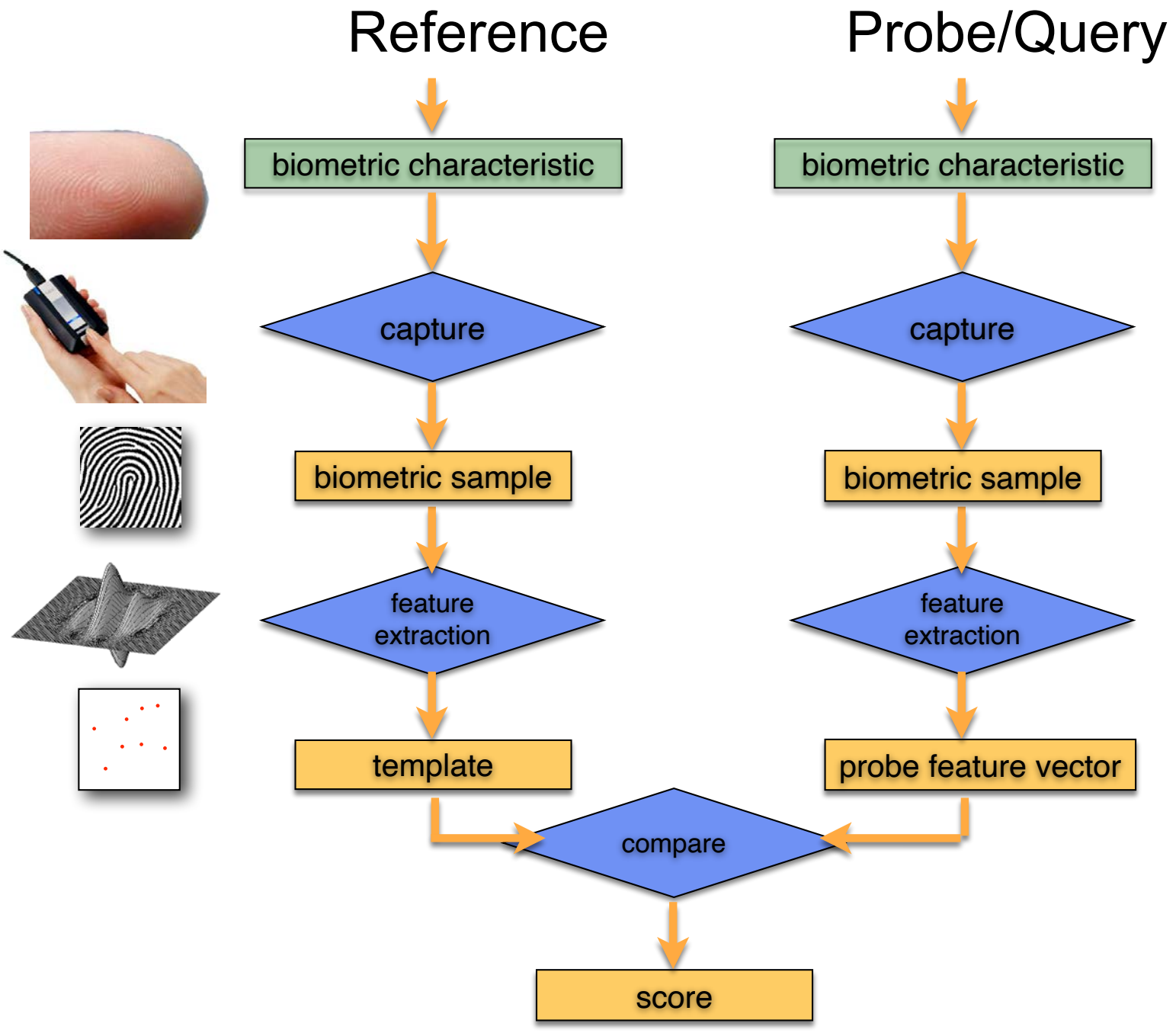
Large number of false minutia due to high pressure

Fingerprint Recognition

Analysis of Galton Details (2. level)

- Captured Image
- Preprocessing
- Feature Extraction
  - Bifurcations and endpoints of ridge lines
  - Feature Set
- Count corresponding minutiae
  - Same location within a threshold
- Determine comparison score
  - E.g. ratio of corresponding versus total number of minutiae

Fingerprint Recognition



Fingerprint Recognition - Illustrated

Are these fingerprints mated?

- Are they from the same source?

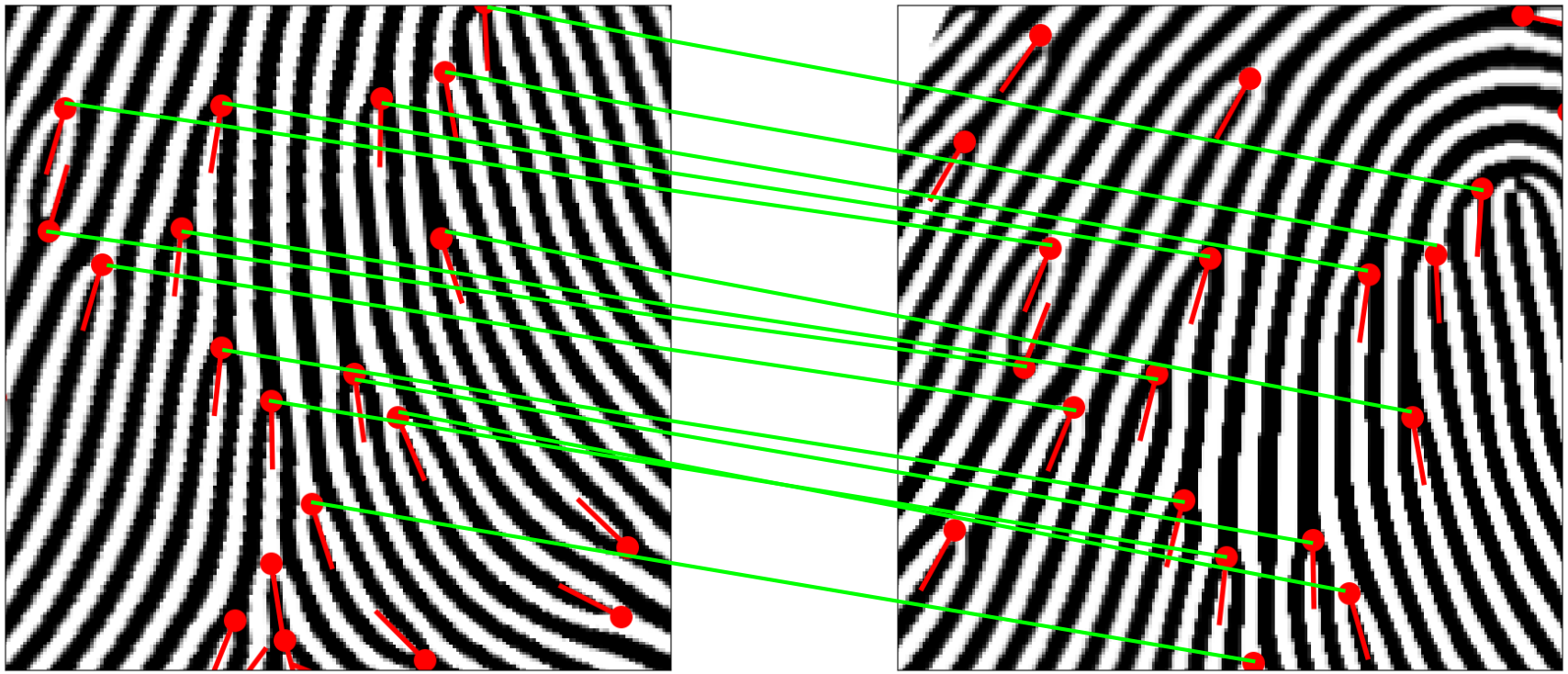
Fingerprint Recognition - Illustrated

Ridge Structure is Most Relevant

Fingerprint Recognition - Illustrated

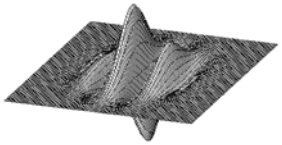
Identifying mated minutiae points

- Mated means stemming from the same source



Feature Extraction Techniques

Preprocessing



biometric characteristic

capture

biometric sample

feature extraction

template

compare

score

biometric characteristic

capture

preprocessing

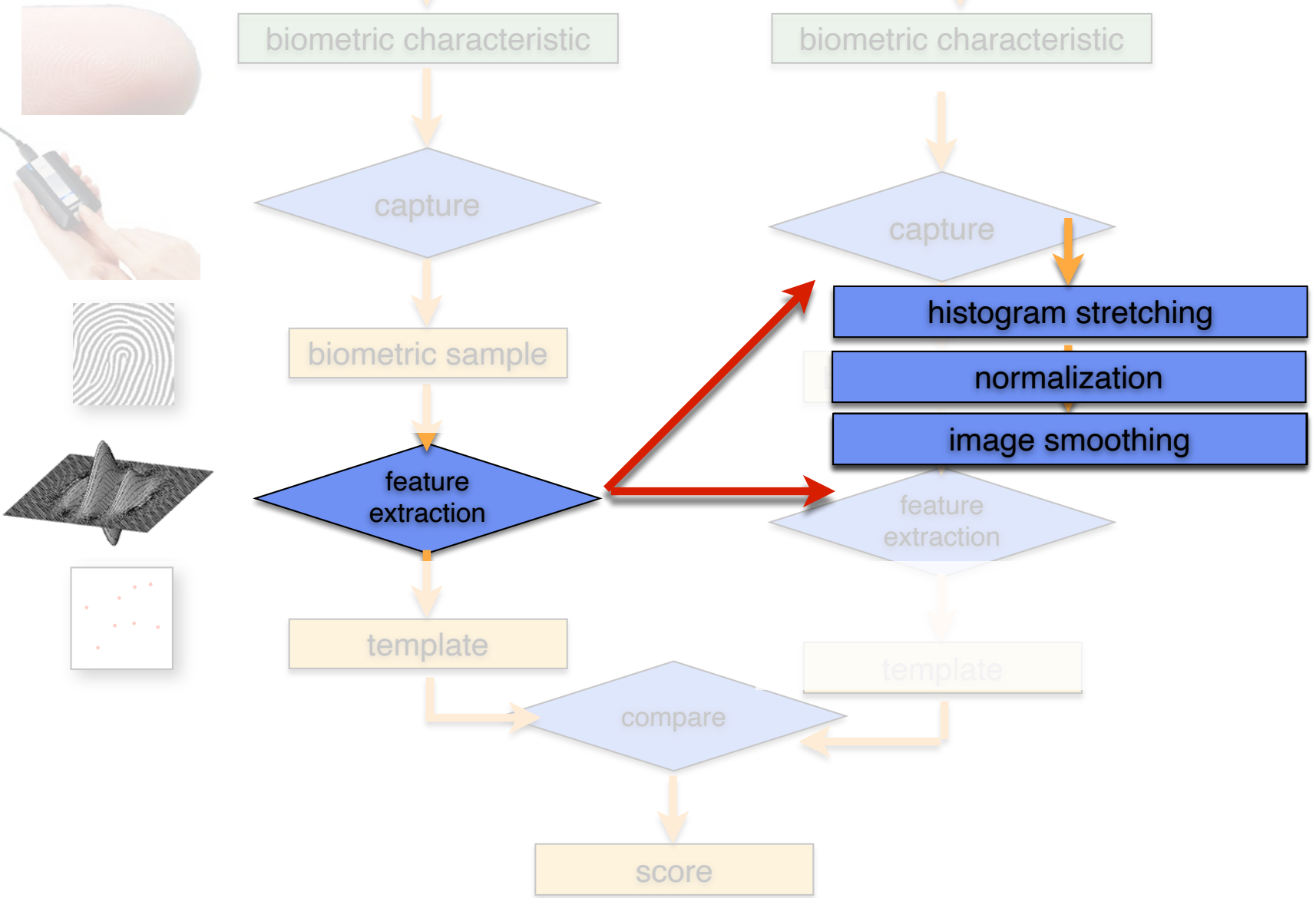
biometric sample

feature extraction

feature extraction

template

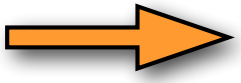
Preprocessing

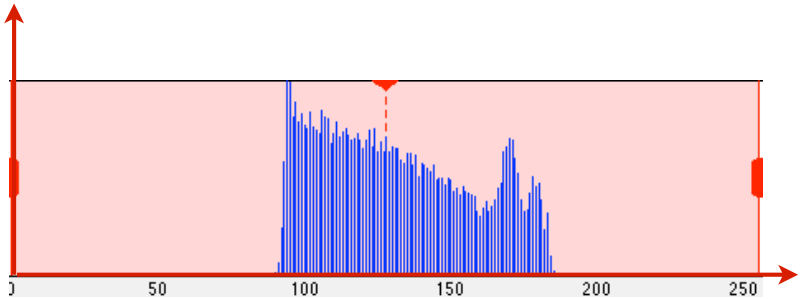


Preprocessing

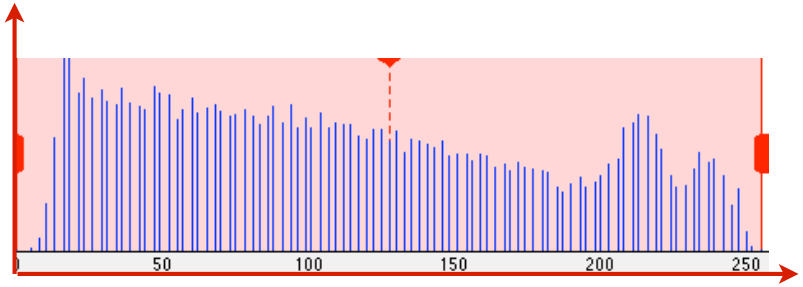
Histogram stretching / equalization

$$\forall i \in \{1...R\}, j \in \{1...C\} : G(i,j) = \frac{g_{max}}{in_{max} - in_{min}}(I(i,j) - in_{min})$$





min=88 max=186



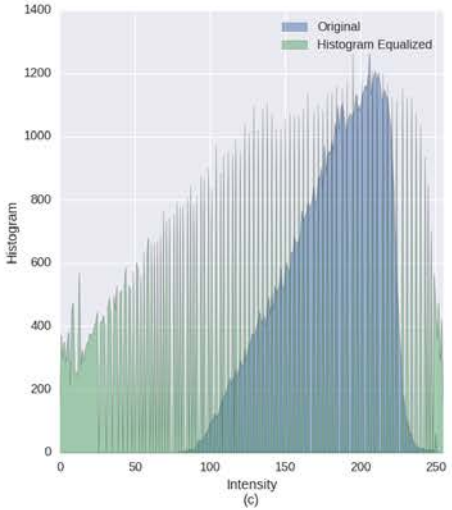
Preprocessing

Histogram stretching / equalization

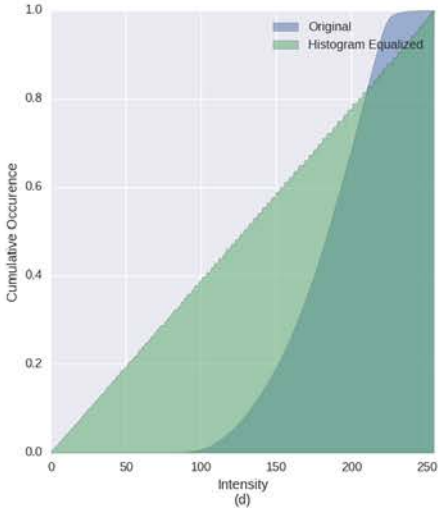
- Intensity values are spread over the entire histogram

original

enhanced image



distribution of grey values (before - blue after - green)

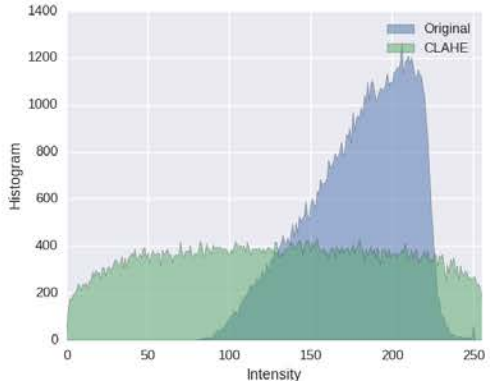


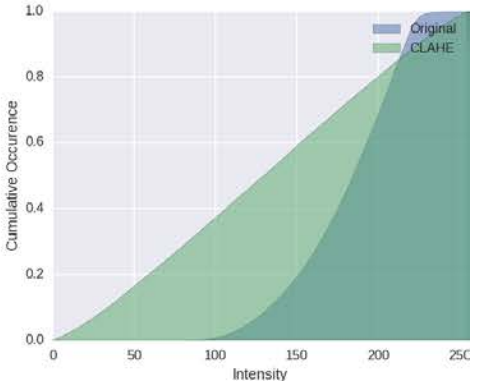
cumulative distribution of grey values (before - blue after - green)

Preprocessing

Contrast limited adaptive histogram equalization (CLAHE)

- A window is moved over the image creating sub images
- Each sub image has a small histogram,
  - which is equalized independently from the rest of the image
  - local histogram equalization leads to better local contrasts and enhances the image's details.
  - the neighboring tiles are then combined using bilinear interpolation to eliminate artificially induced boundaries.
  - CLAHE enhances eventual noise contained in the image.





Preprocessing

Normalization

- $M(I)$ and $V(I)$ are mean and variance of the grey level in the input
- $M_0(I)$ and $V_0(I)$ are mean and variance in the output

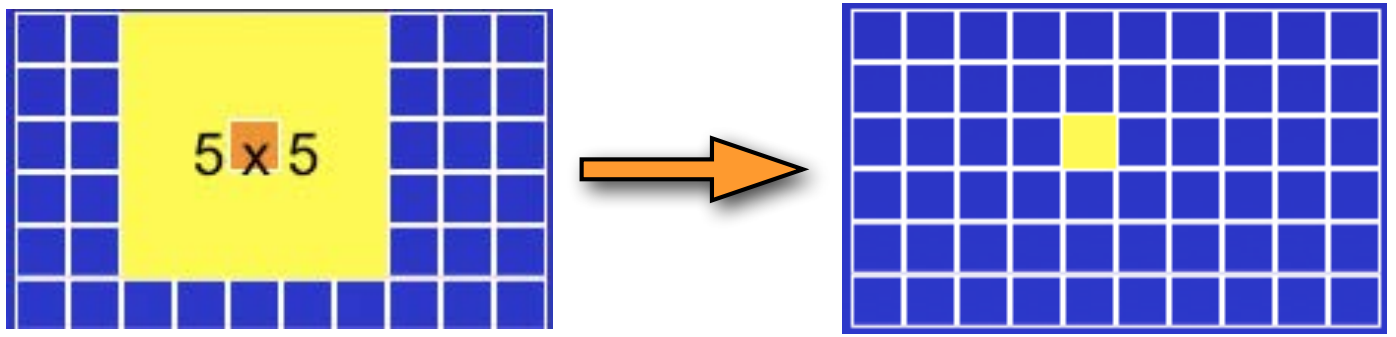
$$M(I) = \frac{1}{RC}\sum_{i=0}^{R-1}\sum_{j=0}^{C-1} I(i,j) \qquad V(I) = \frac{1}{RC}\sum_{i=0}^{R-1}\sum_{j=0}^{C-1} (I(i,j) - M(I))^2$$

$$\forall i \in \{1...R\}, j \in \{1...C\} : G(i,j) = \begin{cases} M_0 + \sqrt{\frac{V_0 (I(i,j)-M)^2}{V(I)}} & \text{if } I(i,j) > M \\ M_0 - \sqrt{\frac{V_0 (I(i,j)-M)^2}{V(I)}} & otherwise \end{cases}$$

Preprocessing

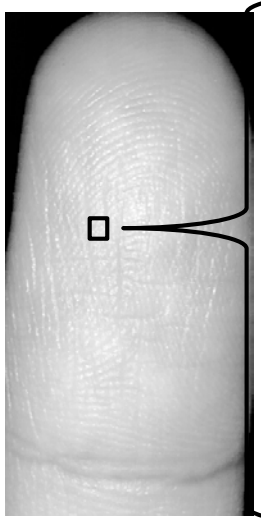
Image Smoothing

- Removal of noise and outliers
  - Low pass filtering in the spatial domain
  - *n x n* neighborhood region (yellow area) (e.g. 3x3, 5x5)
- Methods
  - Neighborhood averaging $g_{average} = \frac{1}{n^2} \sum_{i=0}^{n^2-1} g_i$
  - Median filter $g_{median} = med\{g_i, i = 0...n^2 - 1\}$

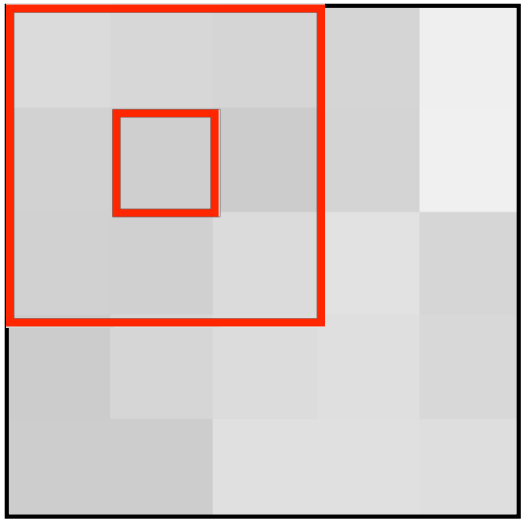


Averaging - Smoothing with 3x3 Kernel

Image

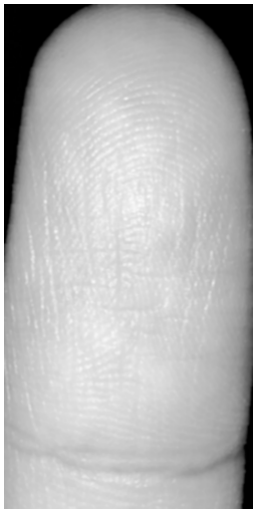


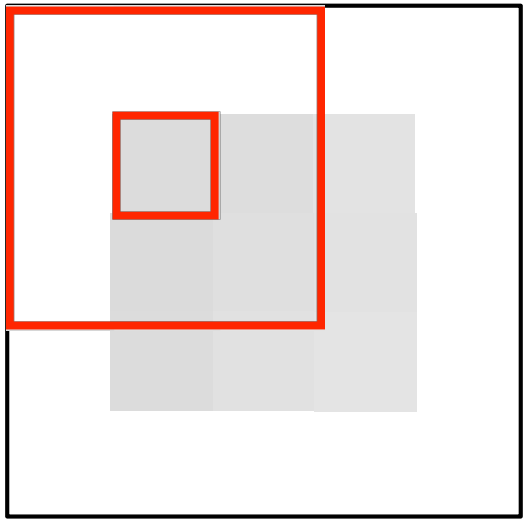
Zoomed Area



Gray Values

219	215	213	213	239
210	207	204	212	240
209	208	219	226	214
204	214	220	223	216
205	205	224	224	222

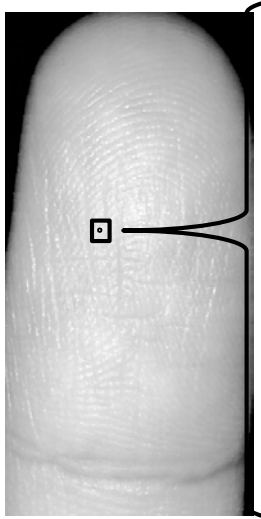




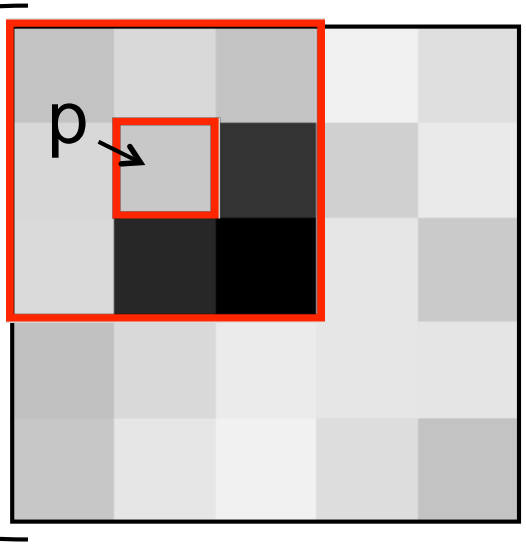
	212	213	220	
	211	215	219	
	212	218	221	

Median Filter - Smoothing with 3x3 Kernel

Image



Zoomed Area



Gray Values

195	217	195	240	223
216	200	51	208	234
218	39	0	230	202
193	217	235	230	229
199	230	241	221	195

Median filter is resistant against outliers

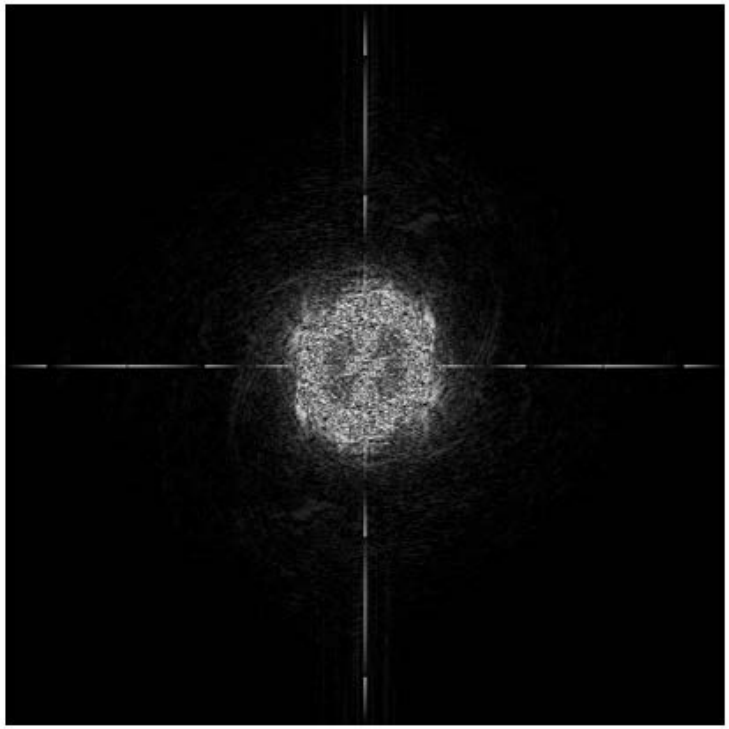
p_{median} = 0, 39, 51, 195, **200**, 210, 216, 217, 218 = **200**

$$p_{average} = \frac{195+217+195+216+200+51+218+39+0}{9} = \mathbf{147,89}$$

Preprocessing

Image Smoothing

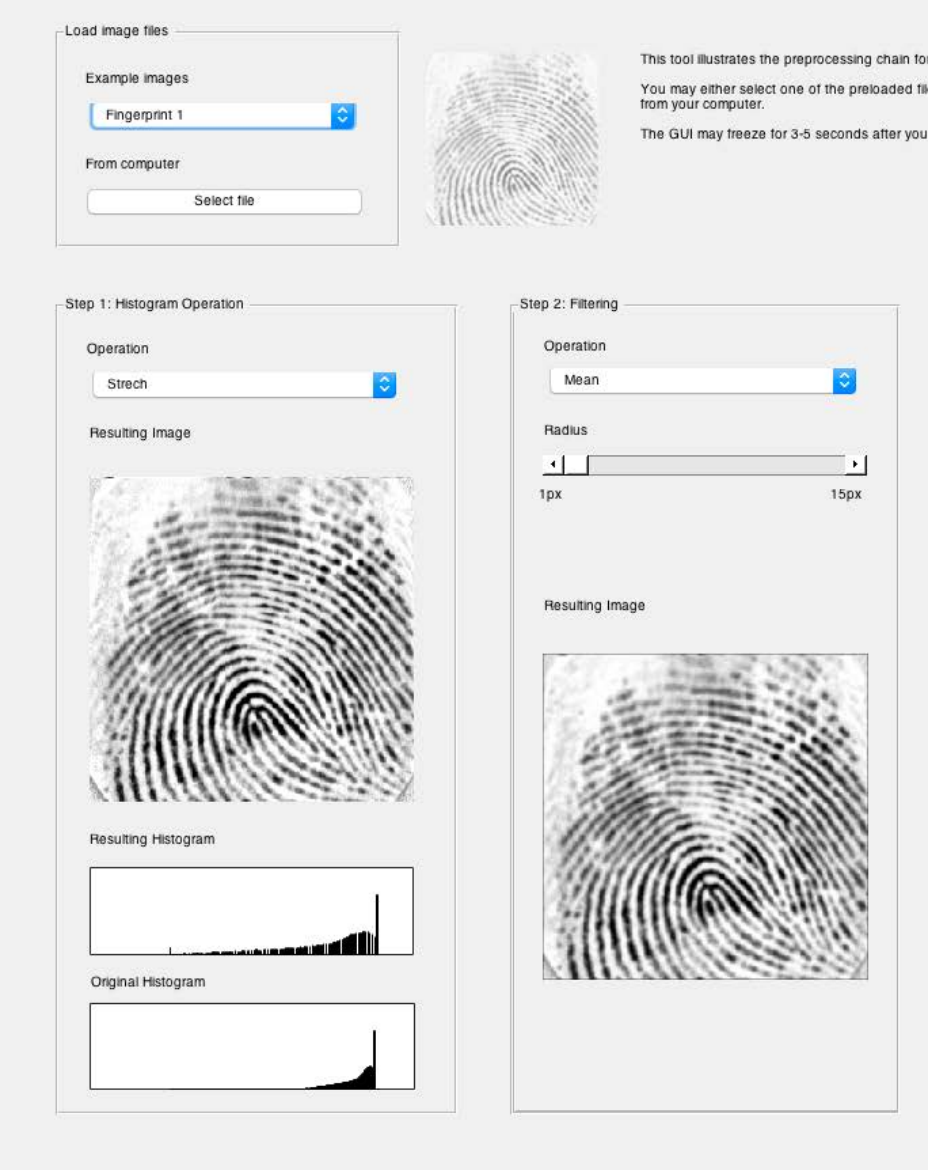
- Removal of noise and outliers
  - Low pass filtering in the Fourier domain



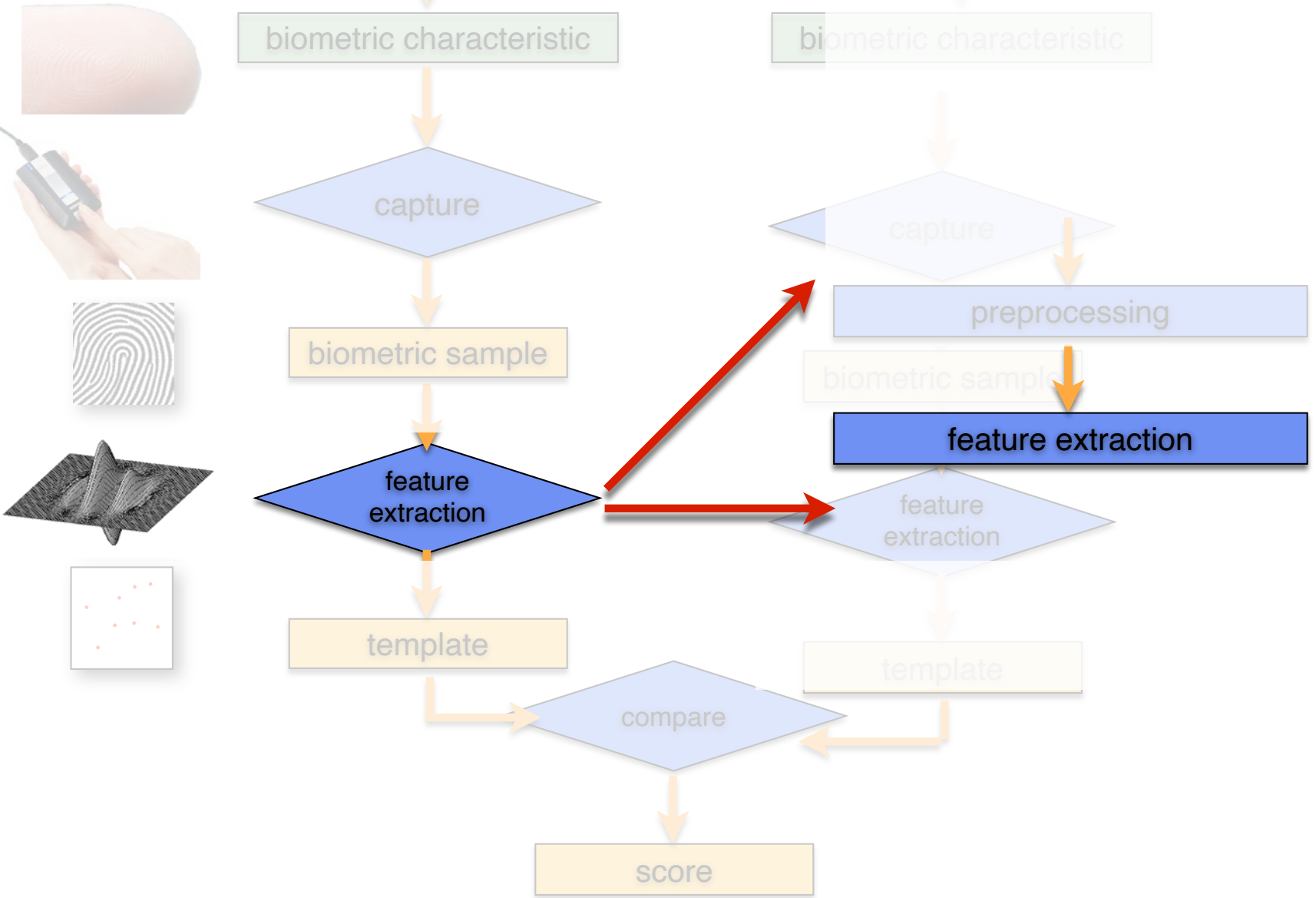
Preprocessing

Try the demo and play around

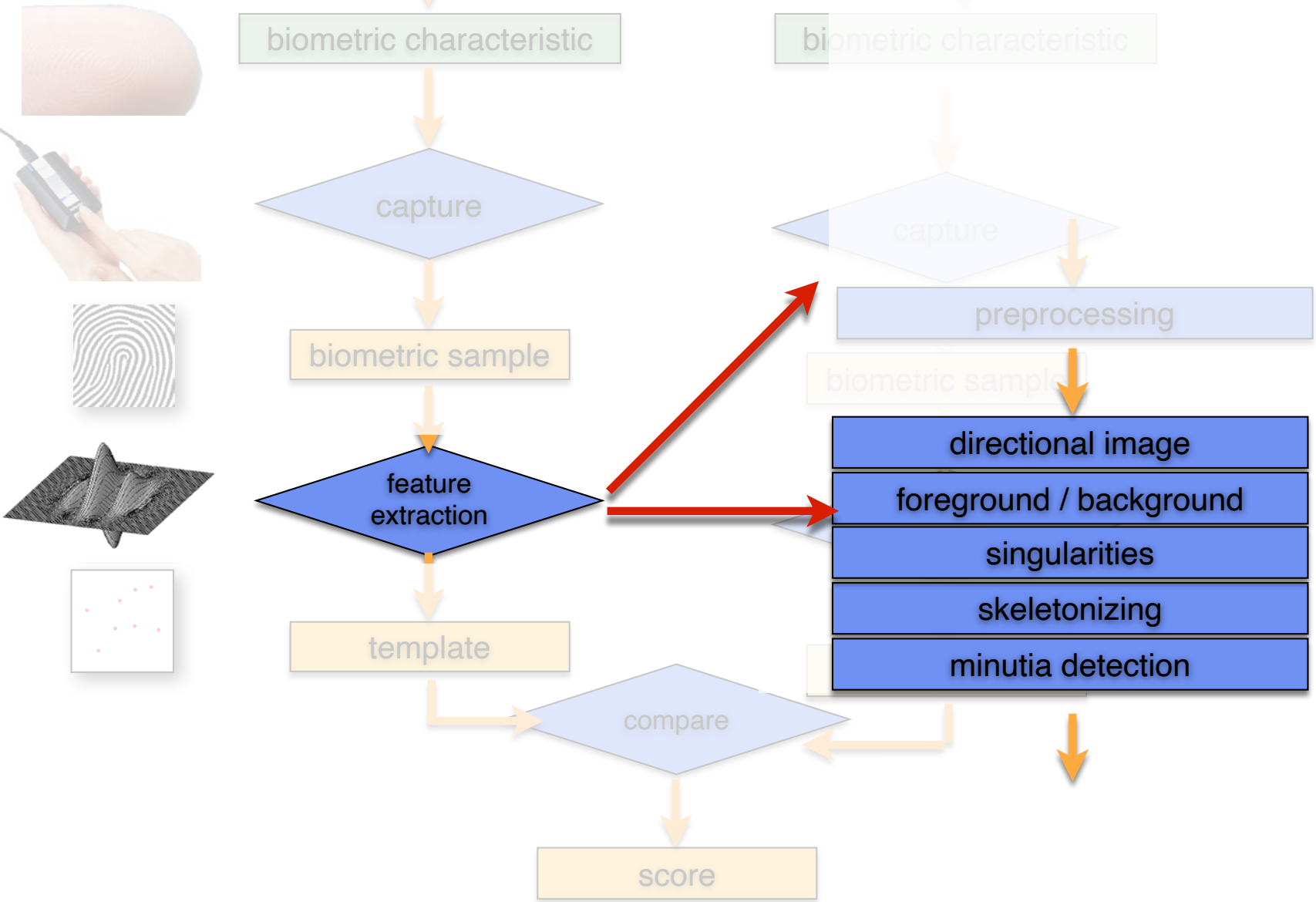
- Demos can be downloaded from the course website
- Demo requires MATLAB
- Preprocessing-Demo:
  - `fingerprint-enhancement-demo.zip`



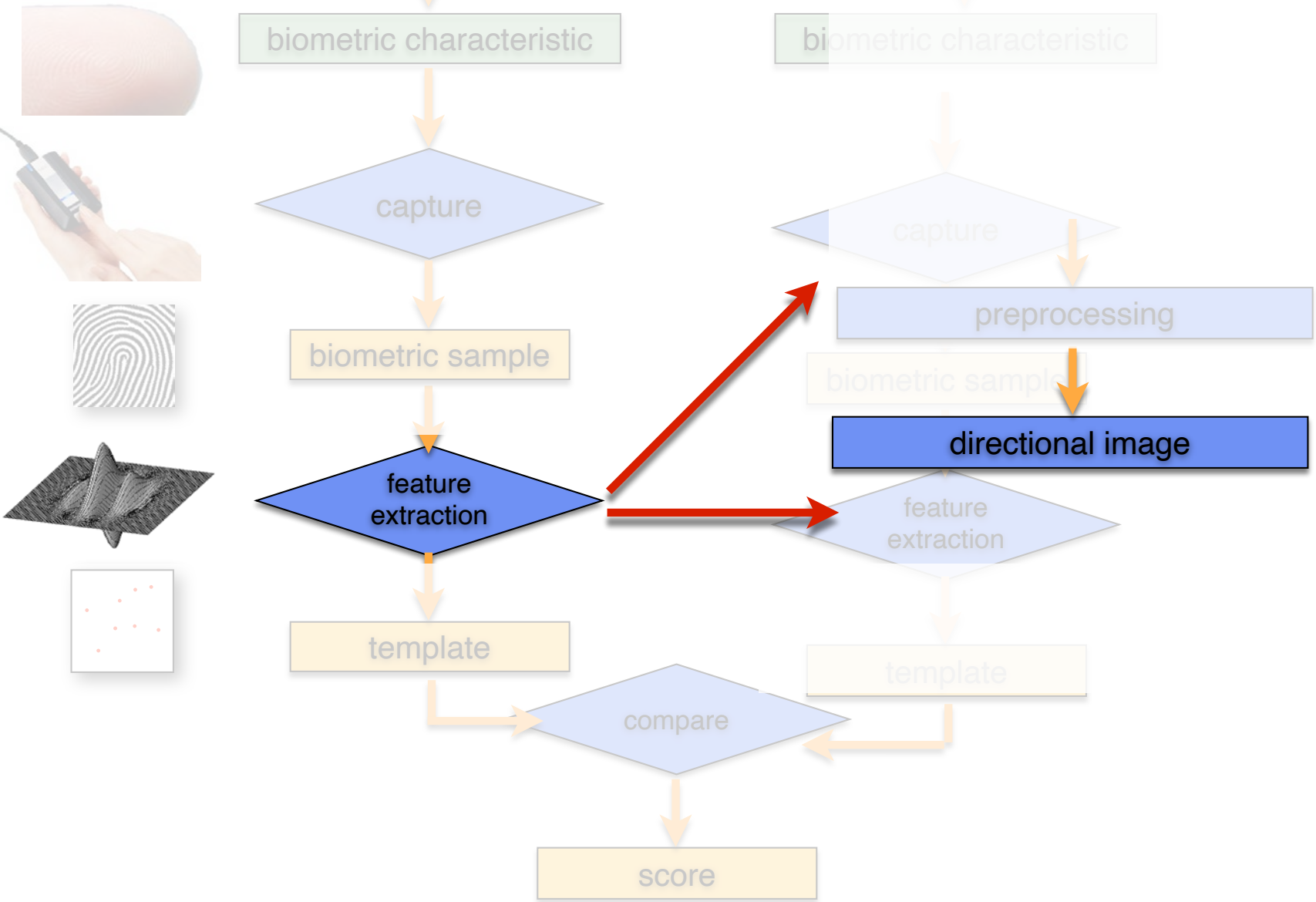
Feature Extraction



Feature Extraction



Feature Extraction



Feature Extraction

Determination of a directional image

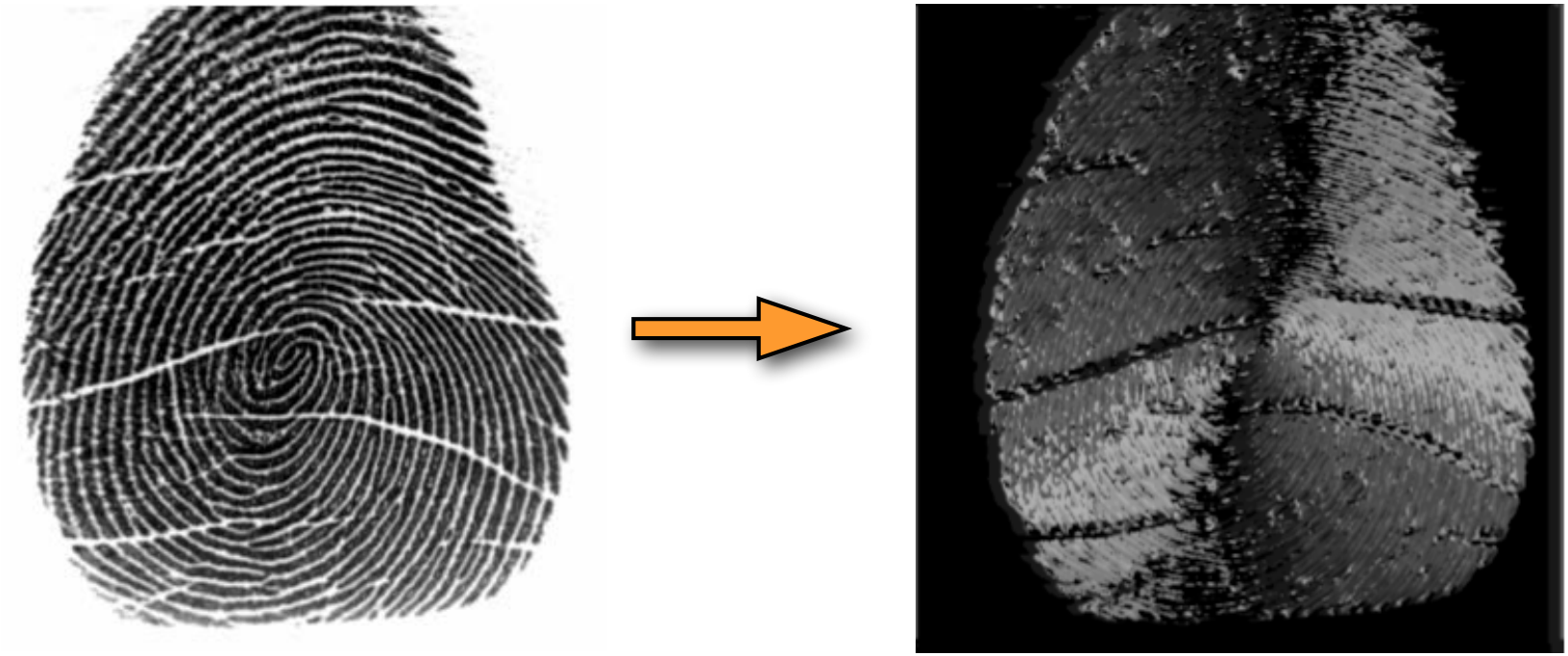
- We can determine the direction of the ridge in terms of the local grey values of the pixels
  - *d* = direction, which is quantized at *N* possible levels
  - *n* = number of pixels to use for direction estimation
  - $I_d(i_k, j_k)$ the grey level in a particular direction

$$\forall i \in \{1...R\}, j \in \{1...C\} : D(i,j) = \min_{d=0...N-1} \sum_{k=1}^{n} \left| I(i,j) - I_d(i_k, j_k) \right|$$

Feature Extraction

Determination of a directional image

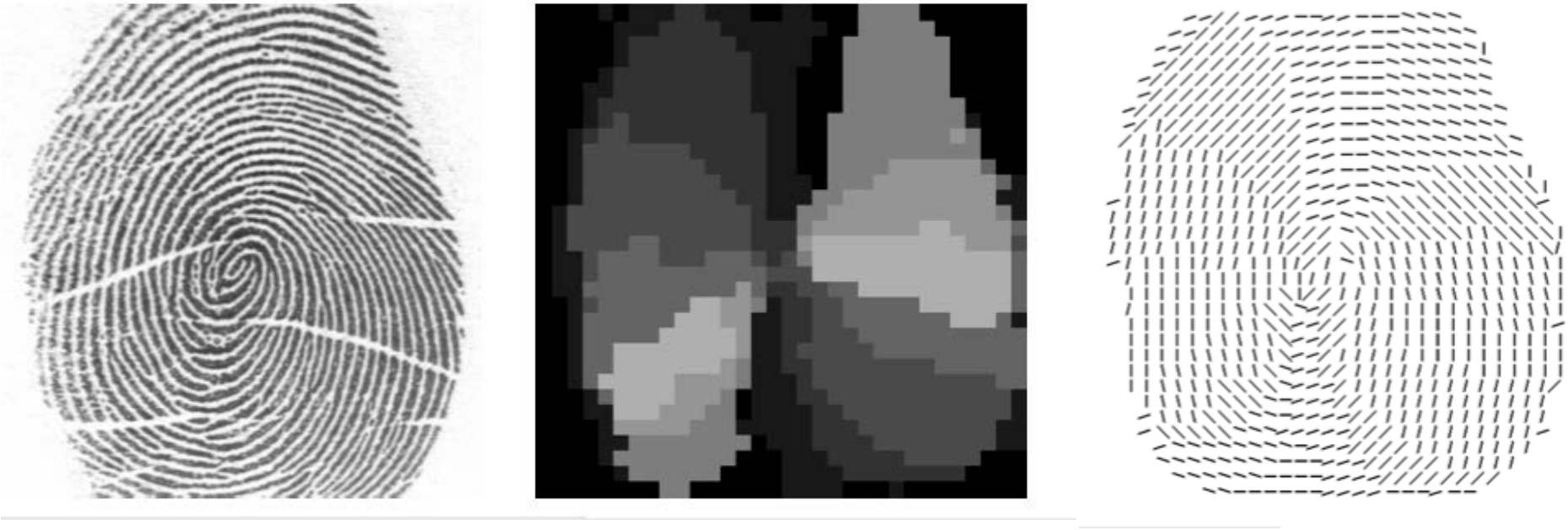
- The pixel-wise directional image is computationally complex



Feature Extraction

Determination of a directional image

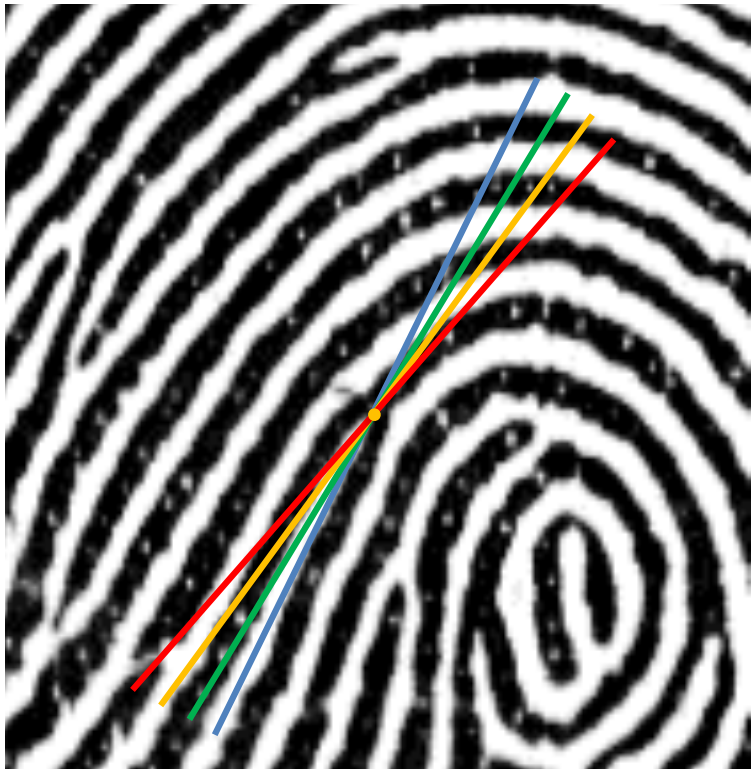
- Block-wise directional image
- Blocks of 16x16 or 32x32 pixels
- Orientation of the block is set to the most common direction of its pixels



Feature Extraction

Accuracy of directional estimation

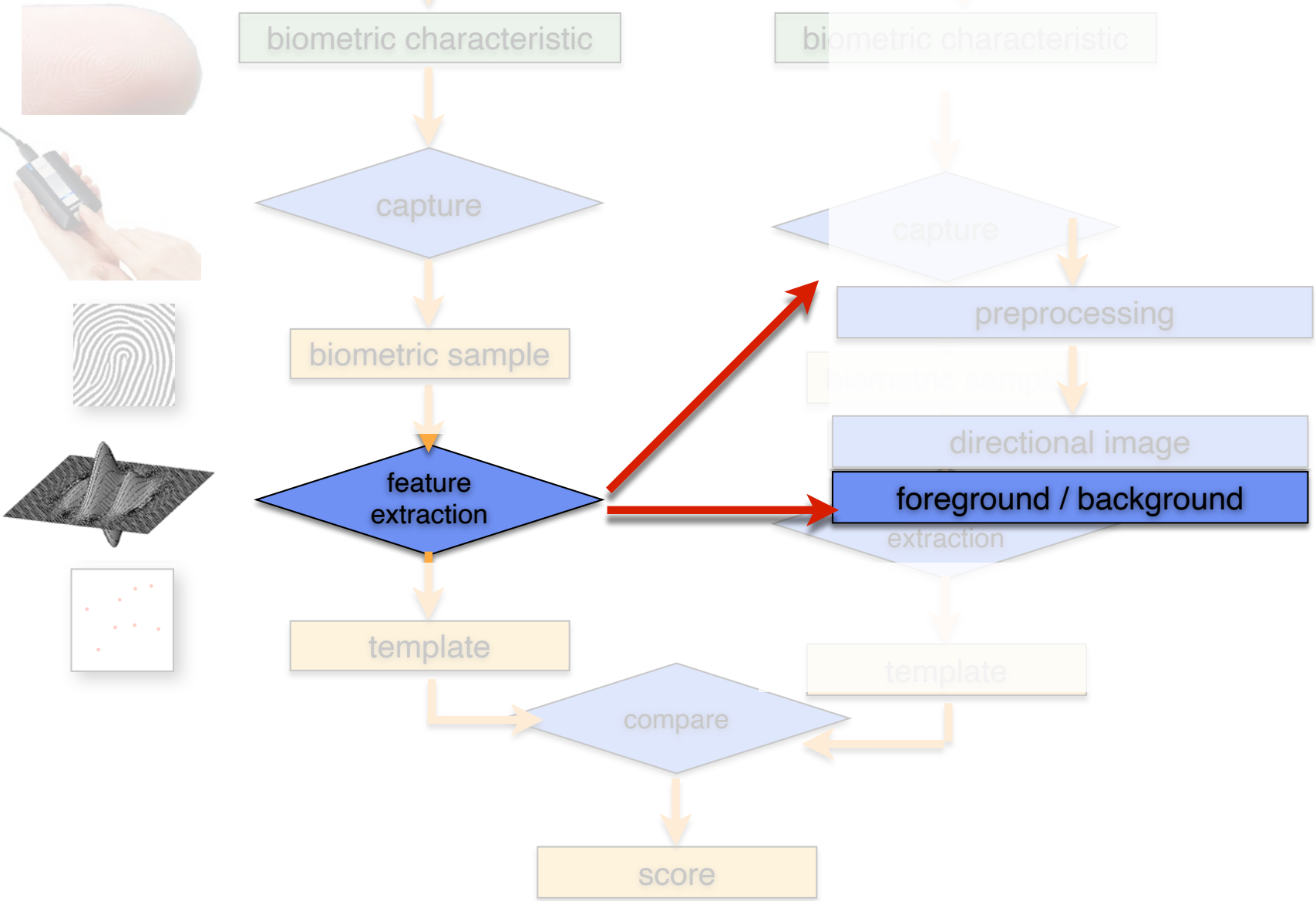
- Benchmark with human experts in their mark-up
- Which direction is correct and can you reproduce it?



- The limits are at ~5° for good quality images

[SSB17c] P. Schuch, S. Schulz, C. Busch: "Intrinsic Limitations of Fingerprint Orientation Estimation", in Proc. of the IEEE 16th International Conference of the Biometrics Special Interest Group (BIOSIG), Darmstadt, (2017)

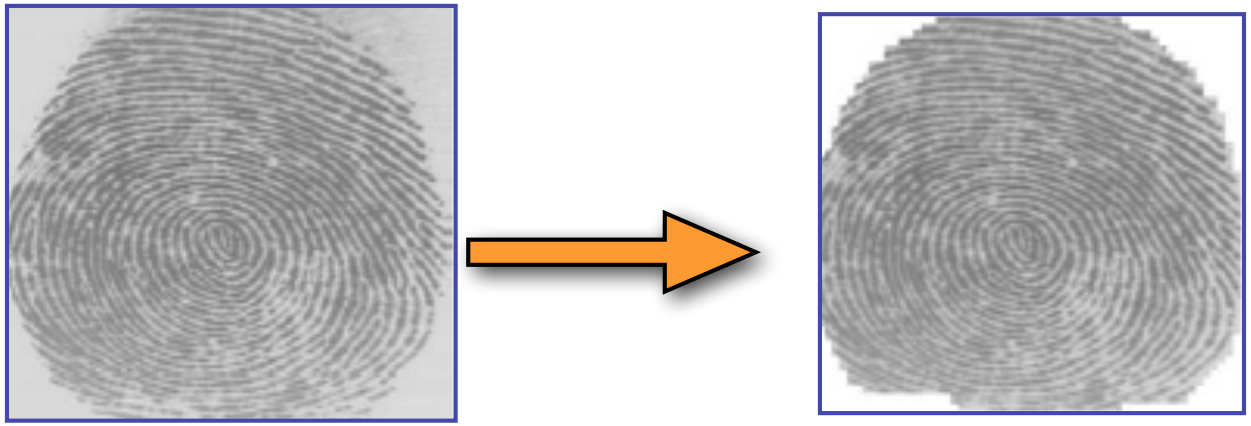
Feature Extraction



Segmentation of FP Area

Segmentation of foreground / background

- Separate the region of interest (ROI) in a fingerprint image where the finger actually had contact with the sensor
  - compute local contrast
- Goals
  - reduce the probability of false minutia determination in noisy areas
  - save execution time as filter operations are not applied on background area



Fingerprint image

Fingerprint ROI

Segmentation of FP Area

Segmentation of foreground / background

- For the foreground we seek for the presence of a striped and oriented pattern
- For the background we expect an isotropic pattern with no orientation
- Compute local contrast
  - Weber Contrast
  - Michelson Contrast

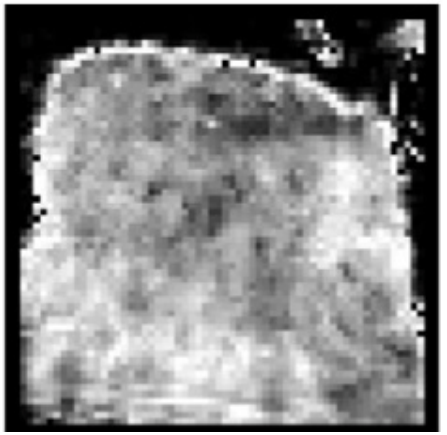
$$Con_{Michelson} = \frac{in_{max} - in_{min}}{in_{max} + in_{min}}$$

Segmentation of FP Area

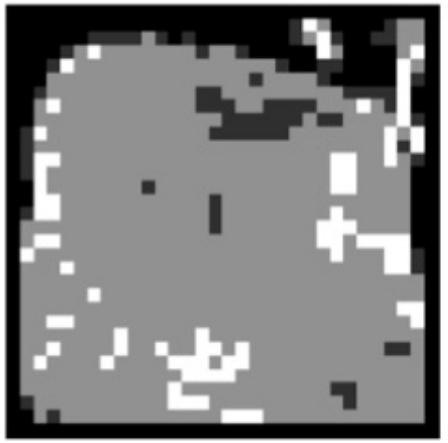
Segmentation of foreground / background

- Other approaches to measure anisotropy
  - presence of well defined peak in a local histogram of orientations (Mehtre 1987)
  - variance of the grey-levels in direction orthogonal to the gradient as illustrated on the right. (Ratha 1995)
  - magnitude of the gradient (Maio and Maltoni 1997)

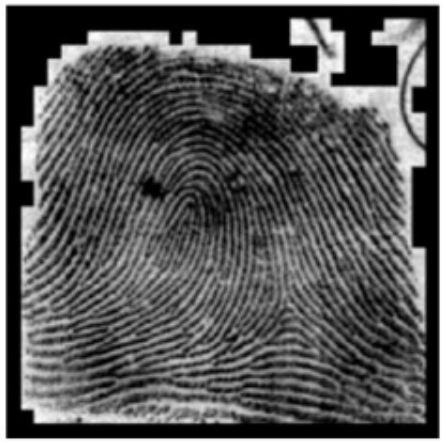
Original image



Variance image



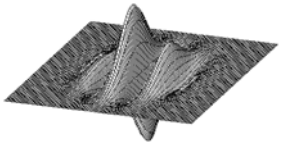
Quality image: „good“, „medium“ or „poor“



Segmented image

Source: D. Maltoni, 2012

Feature Extraction



biometric characteristic

capture

biometric sample

feature extraction

template

compare

score

preprocessing

directional image

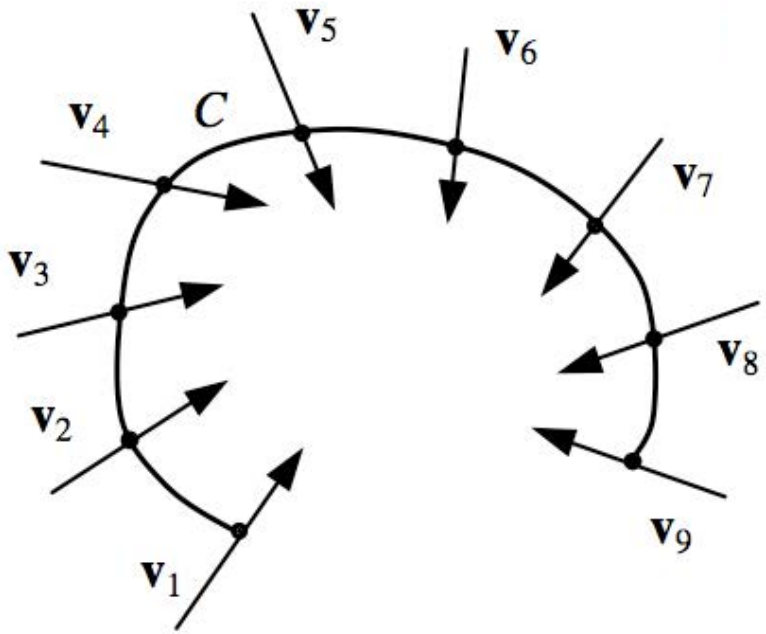
foreground / background

singularities

Singularities - Core and Delta Detection

Poincare index (Kawagoe and Tojo 1984)

- Let ***G*** be a vector field and *C* be a curve in ***G*** then
  - the Poincare index *P* is defined as the total rotation of the vectors of ***G*** along *C* and is
  - algebraically summing the orientation differences between adjacent elements of *C*



Source: D. Maltoni, 2009

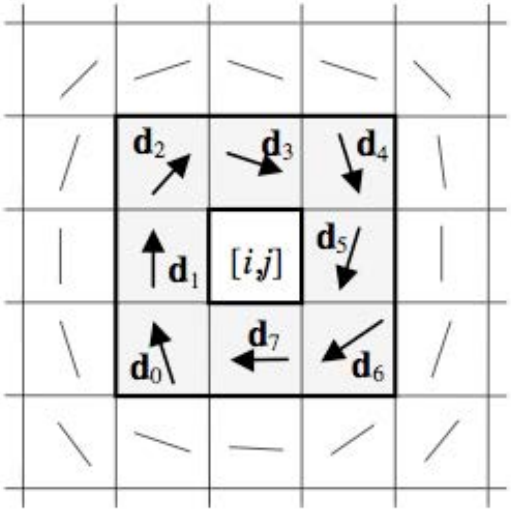
The Poincaré index computed over a curve C in a vector field

Singularities - Core and Delta Detection

Poincare index

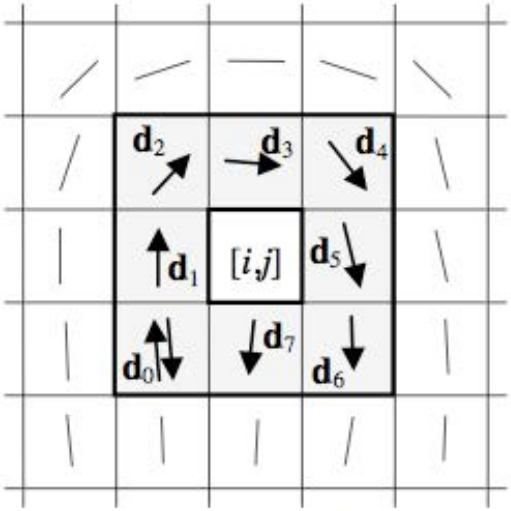
- The Poincaré index is computed as

$$P_{G,C}(i,j) = \sum_{k=0..7} angle\left(\mathbf{d}_k, \mathbf{d}_{(k+1) \bmod 8}\right).$$



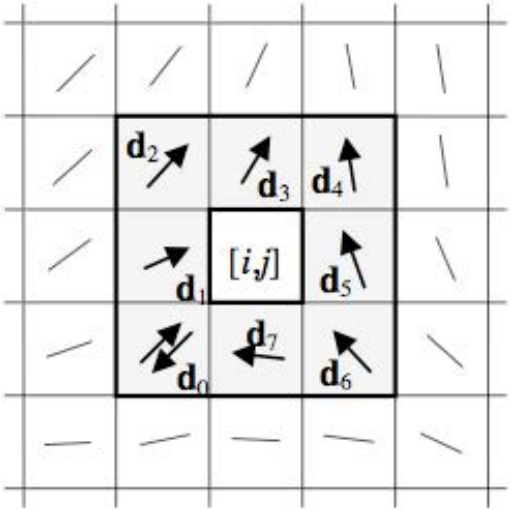
$P_{G,C}(i,j) = 360°$

Whorl



$P_{G,C}(i,j) = 180°$

Loop



$P_{G,C}(i,j) = -180°$

Delta

Source: D. Maltoni, 2009

Singularities - Core and Delta Detection

Poincare index

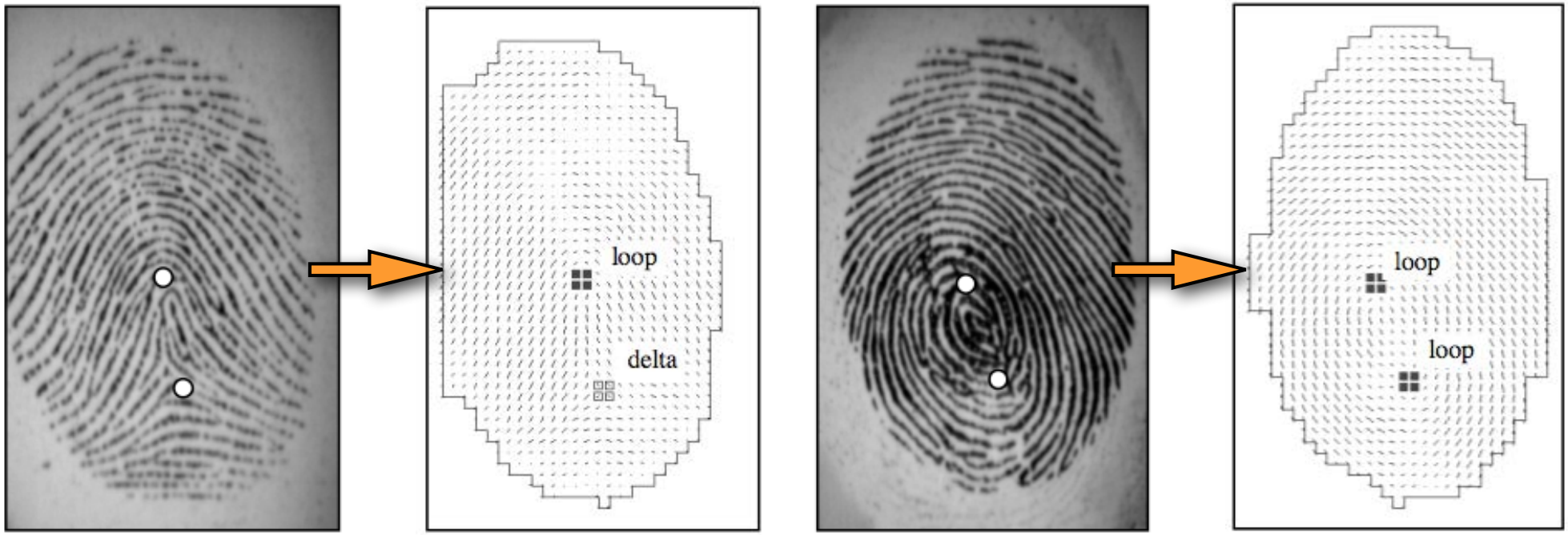
- On closed curves the Poincaré index assumes only one of the discrete values: 0°, ±180°, and ±360°.
- In the case of fingerprint singularities:

$$P_{\mathbf{G},C}(i,j) = \begin{cases} 0° & \text{if } [i,j] \text{ does not belong to any singular region} \\ 360° & \text{if } [i,j] \text{ belongs to a whorl type singular region} \\ 180° & \text{if } [i,j] \text{ belongs to a loop type singular region} \\ -180° & \text{if } [i,j] \text{ belongs to a delta type singular region} \end{cases}$$

Source: D. Maltoni, 2009

Singularities - Core and Delta Detection

Poincare index - Examples



Singularity detection by using the Poincaré index method.

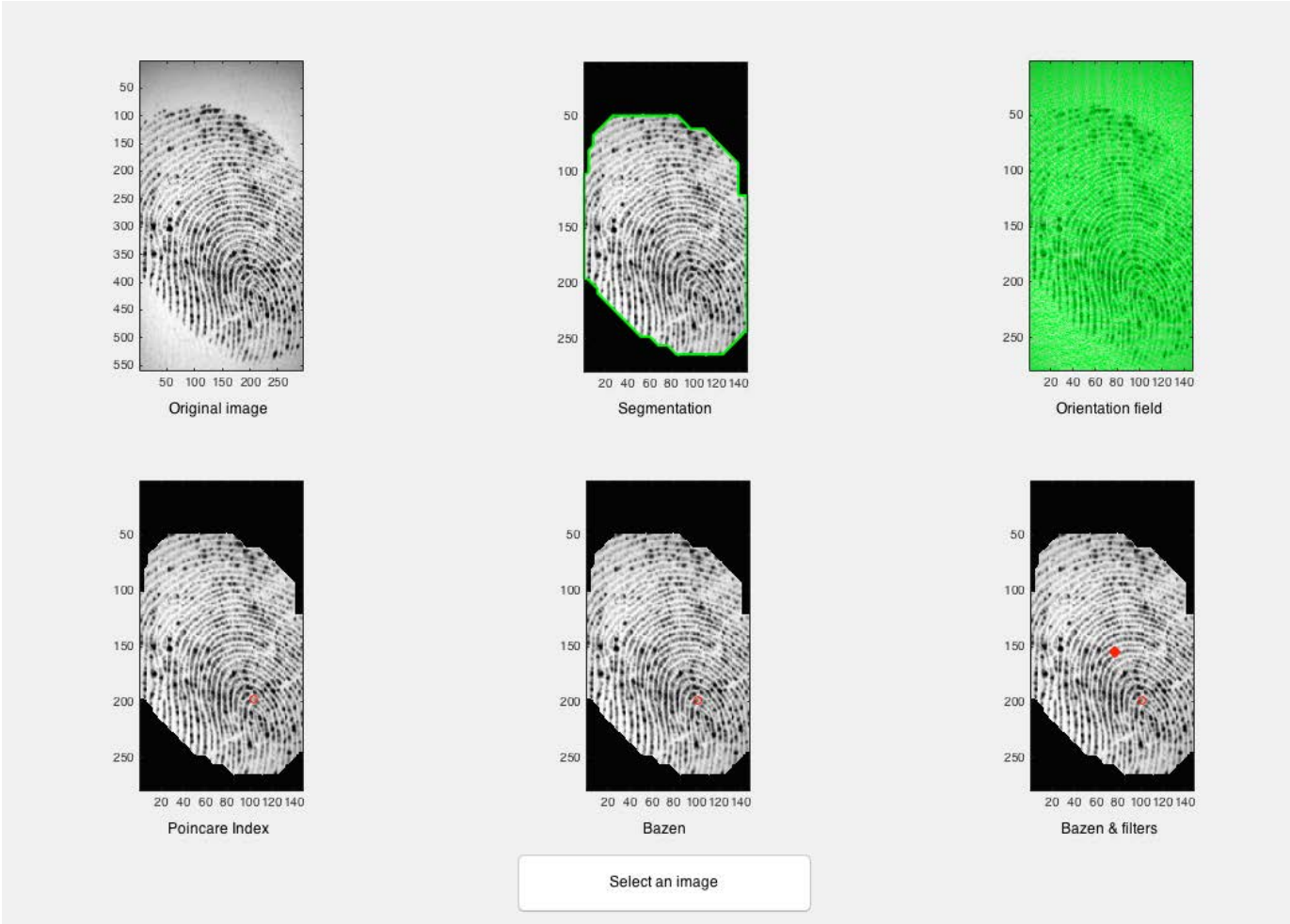
- The elements whose Poincaré index is 180° (loop/core) or -180° (delta) are enclosed by small boxes.
- Usually, more than one point is found for each singular region:
  - hence, the center of each singular region can be defined as the barycenter of the corresponding points.

Source: D. Maltoni, 2009

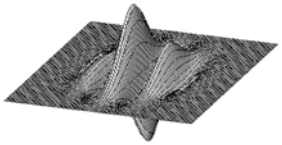
Demonstration

Try the demo and play around

- Singularity Point Detection Demo:
  - `fingerprint-singularity-detection.zip`



Feature Extraction



biometric characteristic

capture

biometric sample

feature extraction

template

compare

score

biometric characteristic

capture

preprocessing

biometric sample

directional image

foreground / background

singularities

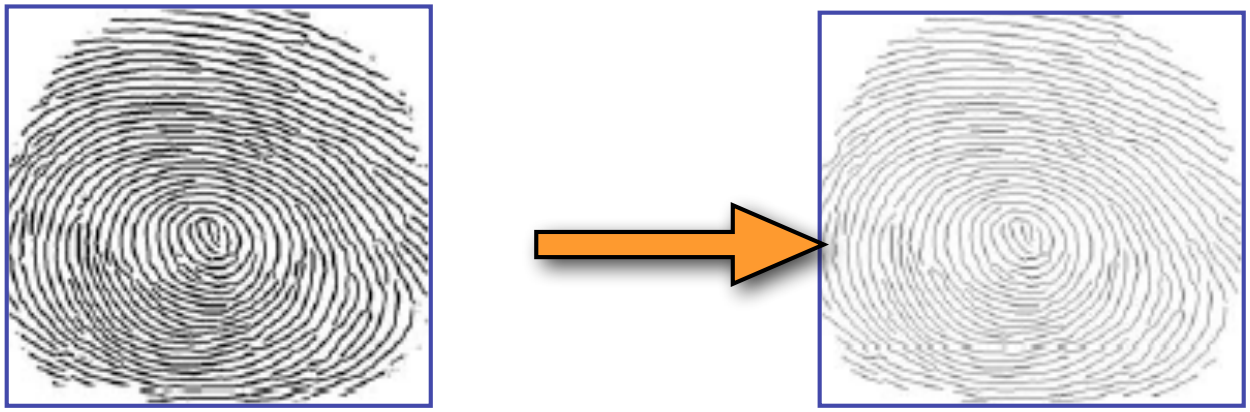
skeletonizing

template

Feature Extraction

Skeletonising

- Objective: Thinning of the ridge line such that remaining line is one pixel wide
- Goal: Positioning of minutia points on the pixel level



Extracted lines

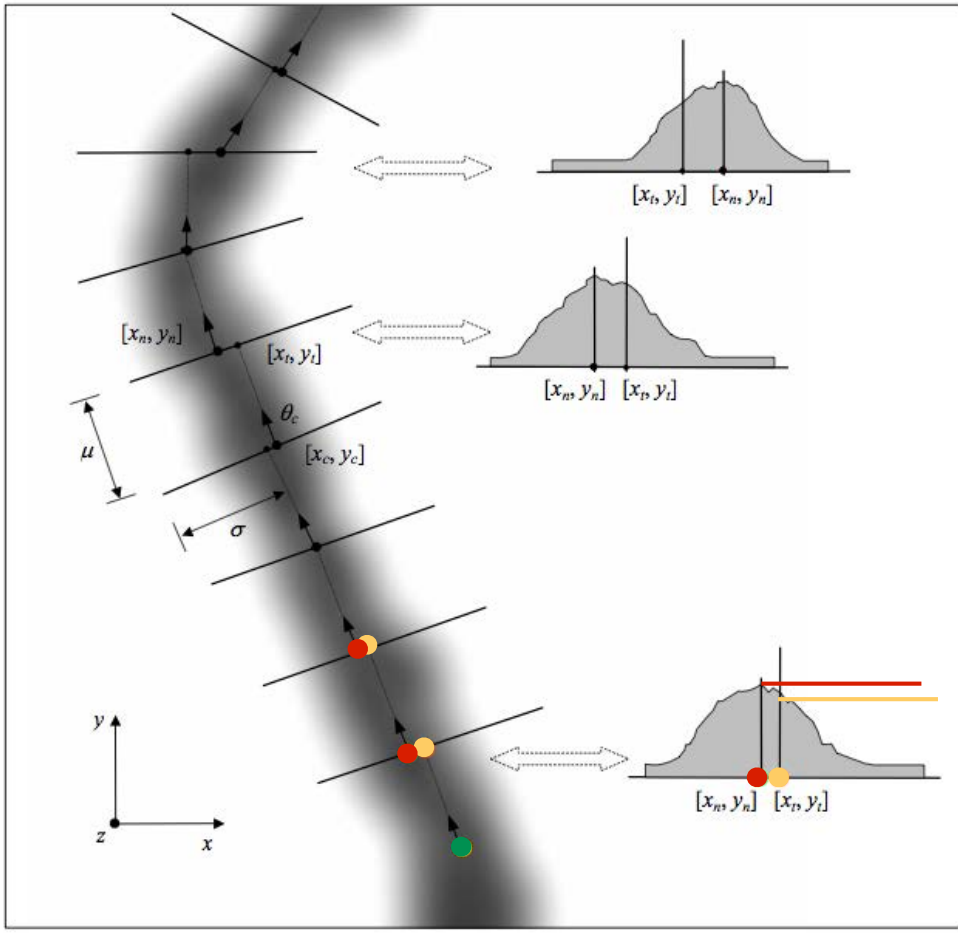
Thinned lines

- Methods
  - Ridge line tracing on grey level images
  - Skeletonisation on binarised images

Feature Extraction

Ridge Line Tracing - Direct grey scale extraction

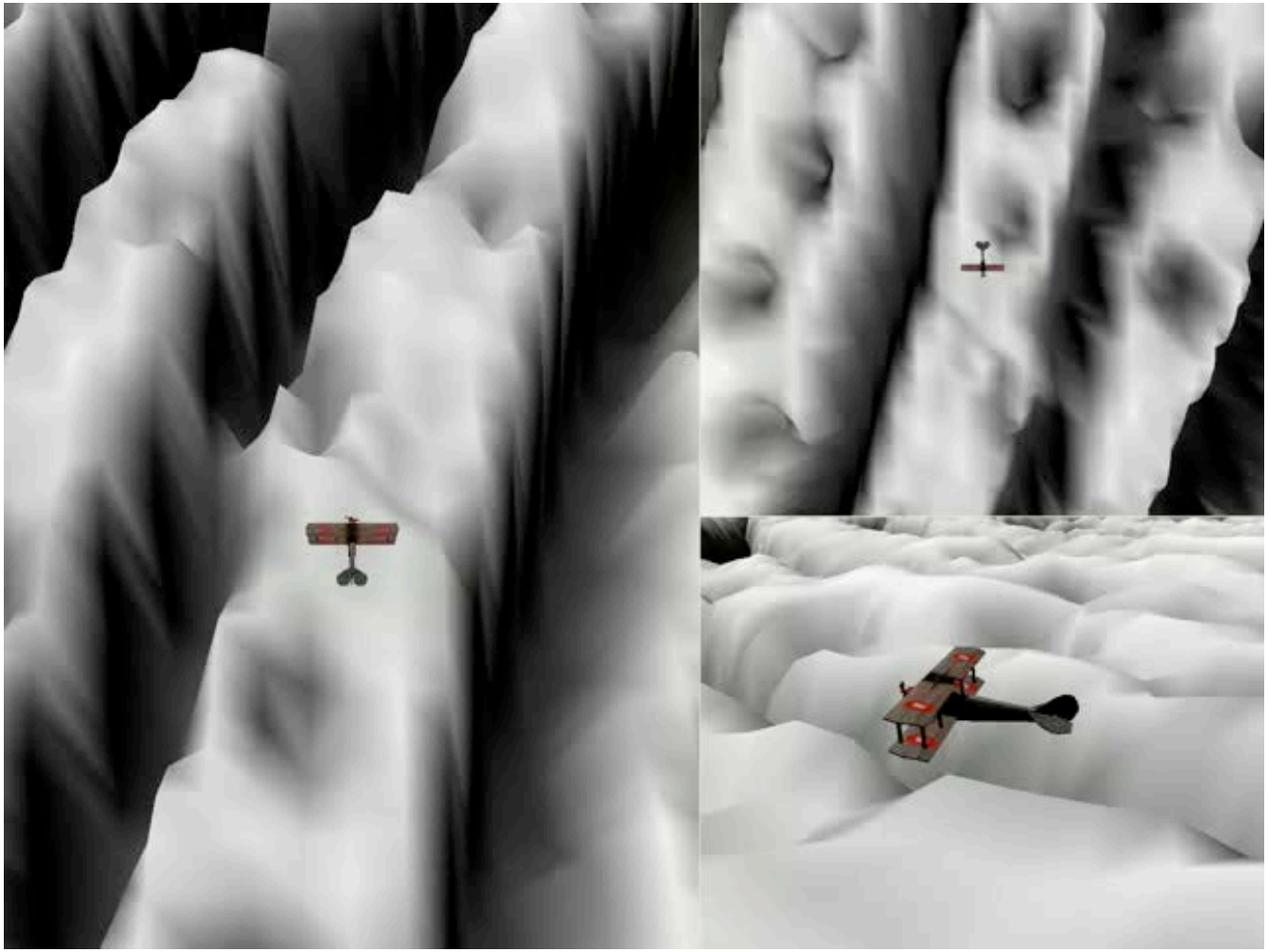
- Walk along the top of the grey level ridge
- Steps
  - First at the green point
  - Move N pixel forward along the estimated ridge direction
  - When you reach the yellow point analyze the cross section profile and find the local maxima
  - Continue with adapted direction until stop criteria is reached
  - Linking the red local maxima points provides the skeleton segment



Feature Extraction

Ridge Line Tracing

- Progress along detected skeletal points

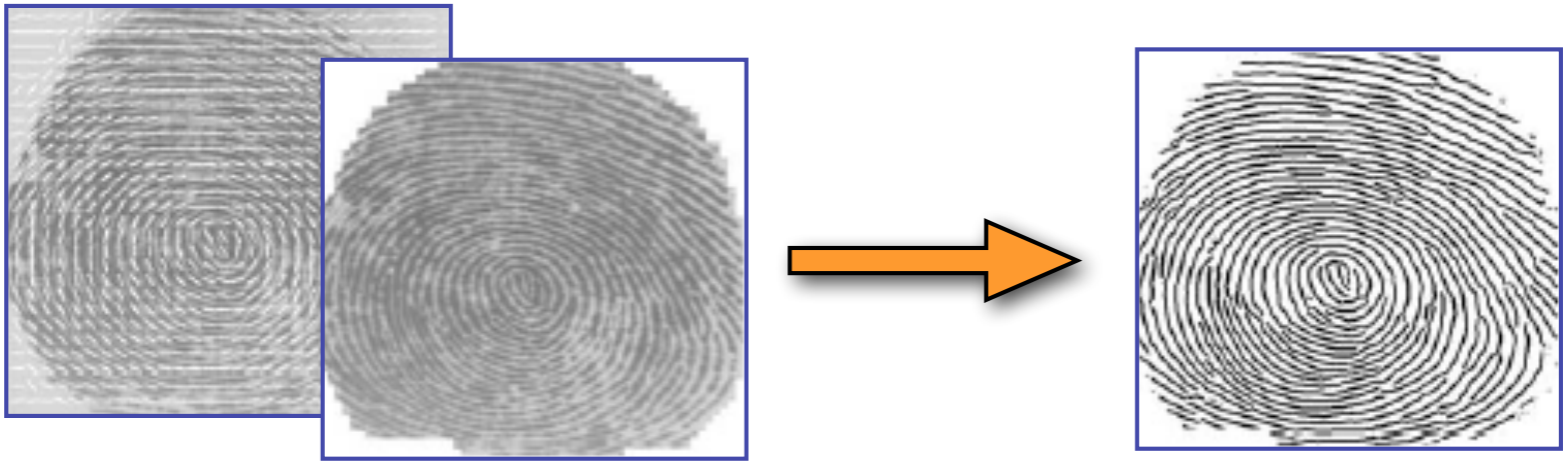


Source: Davide Maltoni 2012

Feature Extraction

Binarisation

- Convert grey-scale representation into a binary image
- Define threshold and assign any pixel, whose grey value exceeds it, as white
  - Regional Average Thresholding (RAT) improves the result
- Goal: Extraction of ridge lines



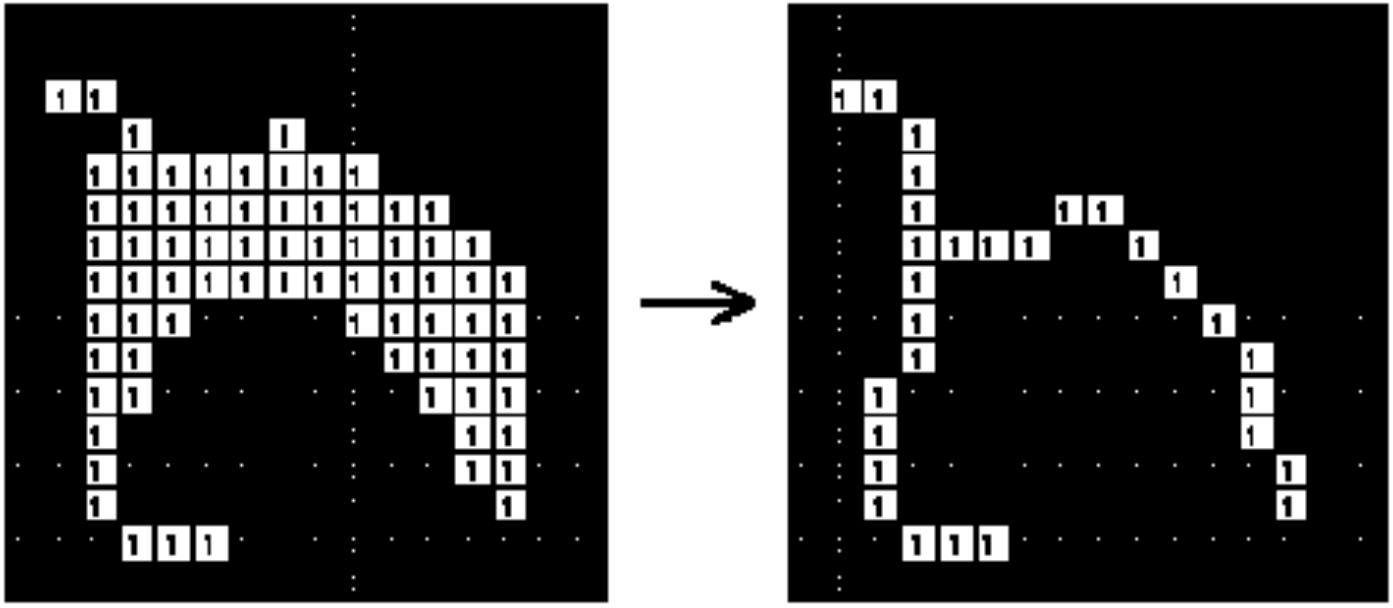
Directional image
+ region of interest

Extracted lines
(binary image)

Feature Extraction

Skeletonising - Thinning through Erosion

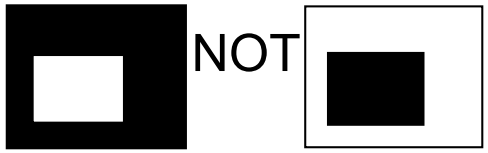
- Operates on binary images
- Remove pixel by pixel,
  until line structures have a width of one
- Options
  - a) Distance transform
  - b) Morphological operation
    Erosion



Morphological Operations

Logical Operations

- NOT operation / negation
  - *The monadic Boolean operation whose result has the Boolean value opposite to that of the operand.*



- AND operation / conjunction / intersection
  - *The Boolean operation whose result has the Boolean value 1 if and only if each operand has the Boolean value 1.*

- OR operation / INCLUSIVE-OR / logical add
  - *The Boolean operation whose result has the Boolean value 0 if and only if each operand has the Boolean value 0.*

- XOR EXCLUSIVE-OR / non-equivalence operation
  - The Boolean operation whose result has the Boolean value 1 if and only if the operands have different Boolean values.

Morphological Operations

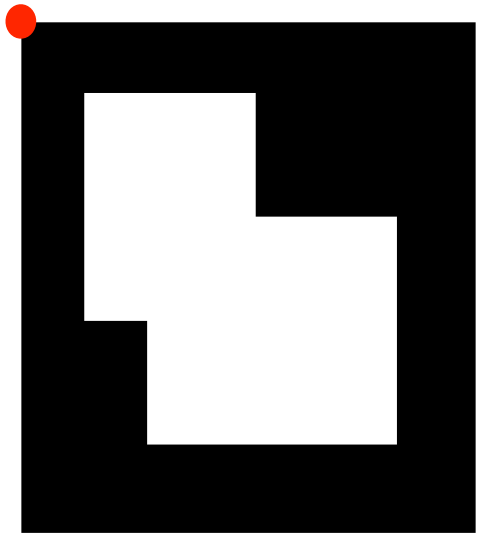
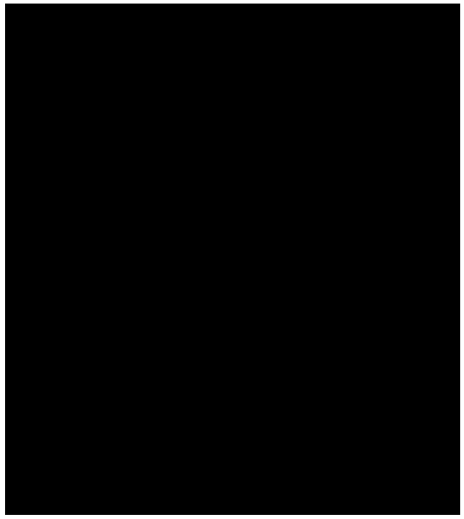


Image $A \subset \mathbb{Z}^2$

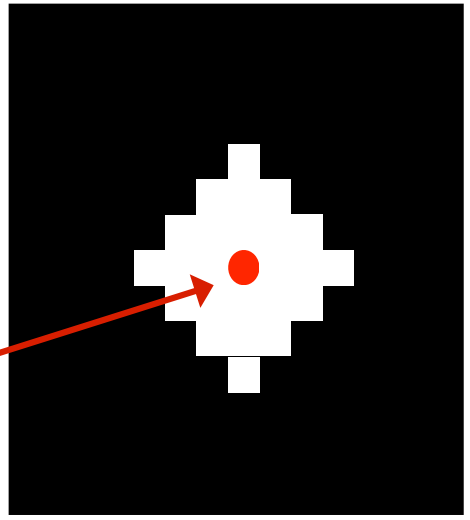
$a \in A: \; a = (a_1, a_2) \; is \; element \; of \; A$

$a \notin A: \; a = \; is \; not \; element \; of \; A$



Empty Set

$\emptyset = \{\;\}$



Structure element

$B \subset \mathbb{Z}^2$

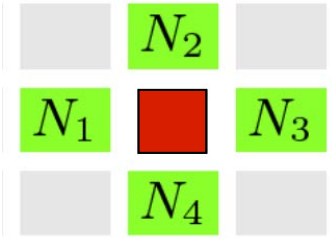
$b \in B$

Morphological Operations

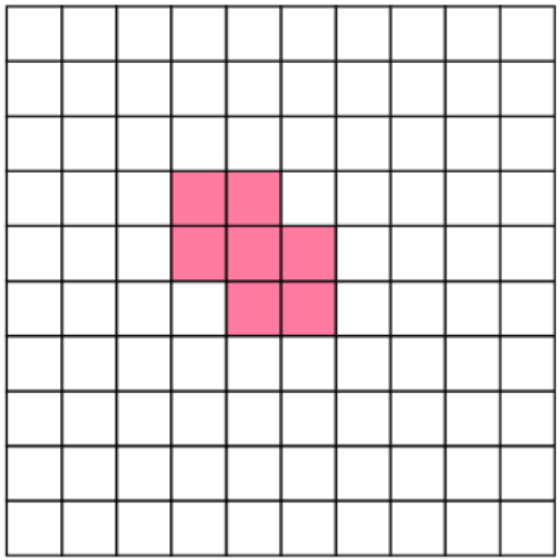
Translation	$(A)_x = \{a_x \mid a_x = a + x, a \in A\}$
Reflection	$\hat{A} = \{\hat{a} \mid \hat{a} = -a, a \in A\}$
Complement	$\bar{A} = A^c = \{\bar{a} \mid \bar{a} = \notin A\}$
Difference	$A - C = \{x \mid x \in A, x \notin C\} = A \cap \bar{C}$
Dilation	$A \oplus B = \{x \mid (\hat{B})_x \cap A \neq \emptyset\}$
Erosion	$A \ominus B = \{x \mid (B)_x \subseteq A\}$
Opening	$A \circ B = (A \ominus B) \oplus B$
Closing	$A \bullet B = (A \oplus B) \ominus B$

Morphological Operations

Dilation $A \oplus B = \{x \mid (\hat{B})_x \cap A \neq \emptyset\}$

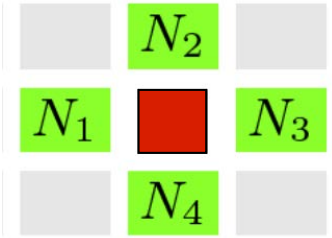


- Binary image plus structuring element
- Rule:
  Change a background pixel to foreground,
  if it has a foreground pixel as 4-neighbor



Morphological Operations

Dilation $A \oplus B = \{x \mid (\hat{B})_x \cap A \neq \emptyset\}$



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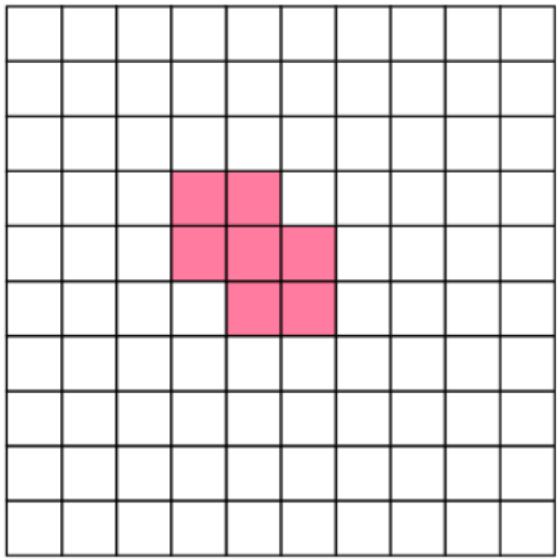
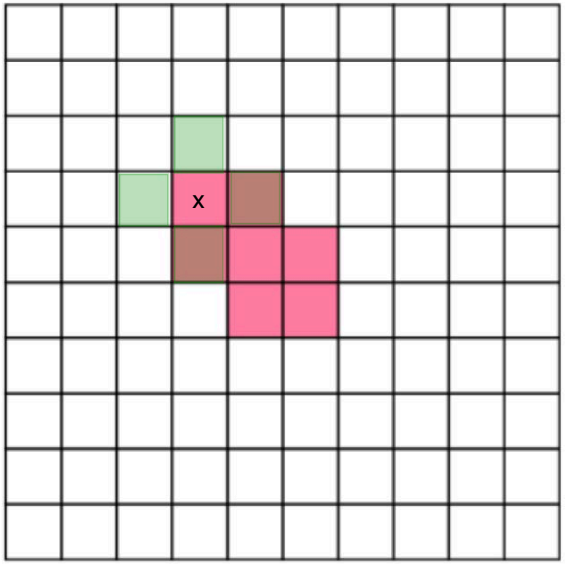
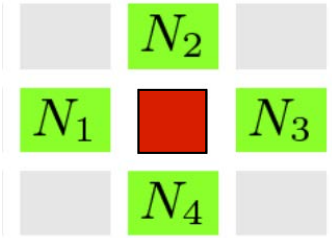




Morphological Operations

Dilation $$A \oplus B = \{x \mid (\hat{B})_x \cap A \neq \emptyset\}$$



- Binary image plus structuring element
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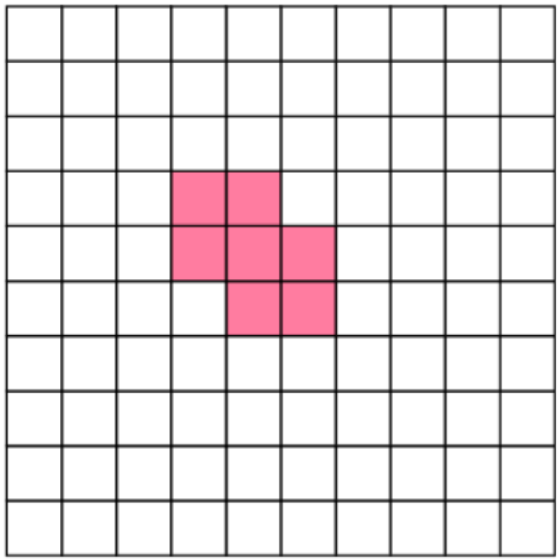
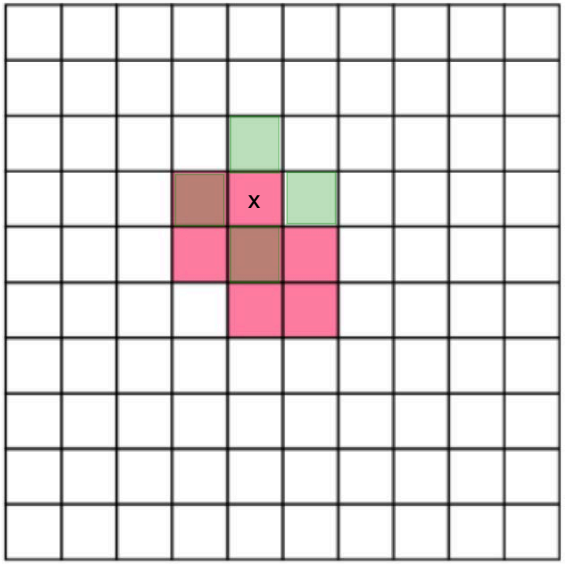
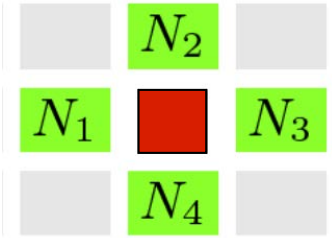
  if it has a foreground pixel as 4-neighbor





Morphological Operations

Dilation $$A \oplus B = \{x \mid (\hat{B})_x \cap A \neq \emptyset\}$$



- Binary image plus structuring element
- Rule:
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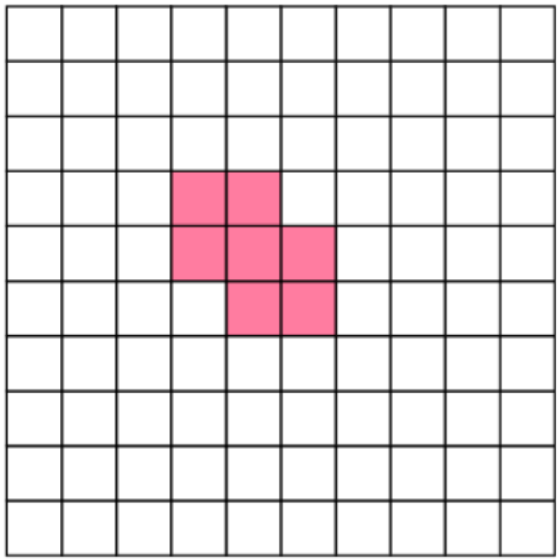
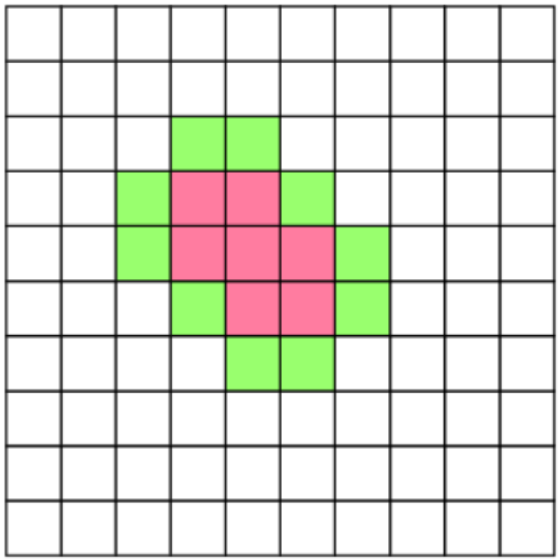
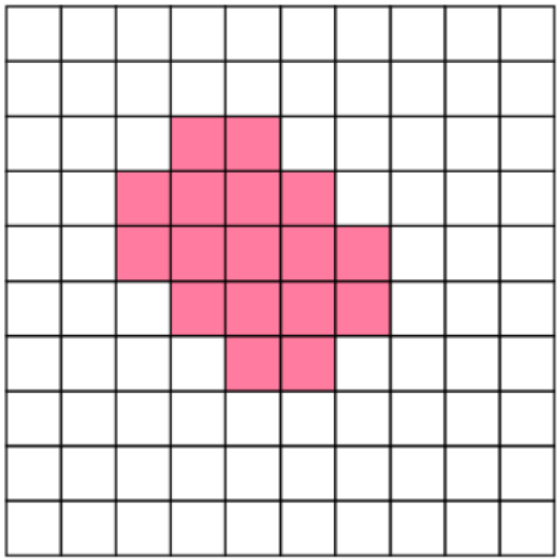
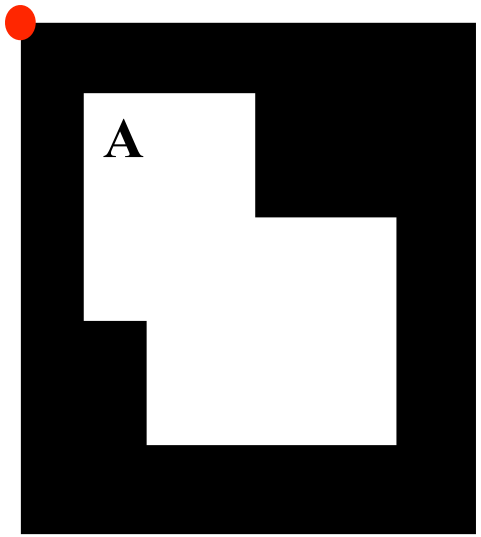




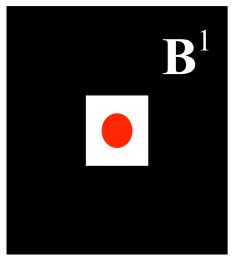


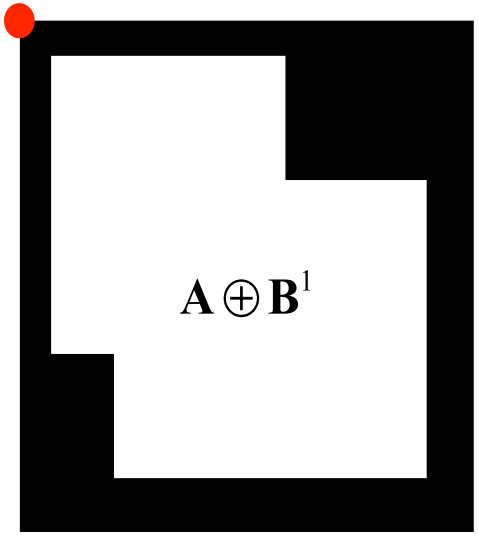
Morphological Operations

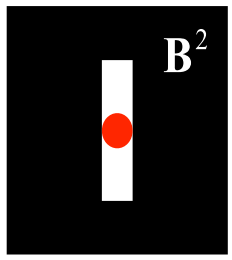
Dilation $A \oplus B = \{x \mid (\hat{B})_x \cap A \neq \emptyset\}$

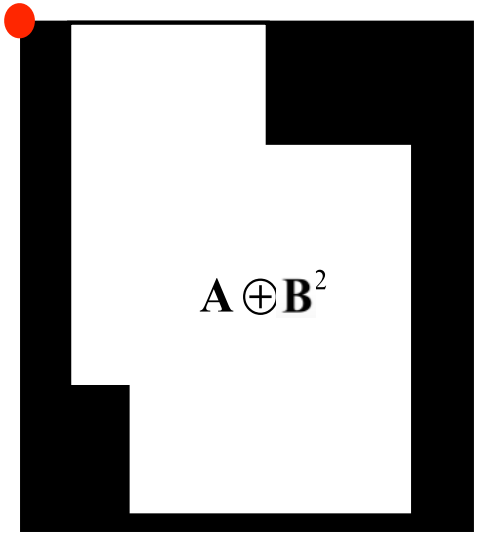


- Binary image plus structuring element
- The object edge outline takes the shape of the structuring element



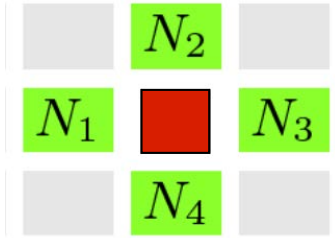




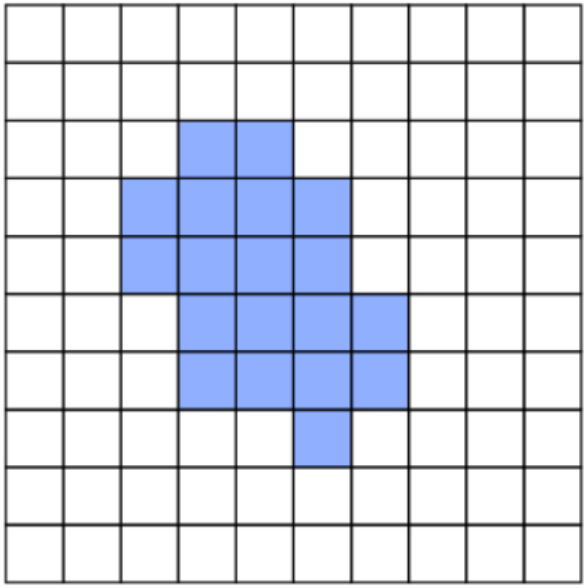


Morphological Operations

Erosion $$A \ominus B = \{x \mid (B)_x \subseteq A\}$$

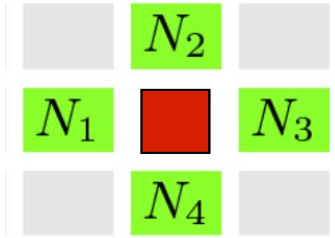


- Binary image minus structuring element
- Rule:
  Change a foreground pixel to background,
  if it has a background pixel as 4-neighbor



Morphological Operations

Erosion $$A \ominus B = \{x \mid (B)_x \subseteq A\}$$



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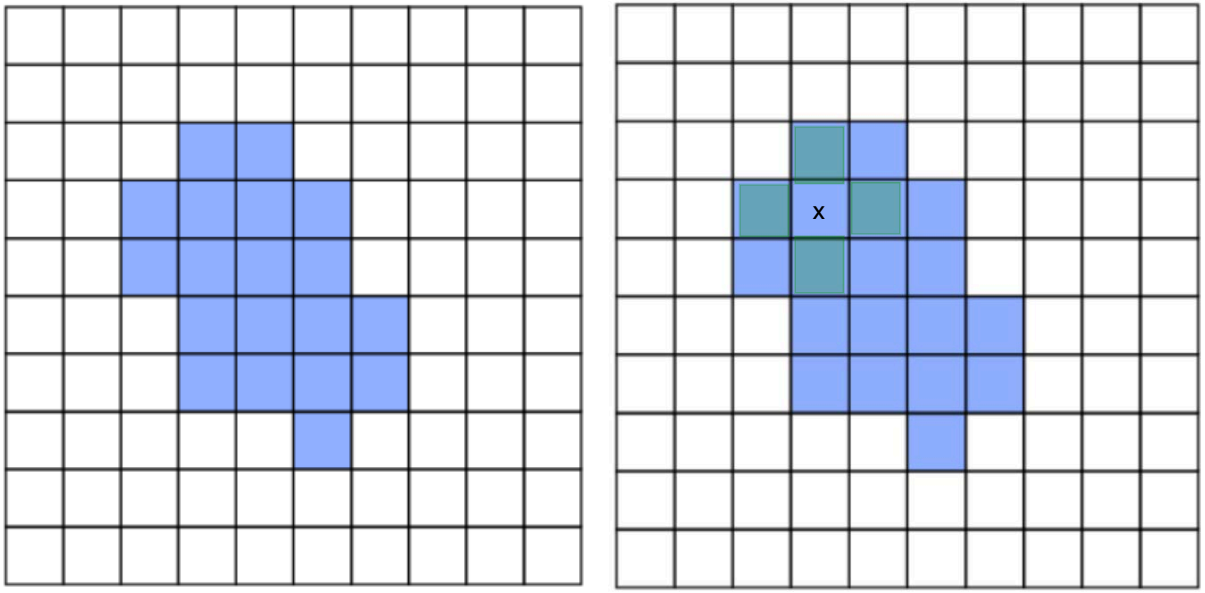
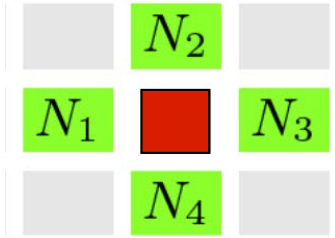


Morphological Operations

Erosion $$A \ominus B = \{x \mid (B)_x \subseteq A\}$$



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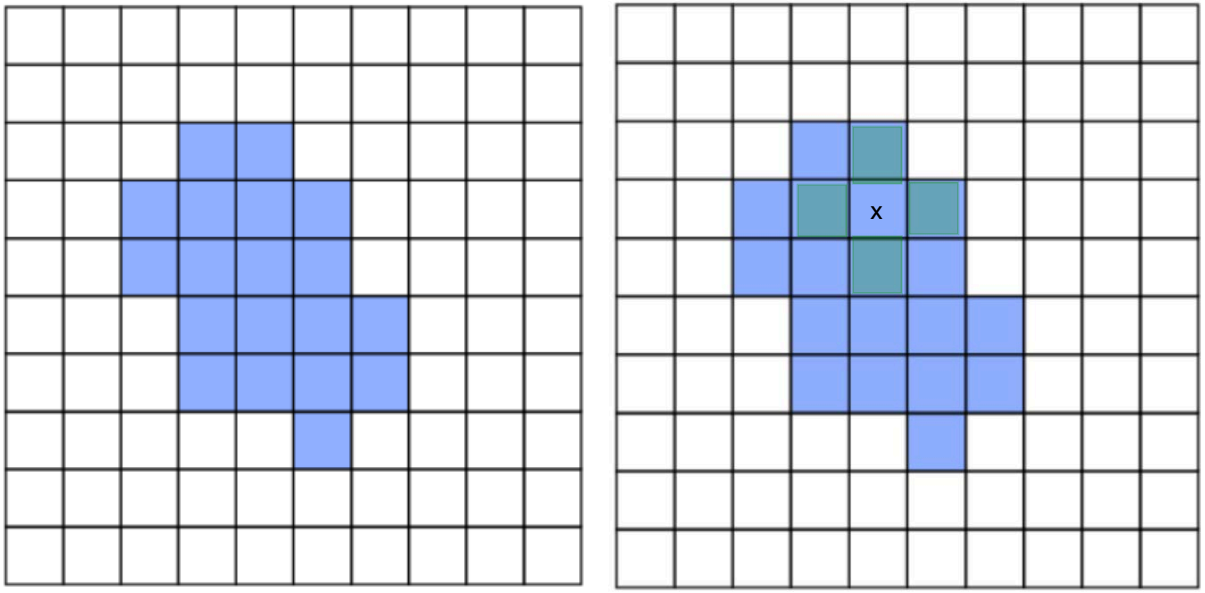
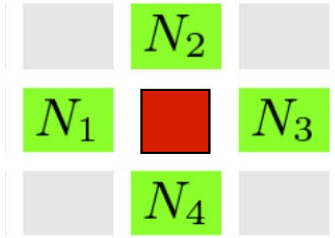
- Rule:
  Change a foreground pixel to background,
  if it has a background pixel as 4-neighbor



Morphological Operations

Erosion $$A \ominus B = \{x \mid (B)_x \subseteq A\}$$



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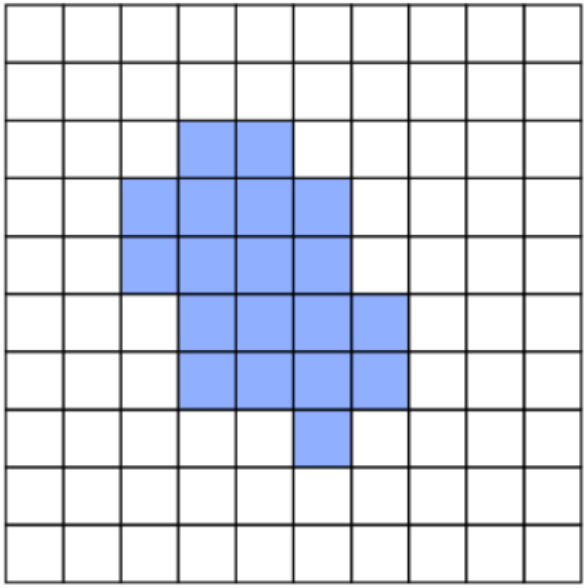
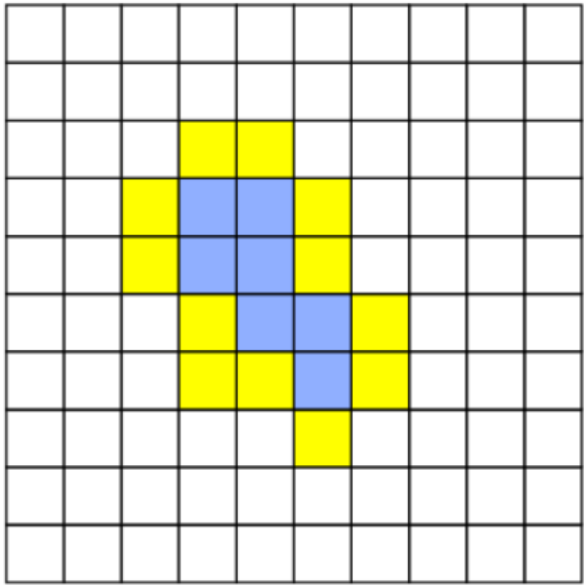
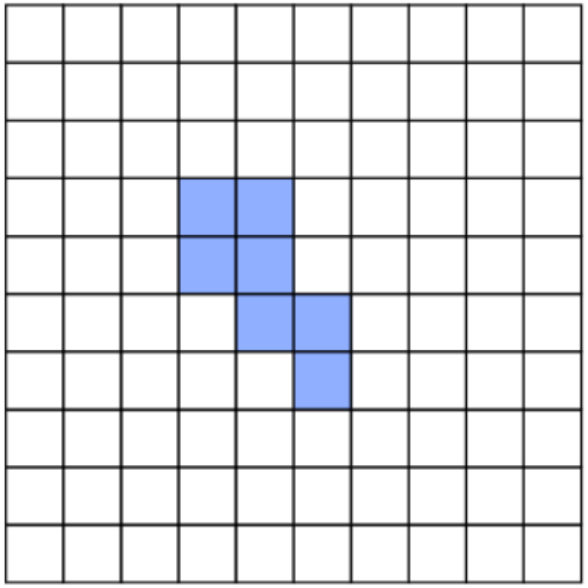
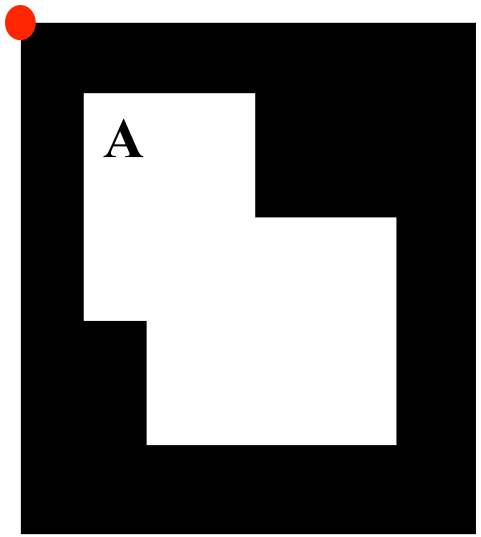




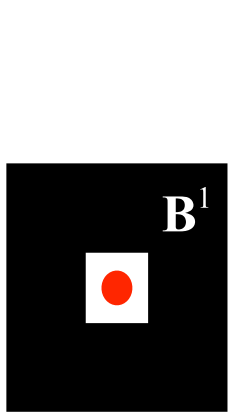


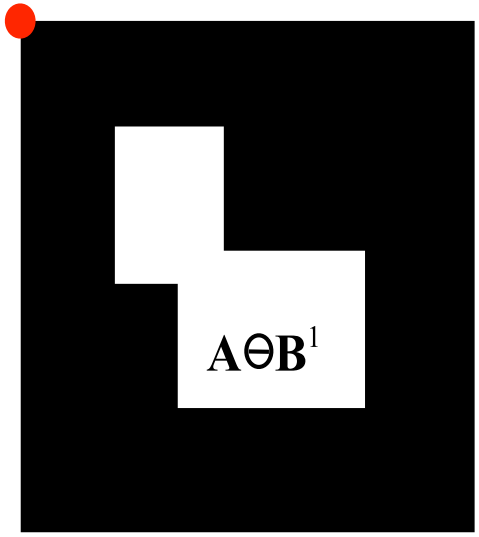
Morphological Operations

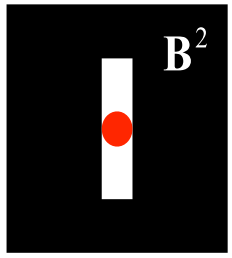
Erosion $A \ominus B = \{x \mid (B)_x \subseteq A\}$

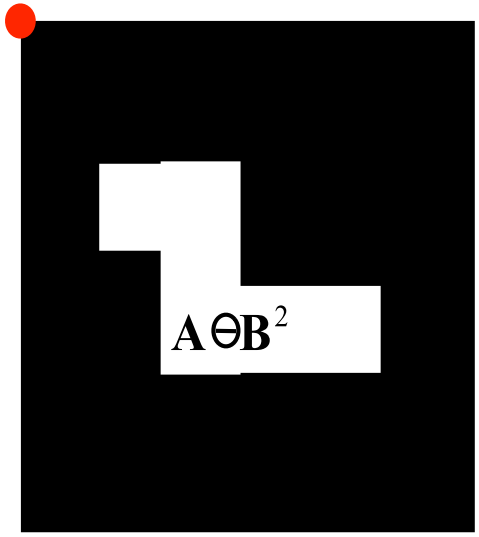


- Binary image minus structuring element
- Structuring element „eats“ itself through the shape and hence erodes it







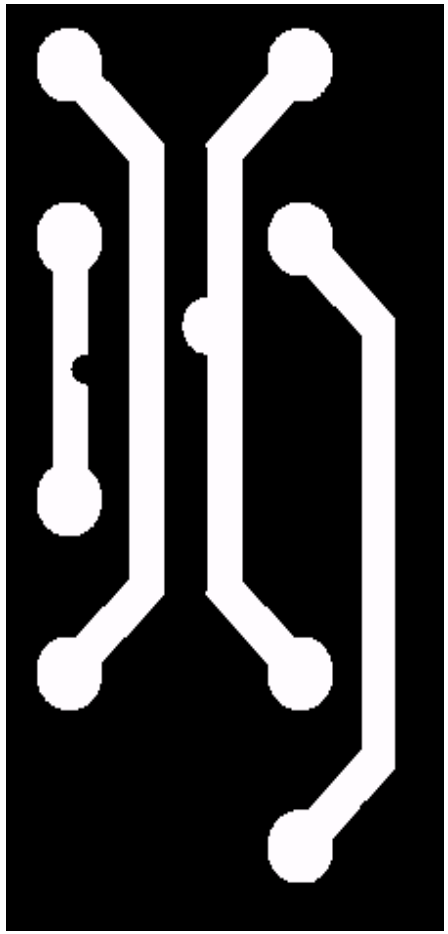


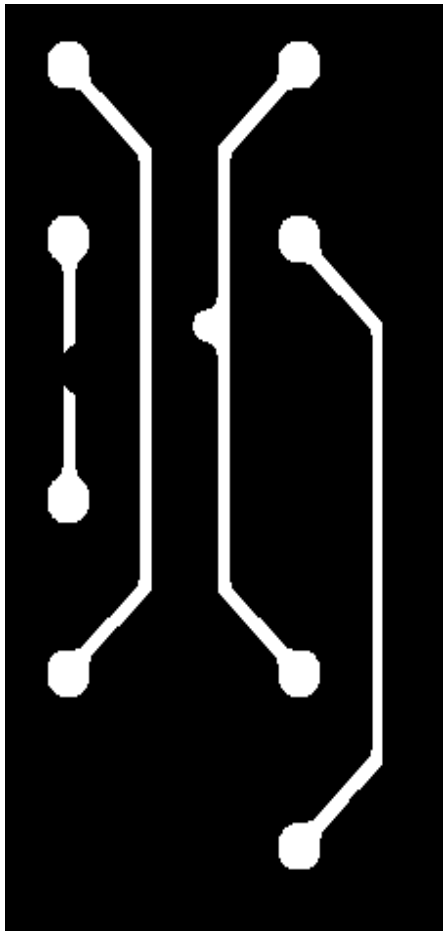
Morphological Operations

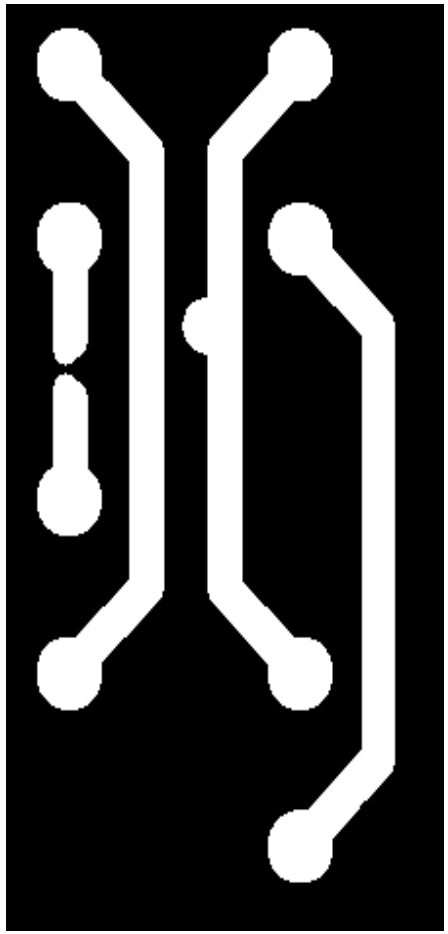
Opening $A \circ B = (A \ominus B) \oplus B$

- smoothening outer edges and removes thin bridges

B 

A 



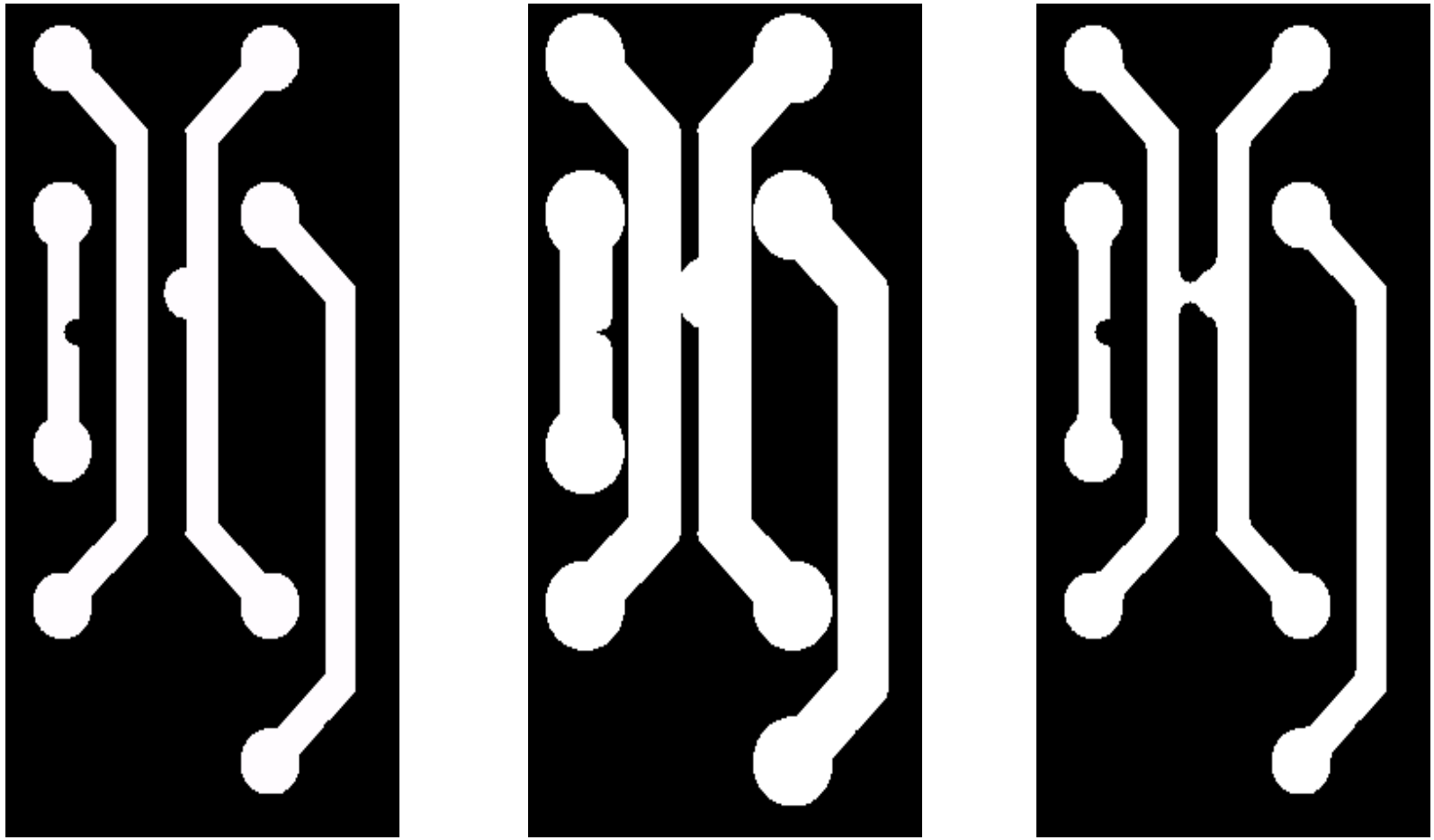


Morphological Operations

Closing $A \bullet B = (A \oplus B) \ominus B$

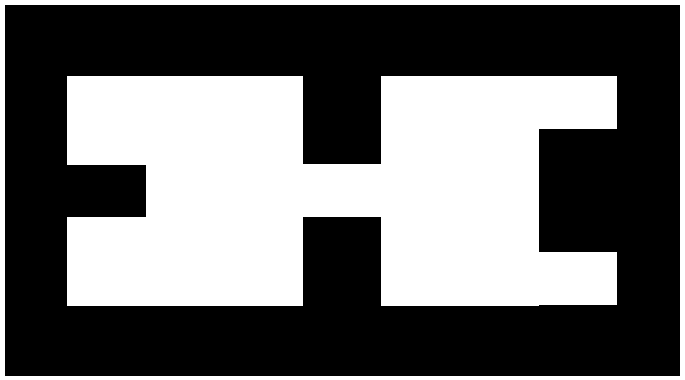
- smoothes inner edges, closes gaps of short distances

B 

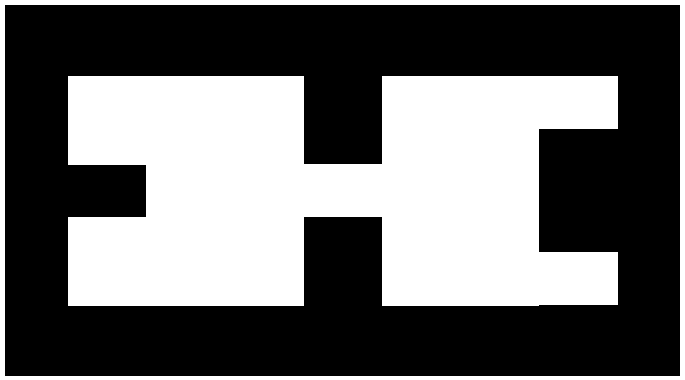
A 

Geometric Interpretation

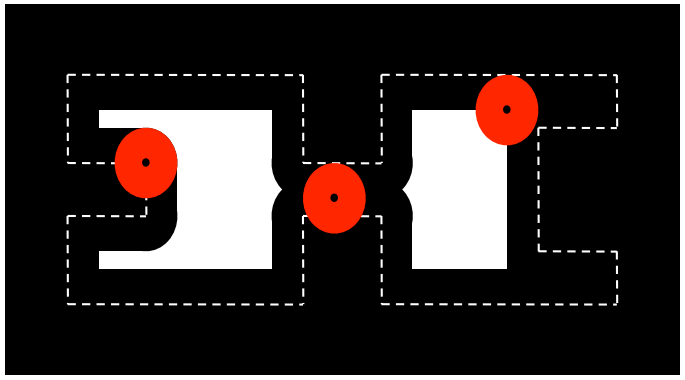
A



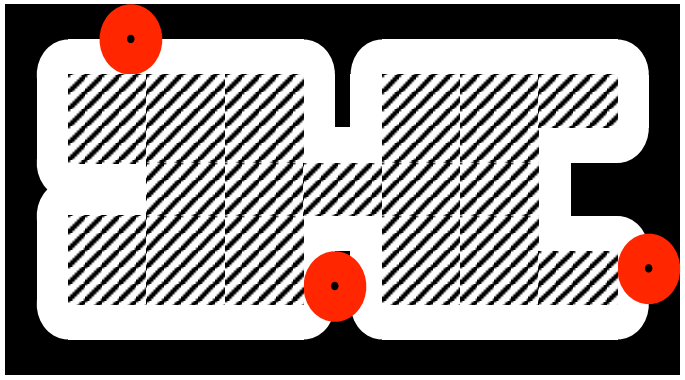
A



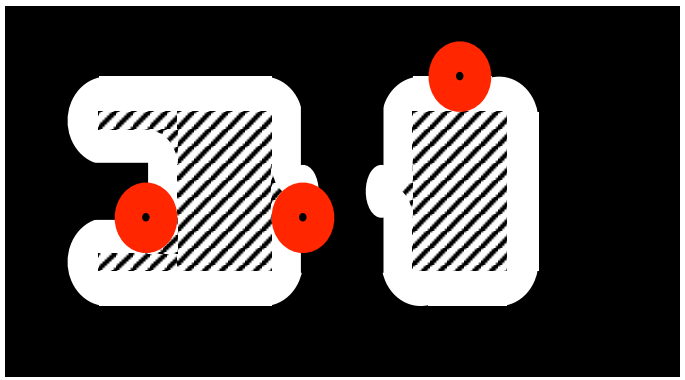
$A \ominus B$



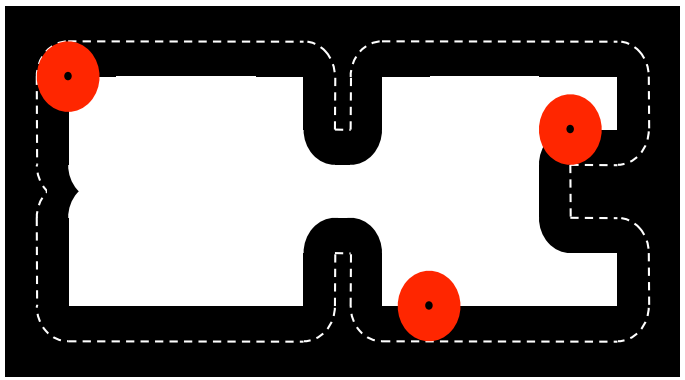
$A \oplus B$



$A \circ B$

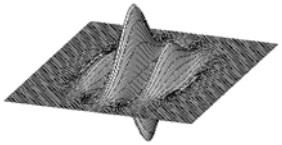


$A \bullet B$



Skeletonisation

Feature Extraction



biometric characteristic

capture

biometric sample

feature extraction

template

compare

score

biometric characteristic

capture

preprocessing

biometric sample

directional image

foreground / background

singularity core

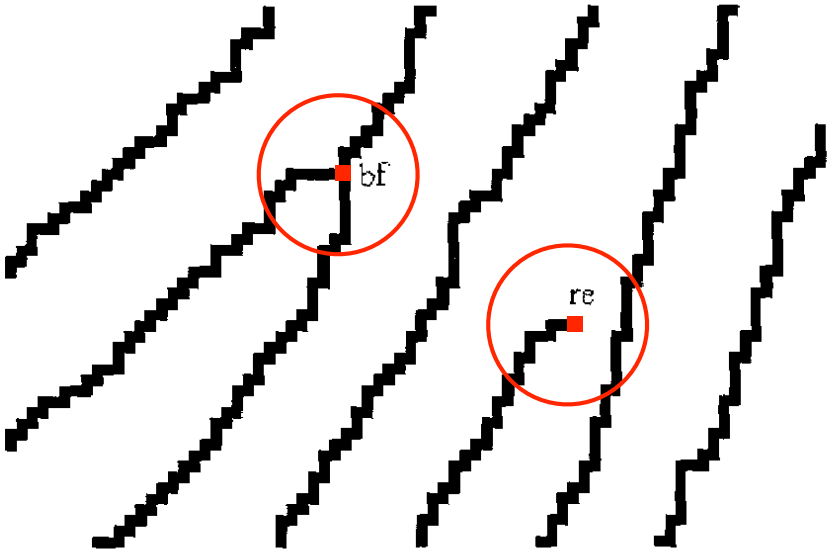
skeletonizing

minutia detection

Feature Extraction

Localization of minutia points

- Identification of minutia points through neighborhood investigation
- Goal: Minutia template



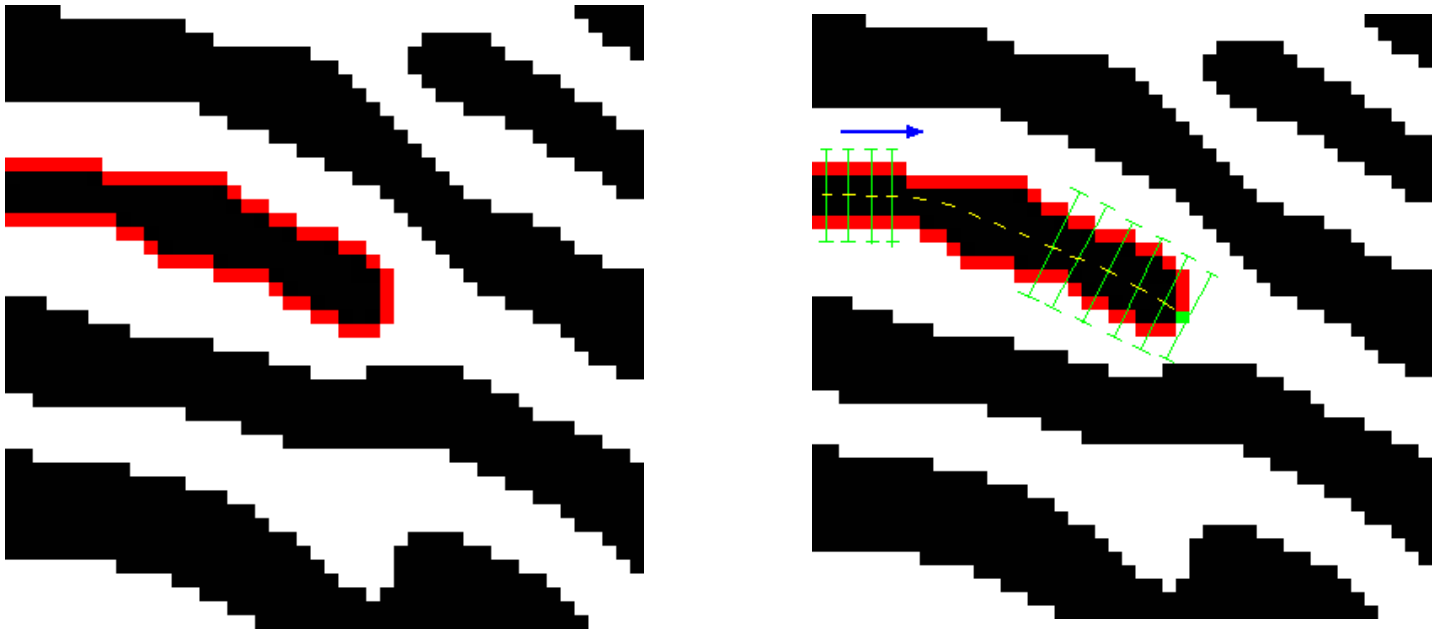
bf = bifurcation
re = ridge ending

Thinned lines

Extracted minutia

Feature Extraction

Localization of minutia points (optimal)



- Approach to clearly locate the minutia
  - The ridge flow is usually in coincidence with a directional image
  - Crossing lines orthogonal to the ridge flow direction are well-defined
  - When following the dominant ridge flow direction, the center of orthogonal crossings lines leaves a clear path and meets the border in a single pixel (the optimal minutia position)

Feature Extraction

Localization of minutia points (practical)

on the skeleton with crossing numbers

- Operator on a binary image
- Crossing number *cn(**p**)* of a pixel ***p*** is defined as half the sum of the differences between pairs of adjacent pixels in the 8-neighborhood of ***p***

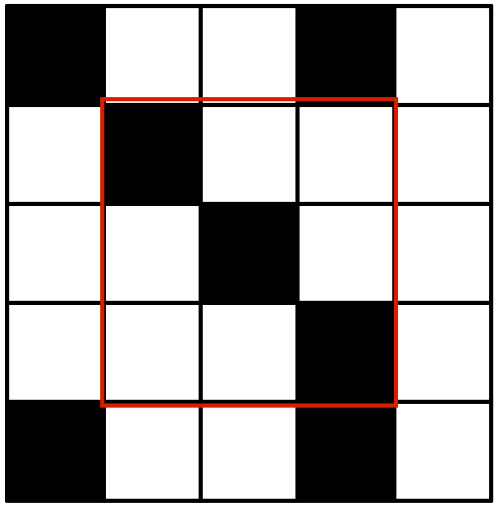
$$cn(\mathbf{p}) = \frac{1}{2} \sum_{i=1,\ldots,8} \left| val(\mathbf{p}_{i \bmod 8}) - val(\mathbf{p}_{i-1}) \right|$$

$\mathbf{p}_0, \mathbf{p}_1, \ldots \mathbf{p}_7$ are the pixels belonging to an ordered sequence of pixels defining the 8-neighborhood of **p** and $val(\mathbf{p}) \in \{0, 1\}$ is the pixel value.

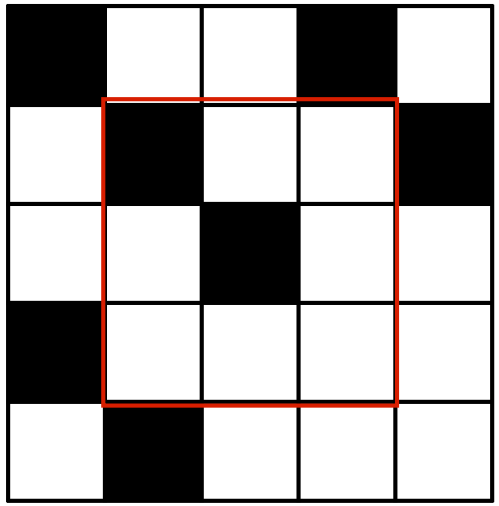
Feature Extraction

Localization of minutia points with crossing numbers

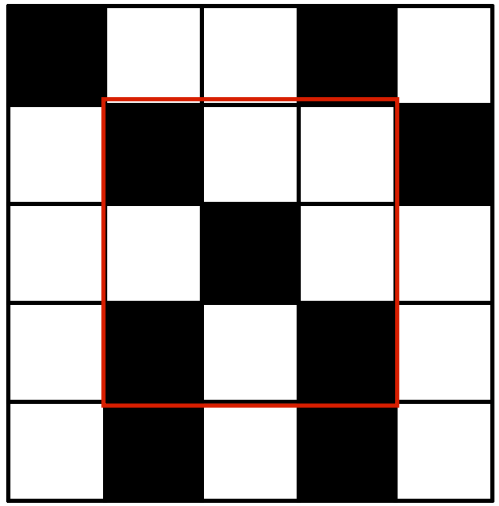
- A pixel p with val(p) = 1 is
  - An intermediate ridge point if cn(p)=2
  - Corresponds to a ridge ending if cn(p)=1
  - Defines a more complex minutia (e.g. bifurcation) if cn(p) >= 3



Intra-ridge pixel



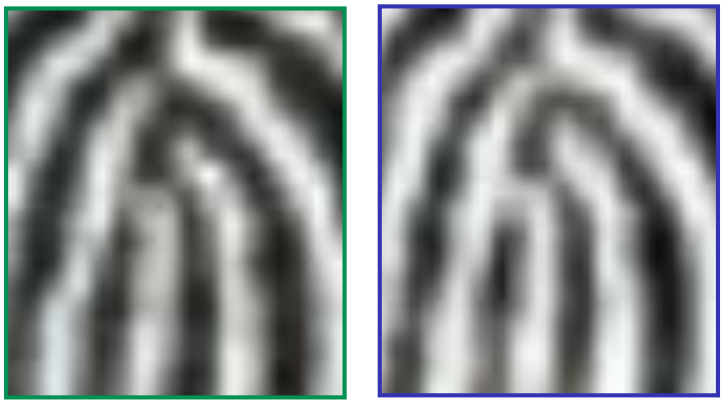
termination minutia



bifurcation minutia

Feature Extraction

Impact of image signal on minutia type?



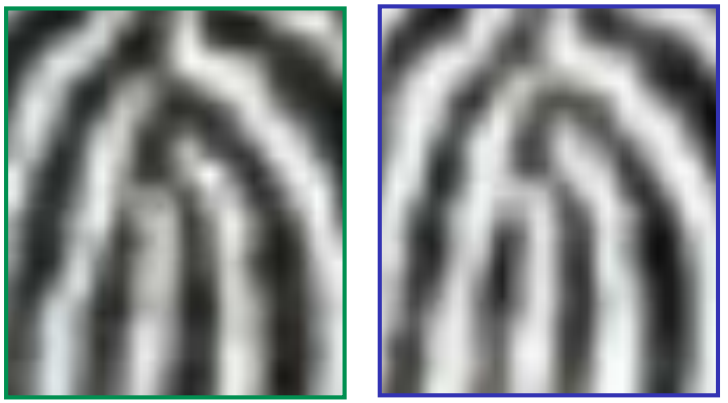
Gray level image representation

Feature Extraction

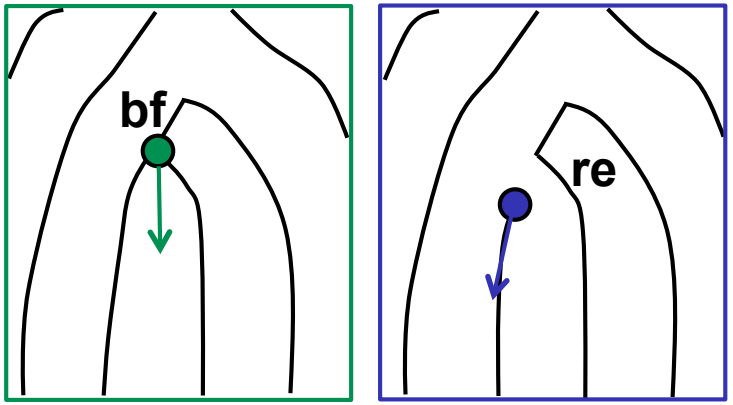
Impact of image signal on minutia type?

A gap in the fingerprint skeleton results in

- a dislocation of the minutia coordinate
- a change of the minutia type



Gray level image representation of reference and probe



Skeletonized representation

Comparison Subsystem

Comparison

biometric characteristic

capture

biometric sample

feature extraction

template

biometric characteristic

capture

biometric sample

feature extraction

probe feature vector

compare

score

Comparison of Minutia Sets

Comparison of corresponding minutia points

- Minimum 12 minutia points in the overlapping area (ISO/IEC 19794-2)
- Positive verification, if threshold number of identical minutia points is reached, e.g. T = 12
  - Up to 40 minutia points in live scans
  - Up to 150 Minutia points in „rolled“ inked impression
- Maximum of 60 minutia points (onion-model reduction)

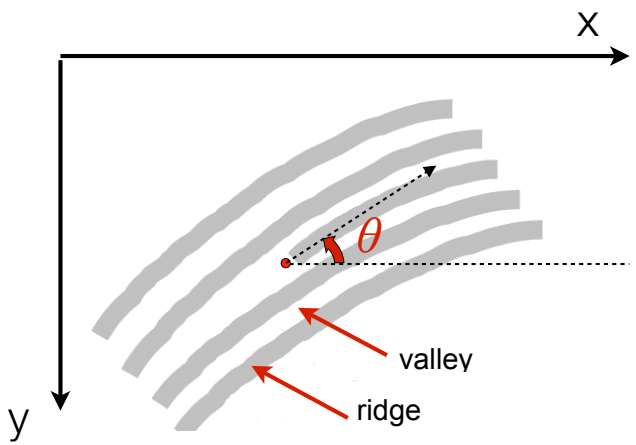
Comparing Minutia Positions

Detecting a corresponding minutia

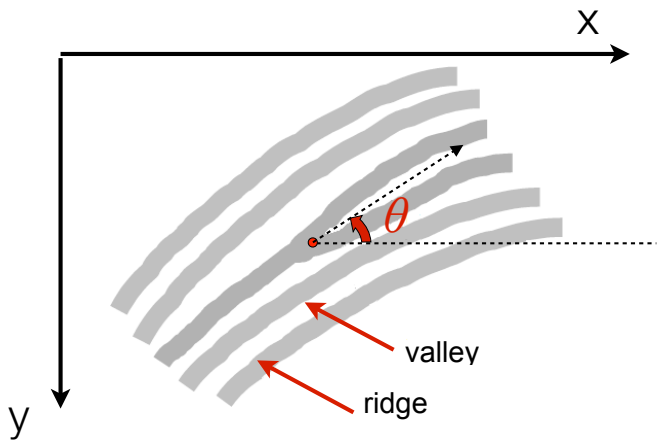
- seeking for „mates“

Minutia

- is considered as a four tuple $m = \langle x, y, \theta, t \rangle \in \mathcal{M}$
  - absolute position (coordinates x,y)
  - orientation (angle θ)
  - minutia type $t \in \{re, bf\}$



ridge ending (re)



bifurcation (bf)

Detect Minutia Mate

Seeking for corresponding minutia (three tuple)

- Reference R
- Probe Q

$$R = \{m_1, m_2, \ldots, m_n\} \subseteq \mathcal{M} \qquad m_i = \langle x_i, y_i, \theta_i \rangle \in R$$
$$Q = \{m'_1, m'_2, \ldots, m'_k\} \subseteq \mathcal{M} \qquad m'_j = \langle x'_j, y'_j, \theta'_j \rangle \in Q$$

where n and k denote the number of minutiae in R and Q, respectively

- We state that two minutiae are mated, if their spatial difference sd and the directional difference dd is within tolerance bounds

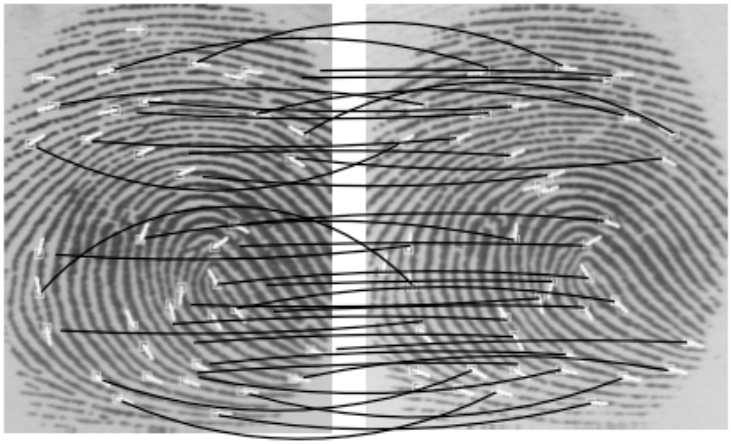
$$sd(m_i, m'_j) = \sqrt{(x_i - x'_j)^2 + (y_i - y'_j)^2} \leq r_0$$
$$dd(m_i, m'_j) = \min\{|\theta_i - \theta'_j|, 360^\circ - |\theta_i - \theta'_j|\} \leq \theta_0.$$

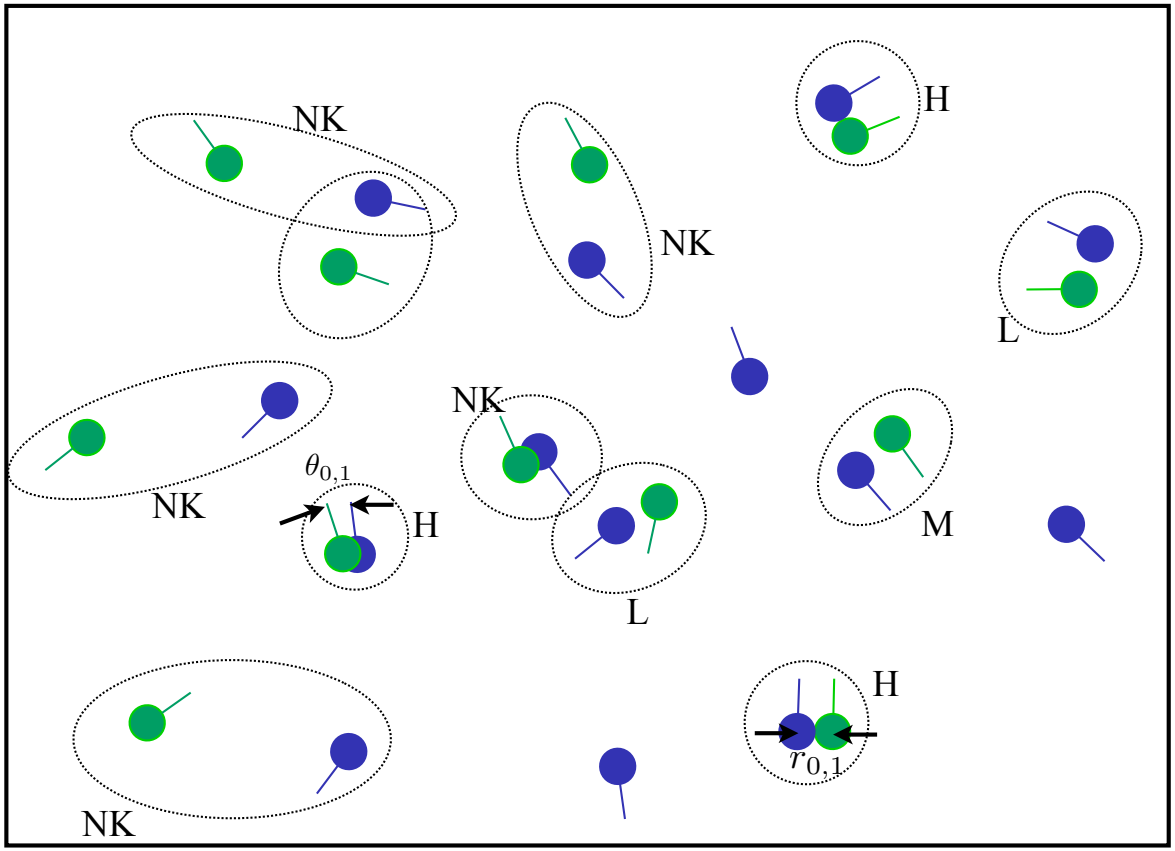
where for dd we take the minimum as the difference between 1° and 359° is only 2°

Comparison Strategies in AFIS

Comparison of point clouds

- classification of minutiae with three accuracy levels:
  - High score $r_{0,1}, \theta_{0,1}$
  - Medium score $r_{0,2}, \theta_{0,2}$
  - Low score $r_{0,3}, \theta_{0,3}$
  - Not Kept





Minutia Vector Similarity Score

Deriving a similarity score from minutiae mates

- Reference R $m_i = \langle x_i, y_i, \theta_i \rangle \in R$
- Probe Q $m'_j = \langle x'_j, y'_j, \theta'_j \rangle \in Q$

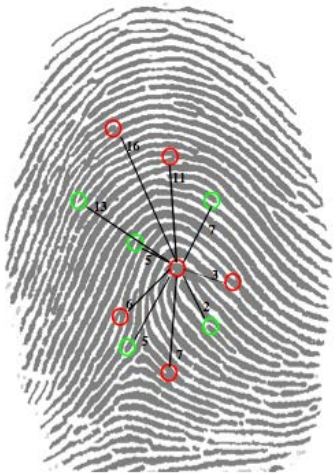
$$R = \{m_1, m_2, m_3, m_4, m_5, m_6, \quad\} \subseteq \mathcal{M}$$

$$Q = \{m'_1, \quad m'_2, \quad m'_3, m'_4\} \subseteq \mathcal{M}$$

Comparator Algorithm Strategies

Ridge count

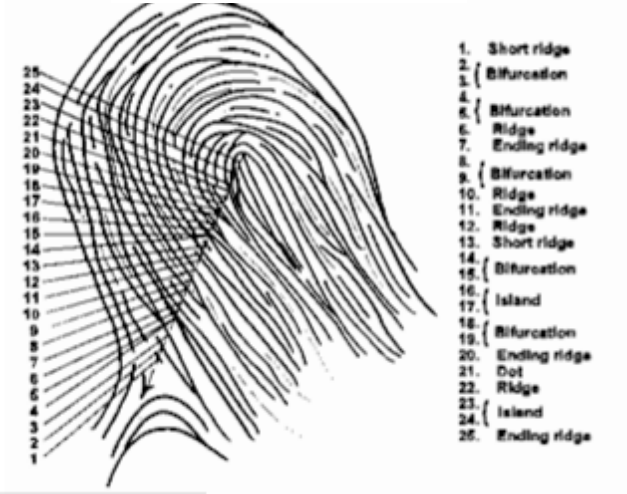
- Identification of a significant minutia
- Connecting line to
  - other significant minutia points
- Storage of
  - Distance to the neighbor
  - Absolute orientation of lines at minutia points
  - Relative angle to connecting line
  - Number of passed lines (ridge count)



bifurcation

ridge end

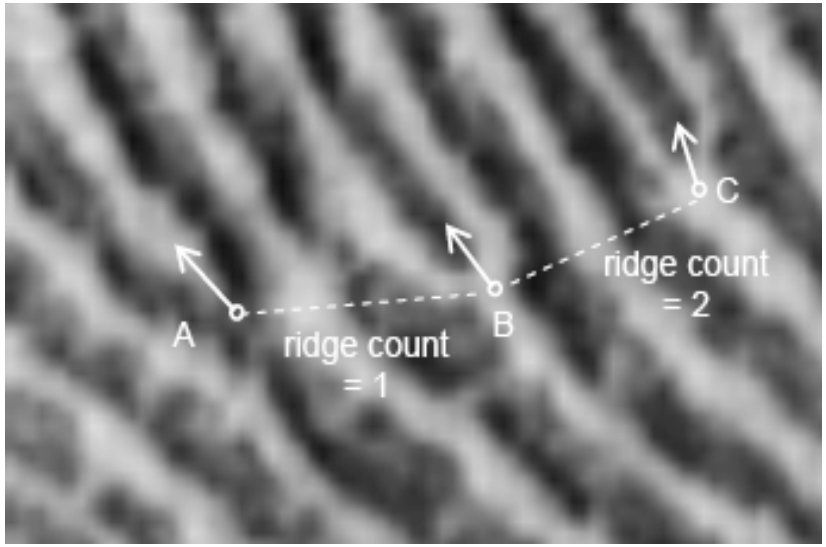
- Advantage:
  - Higher dimensional information space



Comparator Algorithm Strategies

Ridge count data format

- ISO/IEC 19794-2: information on number of ridge lines
- Each connecting line is associated to a minutia pair
  - ridge count between minutia A and B is 1
  - ridge count between minutia B and C is 2



Applications Fingerprint Recognition

Applications of Biometrics

Convenience

- Personalization of automobiles:
  - upon fingerprint recognition of the user the Audi A8 selects personal settings such as seat, steering wheel, mirror etc.
- Secure mCommerce
  - user authentication on mobile devices

Image Source: Sagem 2000

Image Source: HTC's 'Census' 2008

Image Source: AuthenTec 2007

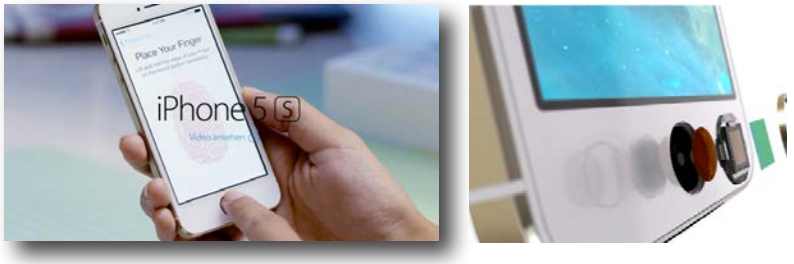


Image Source: www.apple.com, 2013

Applications of Biometrics

Home access control

Motivation:

- no need to worry about losing your keys
- no need about forgetting the password.

- There's also no need to worry about possible sharing or duplication.
- Factors
  - the number of enrolled subject
  - temperature

Entry Exit System

Slides from Istvan Racz (eu-LISA)

European Entry-Exit System

NIST International Face Performance Conference, 27th October 2020

eu-LISA PUBLIC

Smart Borders

eu-LISA

European Union Agency for the Operational Management of Large-Scale IT Systems in the Area of Freedom, Security and Justice (eu-LISA)

- **European Union Agency for the Operational Management of Large-Scale IT Systems in the Area of Freedom, Security and Justice**

- Established in 2011, started operations on 01/12/2012
- Agency's mandate was reinforced with Regulation (EU) 2018/1726

- Headquarters: Tallinn (Estonia)
- Operations: Strasbourg (France)
- Backup site: Sankt-Johann im Pongau (Austria)
- Liaison office: Brussels (Belgium)

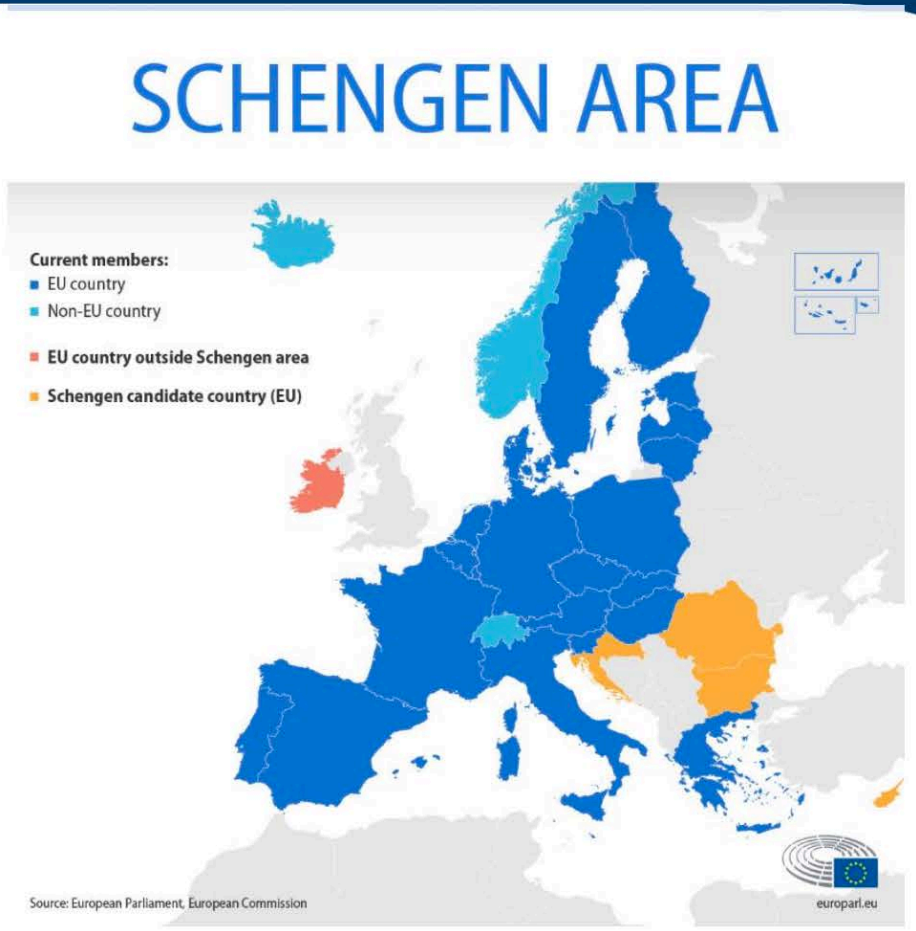
- 243 statutory staff, 10 seconded national experts
- At least 370 posts planned by 2022

Smart Borders

Europe's Schengen Area

European Union Agency for the Operational Management of Large-Scale IT Systems in the Area of Freedom, Security and Justice (eu-LISA)

- Schengen Agreement **signed on 14 June 1985** by **five** of the ten member states of the then European Economic Community
- The Schengen Area includes **26 countries** (22 are EU member states), with a population of **~420 million people**
- Core part of EU law, and all EU member states which have not already joined the Schengen Area are legally obliged to do so when technical requirements have been met.



Smart Borders

eu-LISA – System portfolio

European Union Agency for the Operational Management of Large-Scale IT Systems in the Area of Freedom, Security and Justice (eu-LISA)

Visa Information System (VIS)

~80 M visa applications
~70 M FP sets

All time high peak: 139 K operations/hour

Schengen Information System (SIS II)

~93 M alerts
>14K queries/day

~ 2.5K hits/month
~ 280 K FP sets

European Dactyloscopy Database (EURODAC)

~5.6 M asylum applications
~ 145K irregular border crossings

~5.6 M FP sets

INTEROPERABILITY

Entry-Exit System (EES)

European Criminal Records Information System (ECRIS-TCN)

European Travel Information and Authorization System (ETIAS)

Smart Borders

European Entry-Exit system

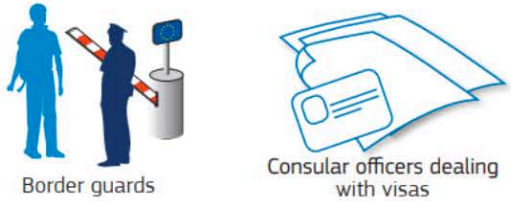
European Union Agency for the Operational Management of Large-Scale IT Systems in the Area of Freedom, Security and Justice (eu-LISA)

To whom will it apply?

to non-EU nationals, visa-required and visa-exempt travellers in the Schengen area.

Who is using EES data?

The **competent Member State authorities**



How will the system work?

EES will collect:

Identity

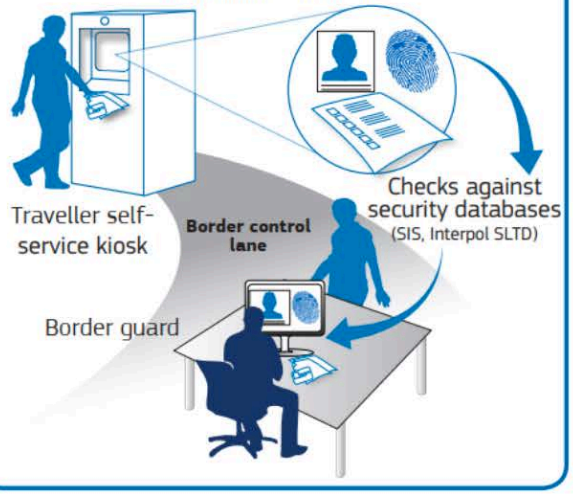
EES will record:

Entry refusals

EES will replace:

Border crossing facilitation

for all non-EU nationals



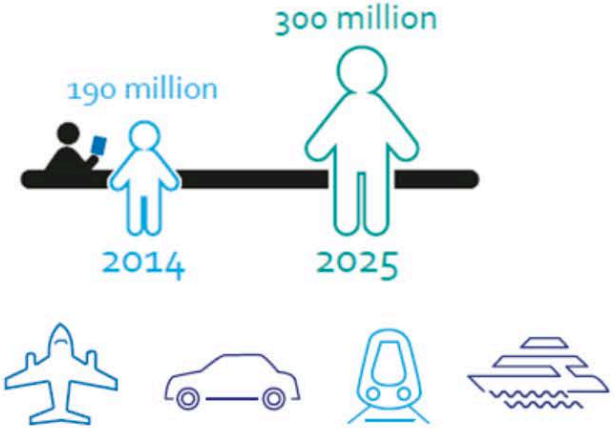
Source: https://ec.europa.eu/home-affairs/what-we-do/policies/borders-and-visas/smart-borders/ees_en

Smart Borders

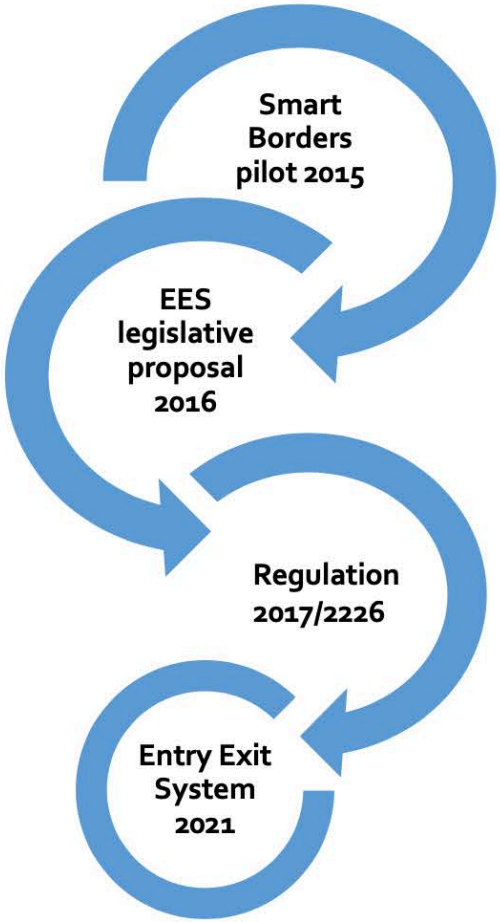
European Entry-Exit System

European Union Agency for the Operational Management of Large-Scale IT Systems in the Area of Freedom, Security and Justice (eu-LISA)

Annual forecast of border crossings (*)



Introduce **biometric technology** at all types of borders and **register entry** and **exit electronically**



EES Regulation 2017/2226 entered into force on 29 December 2017

EES development and operational management entrusted to **eu-LISA**

(*) European Commission, Technical Study on Smart Borders, 2014, ISBN 978-92-79-41798-6

Smart Borders

Main purposes of EES

European Union Agency for the Operational Management of Large-Scale IT Systems in the Area of Freedom, Security and Justice (eu-LISA)

- Enhance the efficiency of border checks
- Effective management of authorised short-stays
- Assist in the identification of third country nationals
- Automation of border checks
- Allow for the identification and detection of overstayers
- Information about authorized stay

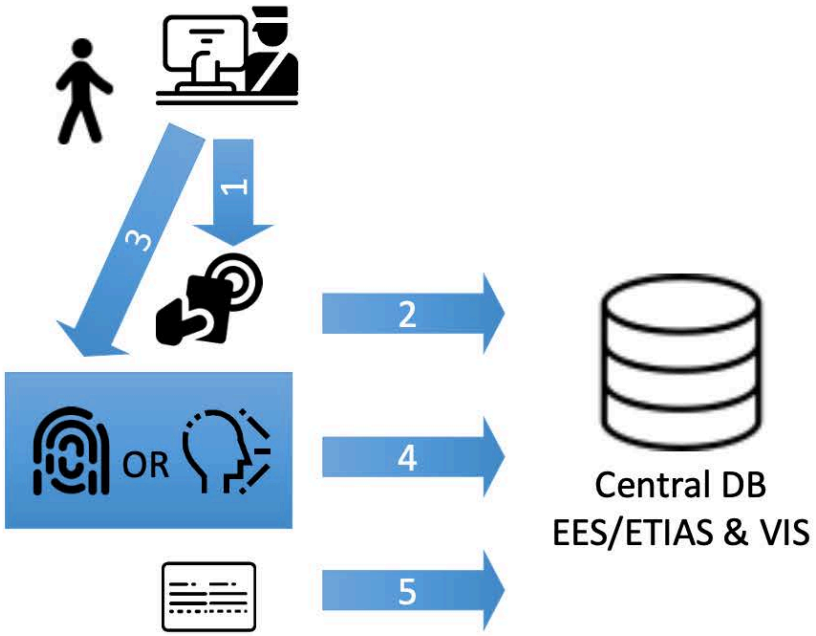
- Support migration policy making
- Reinforce internal security
- Support increased load at the Schengen borders

Smart Borders

Entry & exit workflow at the border

European Union Agency for the Operational Management of Large-Scale IT Systems in the Area of Freedom, Security and Justice (eu-LISA)

Third-country national already registered



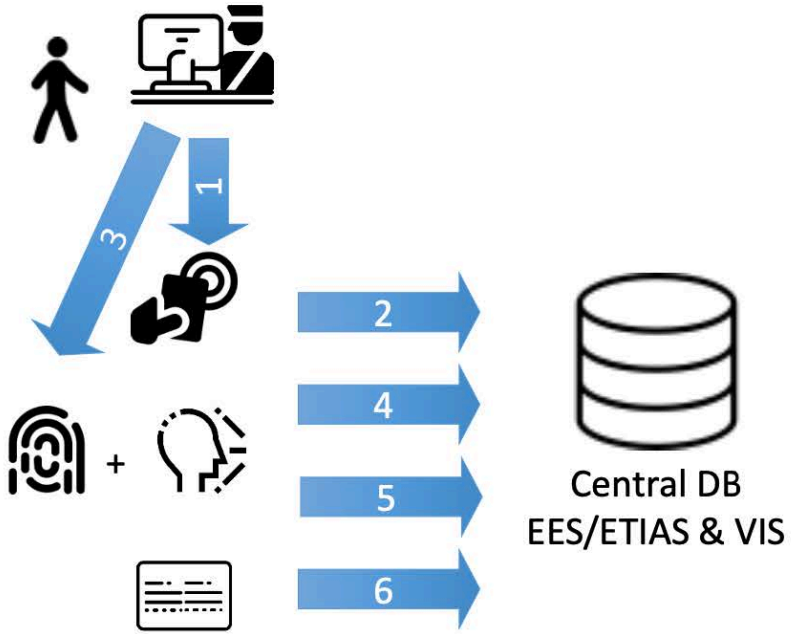
1. Scan MRZ
2. Search
3. Capture one biometric modality
4. Biometric verification
5. If match Interview, creation Entry, Exit, Refusal record

Smart Borders

Entry & exit workflow at the border

European Union Agency for the Operational Management of Large-Scale IT Systems in the Area of Freedom, Security and Justice (eu-LISA)

Third country national not yet registered



1. Scan MRZ
2. Search
3. Capture both biometric modalities
4. Biometric Identification
5. Enrolment
6. Interview, creation Entry, Exit, Refusal record

Smart Borders

Biometrics in EES

European Union Agency for the Operational Management of Large-Scale IT Systems in the Area of Freedom, Security and Justice (eu-LISA)

Data quality check

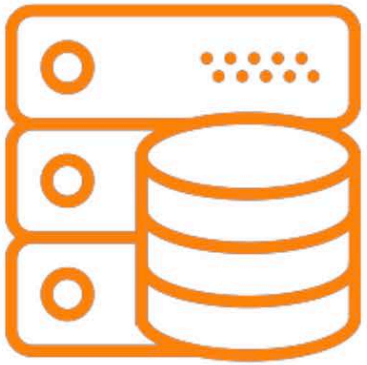
EES

VIS

NIST

Result/Error/ Warning

sBMS (EES + VIS)



★ **Low quality EES data can be updated later !**

- 0-FTE configuration
- 1:1 and 1:N operations: within one of the galleries (EES or VIS)
- FMR, FNMR, FPIR, FNIR: targets defined by the legal base
- accuracy measured centrally on actual data captured
- multi-modal fusion

Facial Images

- Min 600x800 px (in portrait mode)
- Max 1200x1600 px
- Min 120 px between eyes
- ISO/IEC 19794-5:2011 Frontal image type

Fingerprints

- 4 fingers
- 500 or 1000 ppi
- 256 grey levels

- Data capture
- Segmentation, sequence check, uniqueness check, **biometric data quality check**
- Creation of data container(s) (ANSI/NIST-ITL 1-2011: Update 2015)
- Validation of data container(s)
- Submission to EES

Conclusion

Summary Fingerprint Recognition

Lines - image representation of the ridges

- Significant information: Minutia points

Biometric method with long tradition

- Identification applications
  (pension funds, elections, forensics)

Categorization:

- Static method, cooperative, habituated, body contact

Method assessment:

Universality	medium
Uniqueness	high
Performance	high
Permanence	high

Collectability	medium
Convenience	high
Acceptability	medium
Security	medium

Summary Fingerprint Recognition

Applications

- Mobile phone access control
- Membership cards
  - fitness studio
  - zoo
  - Disneyland
- Authorized-User-Only Handgun (Smith&Wesson)
- Automated Fingerprint Identification Systems (AFIS)
  - large databases (US-Visit, EURODAC, ViS, EES)
- Duplicate enrolment check

References

Web

- National Institute of Standards and Technology
  http://fingerprint.nist.gov/

Complementary reading

- Section 5.2 to 5.7 and Section 6 of
  R. Müller: „Fingerprint Verification with Microprocessor Security Tokens“, PhD-thesis, TU München, 2001
- L. Hong et al. „Fingerprint image enhancement: Algorithm and performance evaluation“ PAMI , 1998
- B. K. Jang and R. T. Chin: „Analysis of thinning algorithms using mathematical morphology”, PAMI, 1990
- Section 3.6, 3.8 and 4.3 D. Maltoni, D. Maio, A.K. Jain, S. Prabhakar: „Handbook of Fingerprint Recognition”, 2003
- S.Pankanti, S. Prabhakar and A.K. Jain: „On the Individuality of Fingerprints“, Proc. IEEE CVPR, pp. 805-812, 2001