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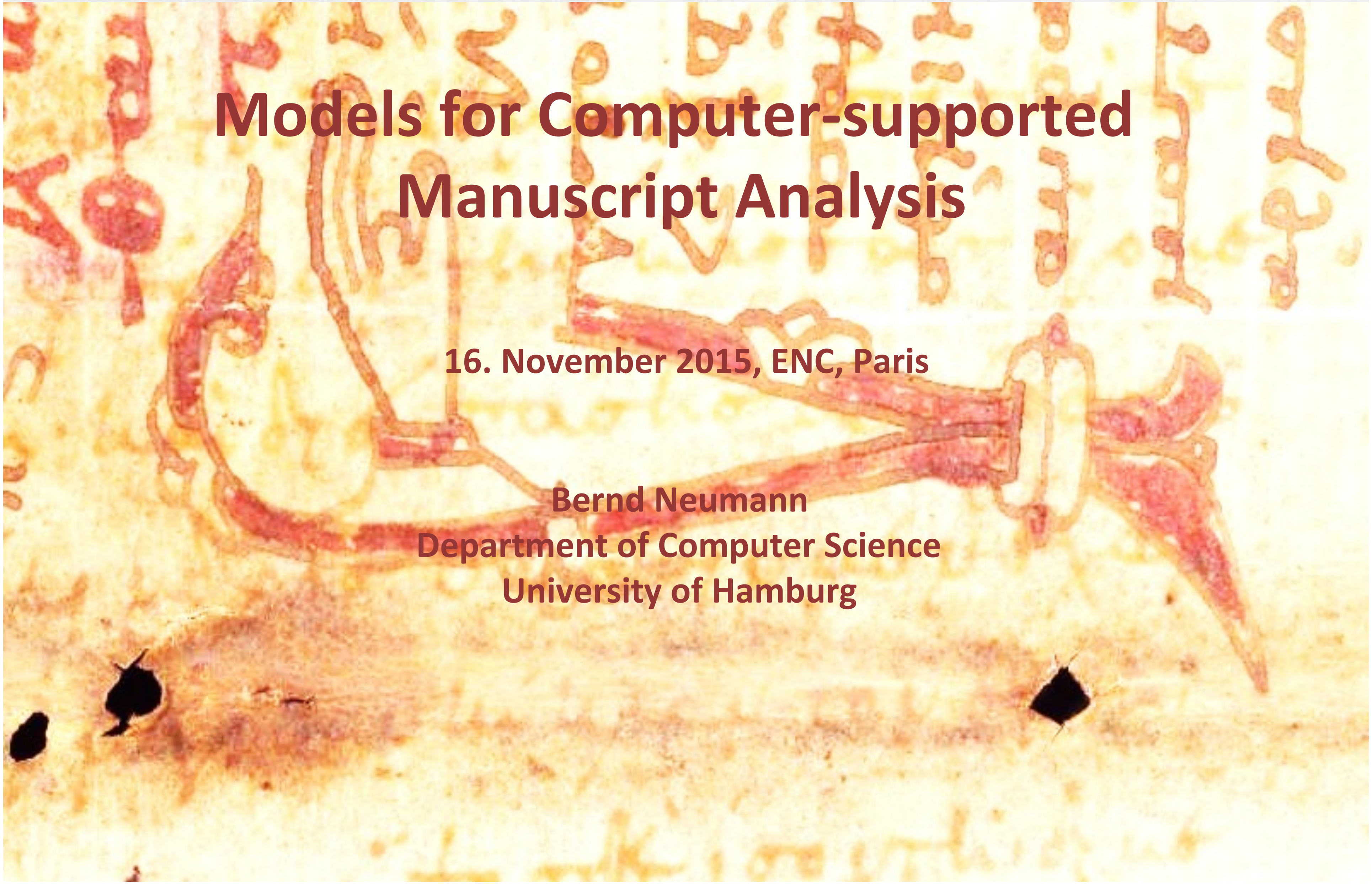
Collaborative Research
Centre for the Study of Manuscript Cultures
Manuskriptkulturen in Asien, Afrika und Europa
Sonderforschungsbereich 950



Models for Computer-supported Manuscript Analysis

16. November 2015, ENC, Paris

Bernd Neumann
Department of Computer Science
University of Hamburg

Cognitive Systems Laboratory

1971

1980

1990

2000

2010

Image Sequence Analysis

Natural-language Description of Image Sequences

Model-based Scene Interpretation

Learning for Scene Interpretation

Real-time Scene Interpretation

Radiological Image Analysis

Image Registration

Subpixel Segmentation

Topology-preserving Sampling

Manuscript Analysis

Aerial Image Analysis

Ocean Current Analysis

Applications of Knowledge-based Systems

Description Logics RACER

Semantic Information Processing

Computer Vision, Artificial Intelligence and Palaeography

Computer Vision

Artificial Intelligence

Image Processing

Pattern Recognition

Image Understanding

Knowledge Representation

Shape Description

Handwriting Recognition

Probabilistic Models

Content-Based Image Retrieval

Forensics

Datamining

Learning

Palaeographic Applications

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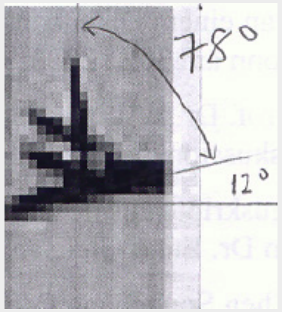
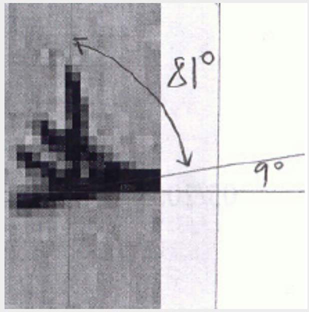
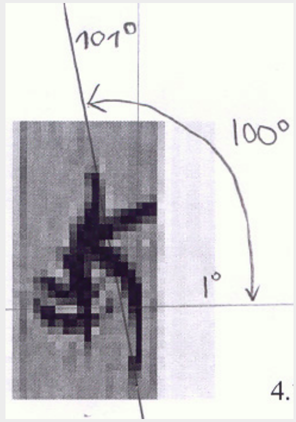
"Can you help?"

Richter 2006:
"Tentative Criteria for Discerning Individual Hands in the Guodian Manuscripts"

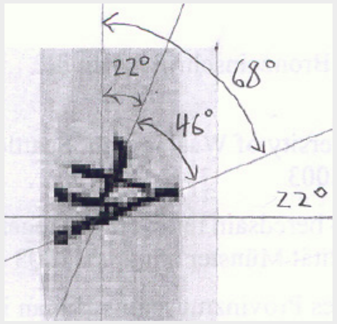
Scribe A:

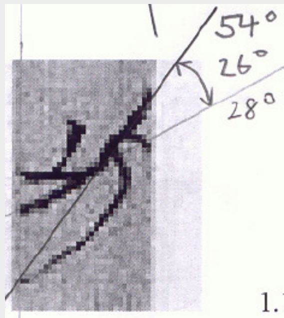


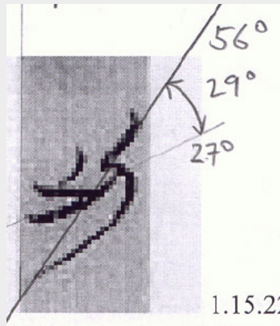




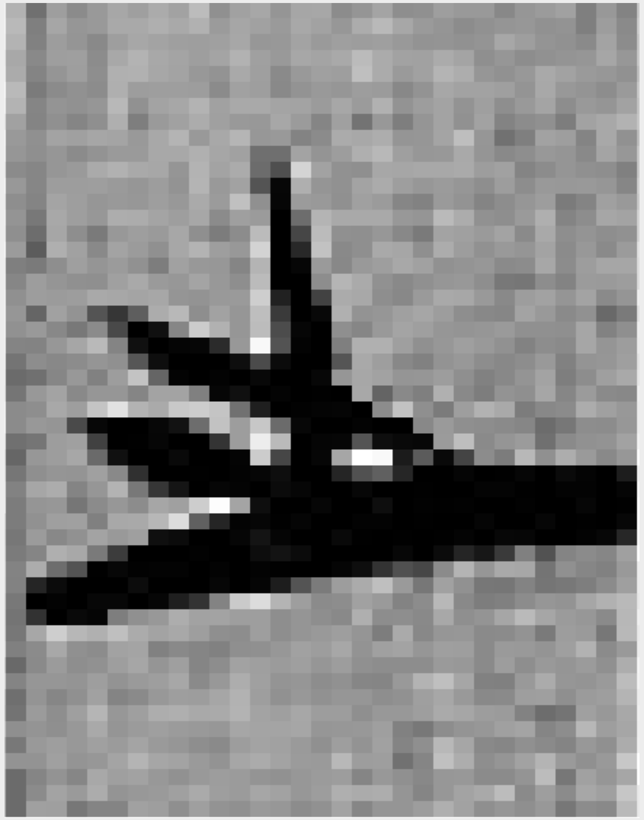
Scribe B:





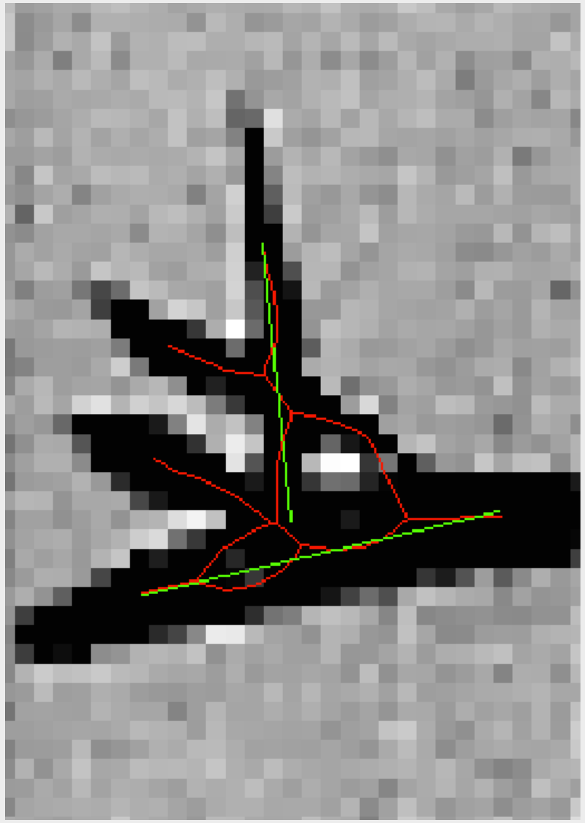


"Yes, we can!"



coarse image

contours



skeleton and axes

Centre for the Study of Manuscript Cultures

DFG Special Research Unit "Manuscript Cultures in Asia, Africa and Europe"

Manuscripts as material entities, relations to social and cultural context

First phase 2011 – 2015

17 sub-projects in diverse areas of the humanities, organized in 3 project areas

- Paratexts
- Visual Organisation
- Manuscript Collections

3 "Scientific Service Projects"

- Recovering lost writing
- Reconstructing manuscript history with methods of Material Science
- Determining visual manuscript and character features using computer-based image analysis

Service Project Image Analysis

Project team in the Department of Informatics:
Rainer Herzog, Arved Solth, Bernd Neumann

Work plan:

A Application of image processing methods for projects of the humanities

B Innovative image processing methods for manuscript analysis

C Prototype of a work place for manuscript analysis

Second Phase 2015 - 2019

Same main topics as in Phase 1:

- Paratexts
- Visual Organisation
- Manuscript Collections

3 Working Groups (cross-section topics)

- Learning
- Ritual
- Agency

Same service projects

- Main goal of image analysis project: Development of Advanced Manuscript Analysis Portal (AMAP)

* Different team: Siegfried Stiehl, Volker Märgner (PIs), N.N., N.N.

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Interest in Computer Support for Manuscript Analysis at CSMC

Pattern Retrieval
Hebrew & Aramaic magic signs

Word Spotting
Ethiopian month names

Retrieval

Descriptors
Ethiopian month names
Medieval European mss
Thai-Lao palm-leaf mss
Swahili mss
Hebraic mss

Layout Analysis
Different Alevitic cultures
Colophons of Tamil palm-leaf mss

Feature Extraction

Regional and Temporal Classification
Thai-Lao palm-leaf mss
Different Alevitic cultures
Ethiopian month names

Scribe Classification
Medieval European mss
Codex Florentinus
Swahili mss
Hebraic mss

Grouping and Classification

Reconstruction of Social and Cultural Context

Interpretation

Agenda

- **Retrieval**

  Layout Analysis

  Content-based Image Retrieval
- **Animated overview of scribe comparison**
- **Feature Extraction**

  Stroke Analysis
- **Grouping and Classification**

  Shape-Context Analysis
- **Interpretation**

  Recognition of compositional structures

  Clustering
- **Summary**

What is Layout Analysis?

Determining the locations of

- **text blocks (incl. paratexts)**
- **text lines (columns)**
- **characters**

(- strokes)

- **non-textual elements**

Arabic Manuscript Multaqā al-abḥār (1641)
Ms.or.oct.261, p13v, Staatsbibliothek Berlin

Why use Computers?

Human eyes are very good at discerning text block and character boundaries.

Main purpose of computer methods is to handle large data volumes.

- **Layout analysis provides inventory of main text blocks, paratexts and other layout elements.**
- **Layout analysis delivers useful information (line frequency, orientation) for word and character segmentation.**
- **Layout analysis allows rectification of text blocks and thus application of well-developed methods for analyzing horizontal or vertical lines:**

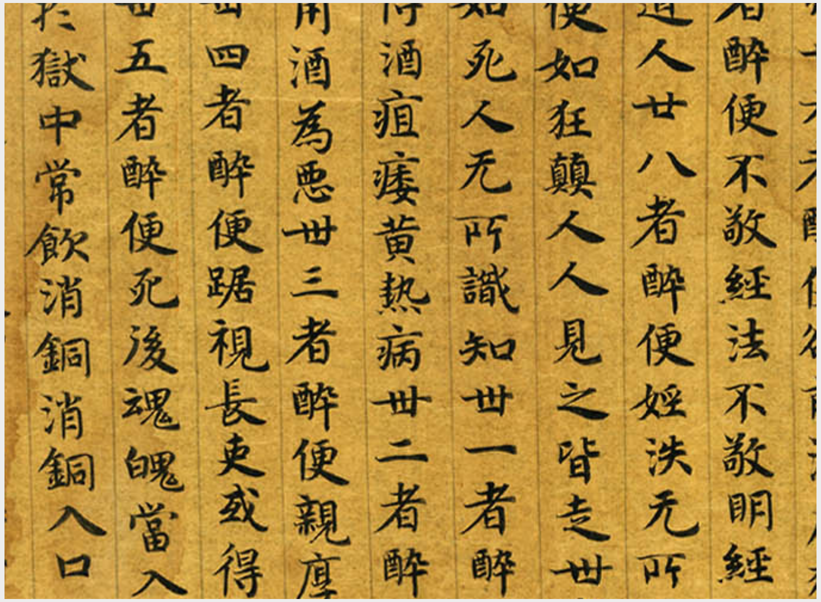
  - Line Segmentation

  - Word Spotting

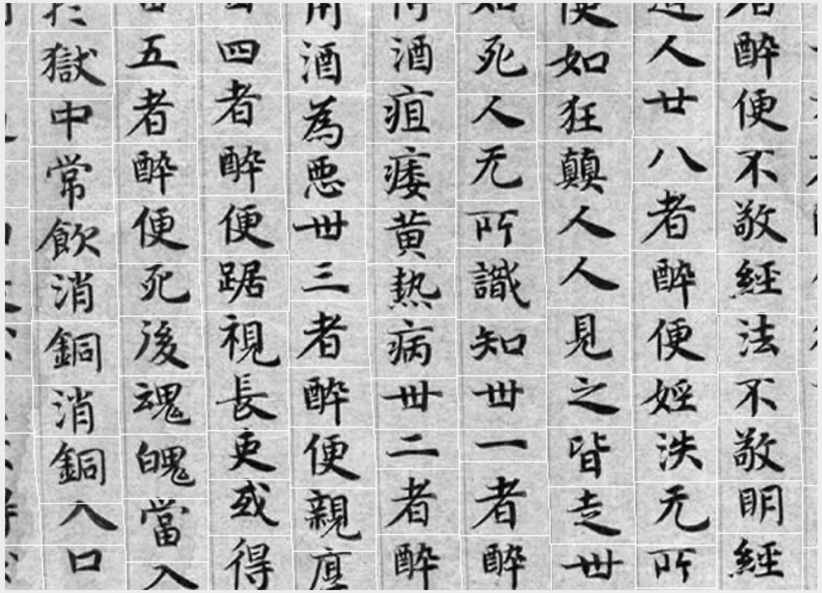
  - Writer Identification

Easy Cases

- **Text lines parallel to image rows (columns)**
- **No overlap between characters**



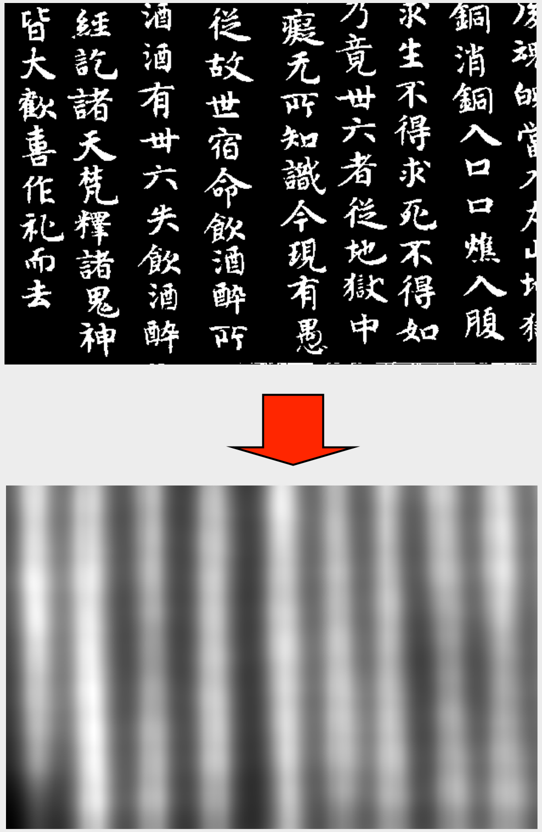
Section of the *Fo shuo Tiwei jing* 佛說提謂經 (British Library Or.8210/S.2051)



Columns and characters automatically isolated (white lines)

Simple Processing Steps

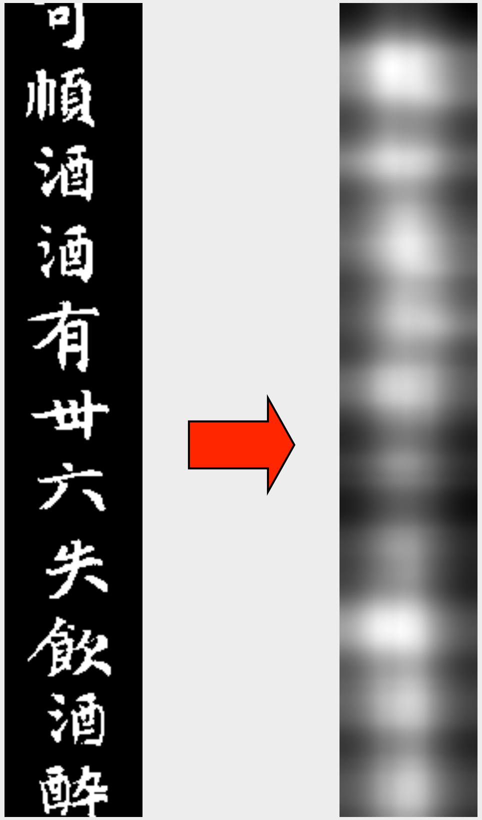
Column structure



horizontal
low-pass
filtering

column boundaries at minima

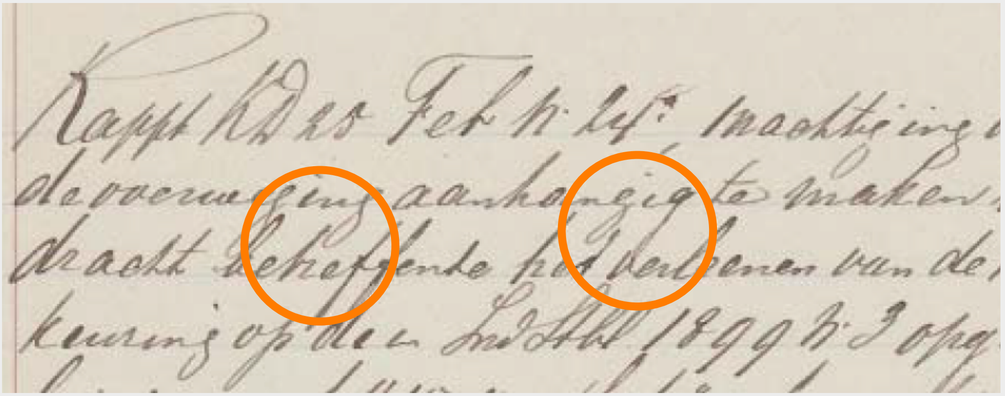
Line structure

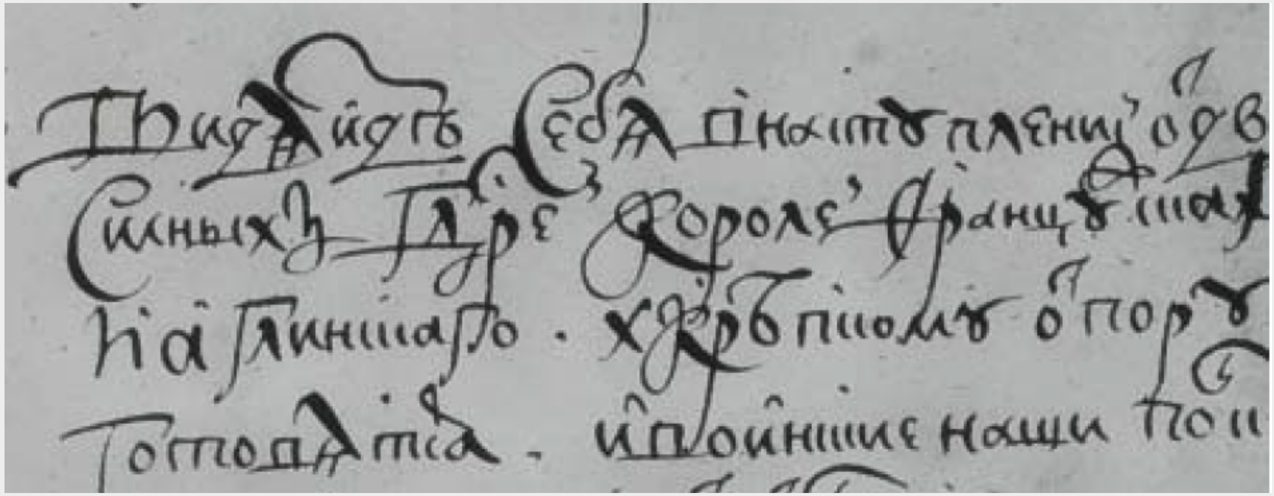


vertical
low-pass
filtering

character boundaries at minima

Localizing Overlapping Text Lines

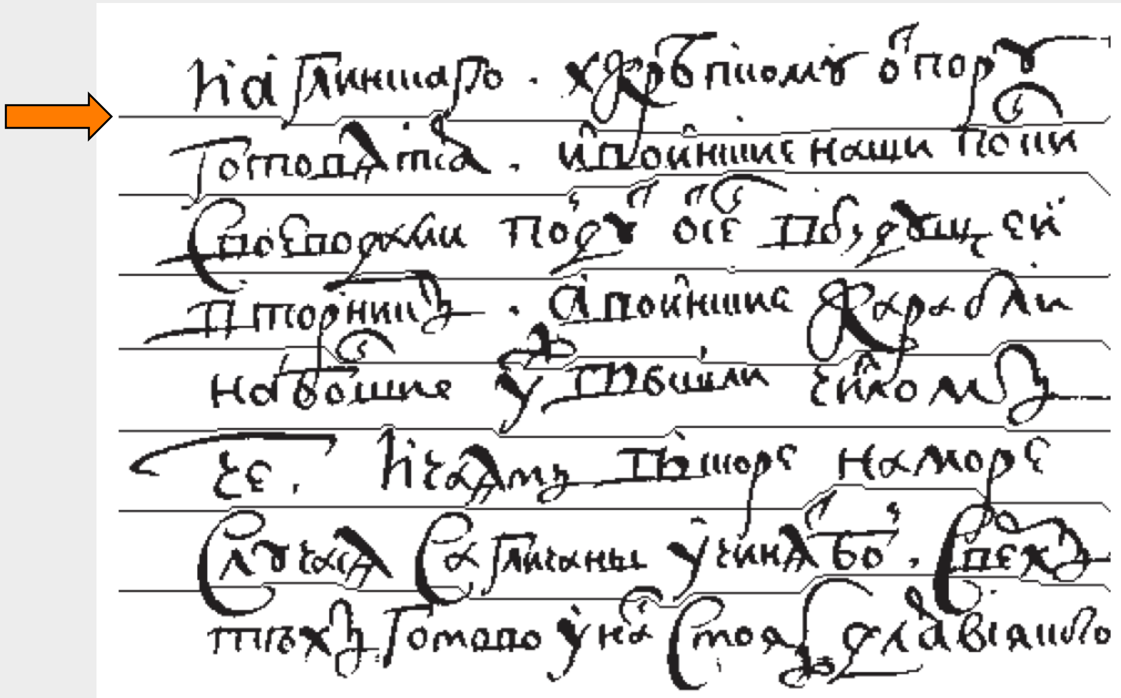




Examples from
Surinta et al. 2014: A* Path Planning for Line Segmentation of Handwritten Documents.

Planning a Path between Lines

A* Algorithm of Artificial Intelligence finds "minimal-cost" paths from initial state (left margin) to final state (right margin).



Judicious cost definition determines performance of algorithm.

Layout Analysis by Gabor Transformation

(Herzog et al. 2014)

- **Location of text blocks in manuscript pages**
- **Line structure**

Main idea:

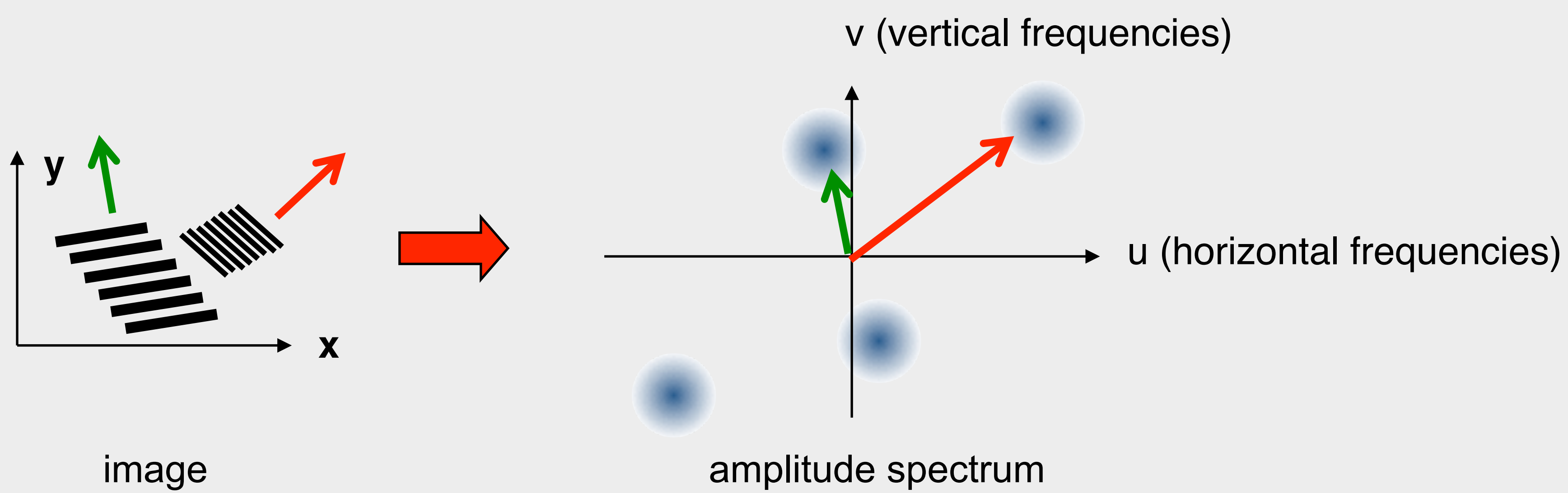
Use local 2D Fourier Transforms (= Gabor Transform) to determine frequency and orientation of text lines.

What is a 2D Fourier Transform?

An image function may be considered a sum of spatial sinusoidal components of different frequencies and directions.

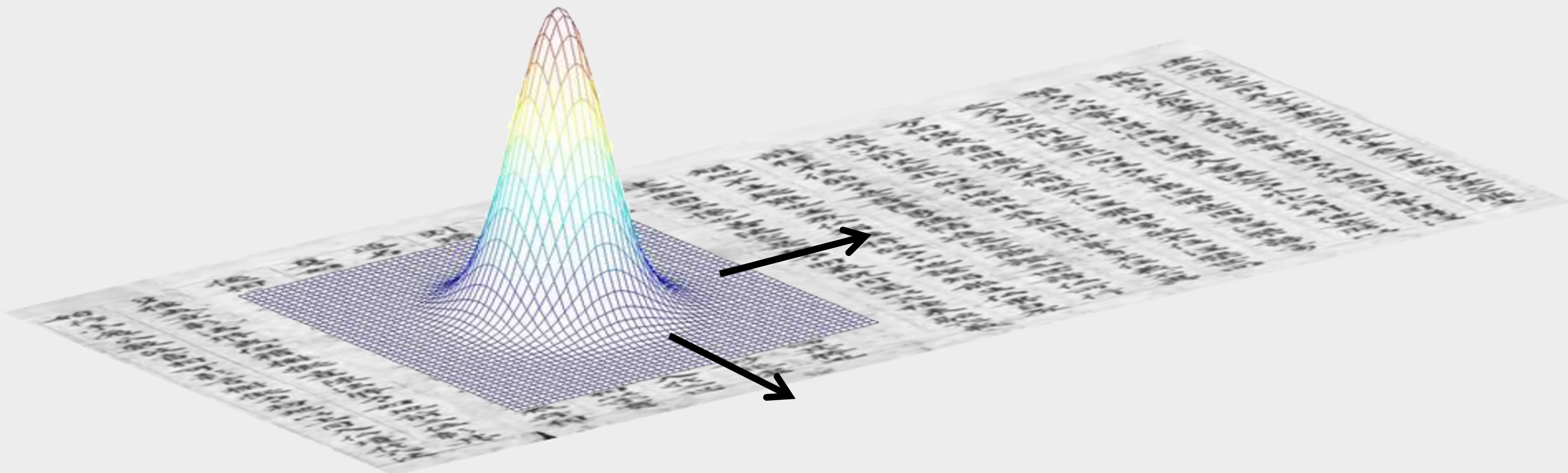
The 2D Fourier Transform computes the *spectrum* of the image function, which indicates the amplitudes, orientations and phases of the spatial sinusoidals contained in an image.

Principle:



What is a Gabor Transform?

A Gabor Transform is a Fourier Analysis applied to a circular local area, weighted by a Gaussian centered at the circle.



By applying the Gabor Transform at all image locations, the locally dominating line frequencies and orientations can be determined.

Processing Steps

A Determine dominating frequency and orientation ("line signature") at each image location.

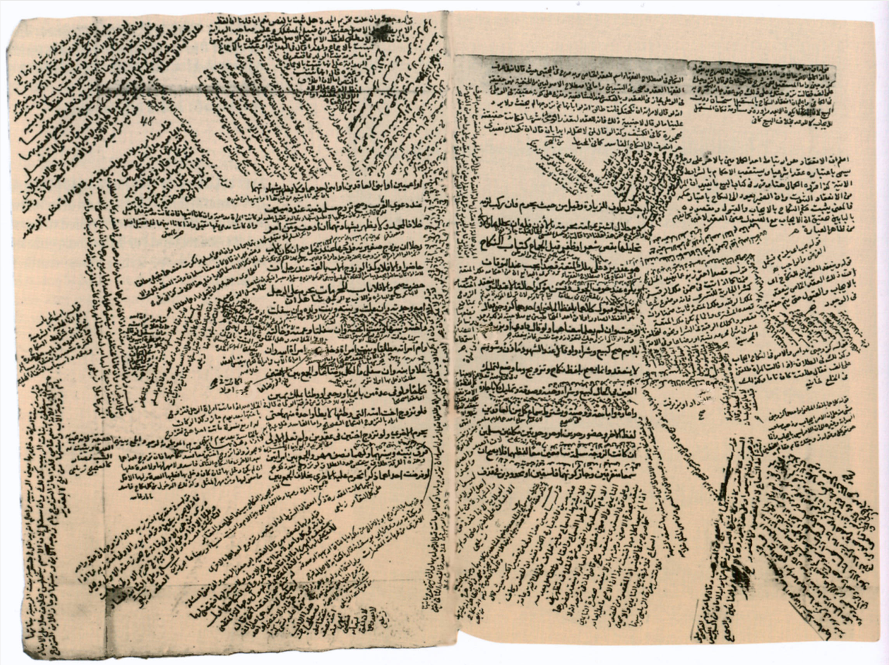
B Determine local inhomogeneity by computing differences (gradient magnitudes) between adjacent line signatures.

C Segment image into text blocks along inhomogeneity maxima.

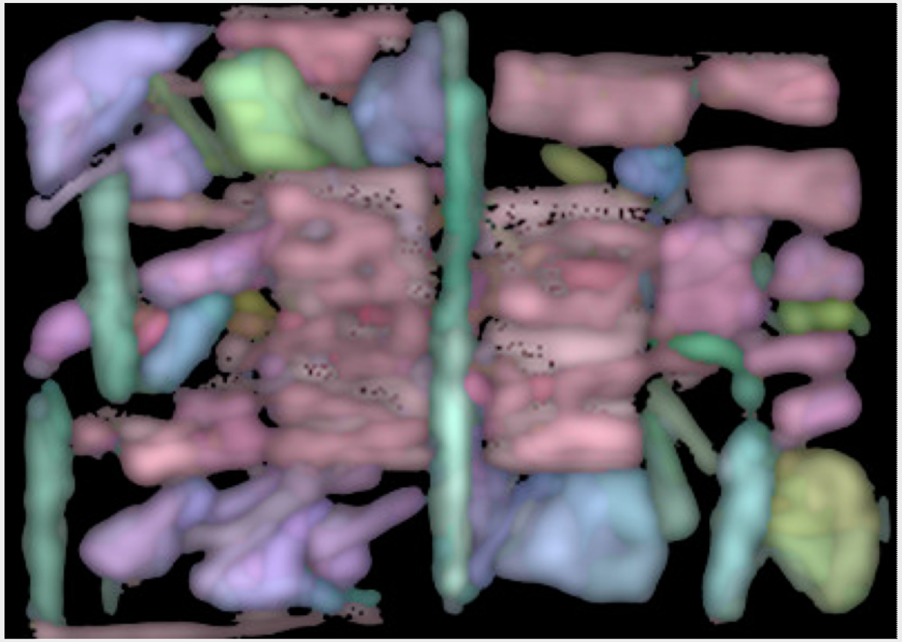
If line distances are unknown or vary strongly, step A must be carried out with several sizes of the Gabor window.

Typical processing time for 2000 x 3000 manuscript page:
10min (in research infrastructure)

Determining Local Line Signatures



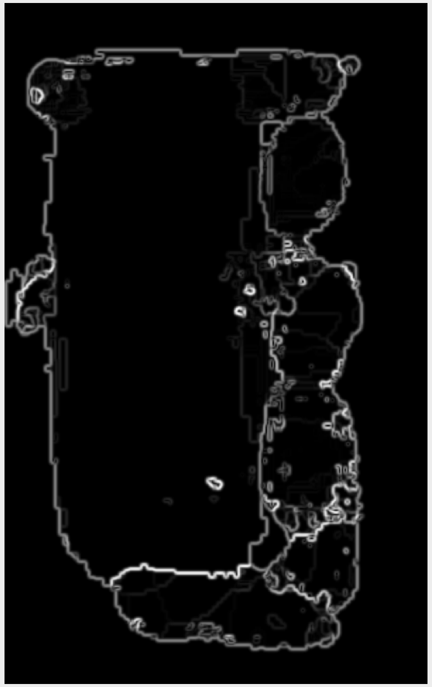
Section of an Arabic manuscript



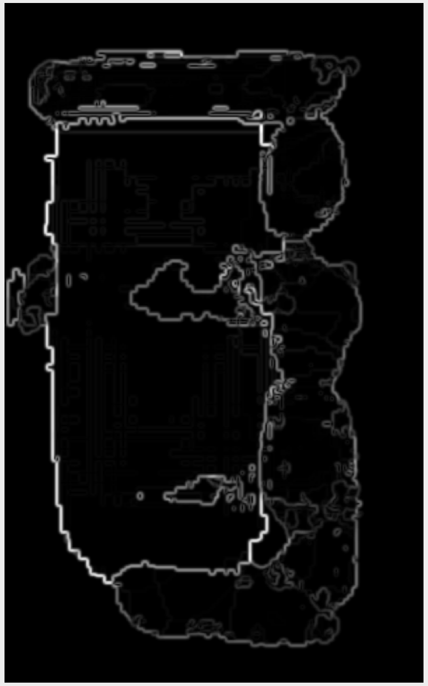
Colour code of line orientations

Note: Orientations ± 180° are not distinguished

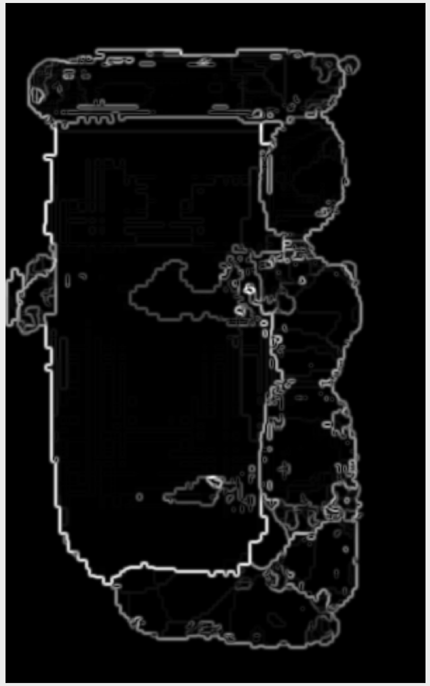
Inhomogeneity Gradients



Orientation gradient magnitudes



Frequency (line distance) gradient magnitudes



Combined inhomogeneity gradient magnitudes

Region Properties

Region boundaries can be derived from the inhomogeneity gradient image with segmentation methods from Computer Vision.

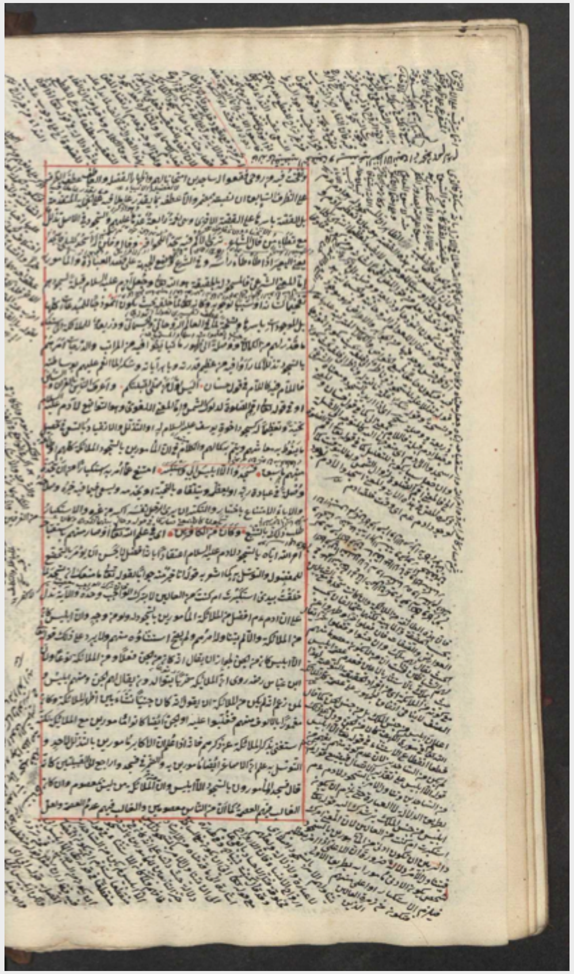
Used here: Watershed segmentation

Several region properties are available for further analysis, e.g.:

	COG (x,y)	Area [Pixel]	Line distance mean [Pixel]	Line distance variance	Line orientation mean	Line orientation variance
Region 1	(545,1220)	45623	89.93	77.777	90.39	64.39
Region 2	(645,300)	10421	44.95	221.5	93.25	317.08
Region 3	(1050,620)	4412	45.78	85.6	29.58	156.48
Region 4	(775,2150)	7108	35.35	60.97	164.12	134.98
Region 5	(1140,1965)	3247	39.55	69.22	33.62	705.81
Region 6	(1075,1380)	10920	40.67	112.92	114.88	977.64
Region 7	(115,1070)	953	36.65	192.38	98.95	1474.81
Region 8	(655,1045)	2226	49.53	133.38	90.43	245.09

Examples (1)

Examples (2)



Examples (3)

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- **Retrieval**

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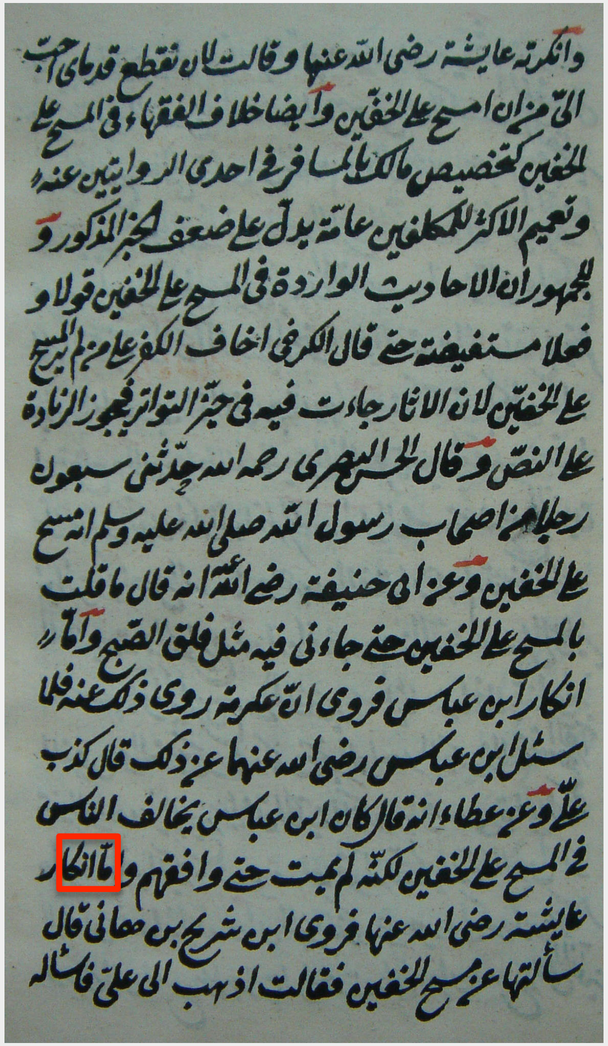
Content-based Image Retrieval

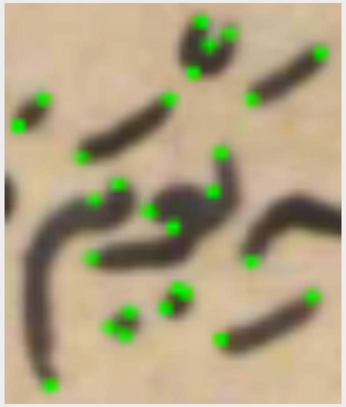
Determine occurrences of example image in large database



Word Spotting with Harris Corners (HCs)

Search and retrieval support for scholars of the Humanities

- **User provides template with query pattern**
- **System determines classified HCs**
  a) for query pattern
  b) for database (only once)
- **System searches for similar patterns**
  a) based on classified HCs
  b) using elastic deformation of query pattern



What is a Harris Corner?

Response of the Harris Corner detector:

Measure of "cornerness" of an image region:

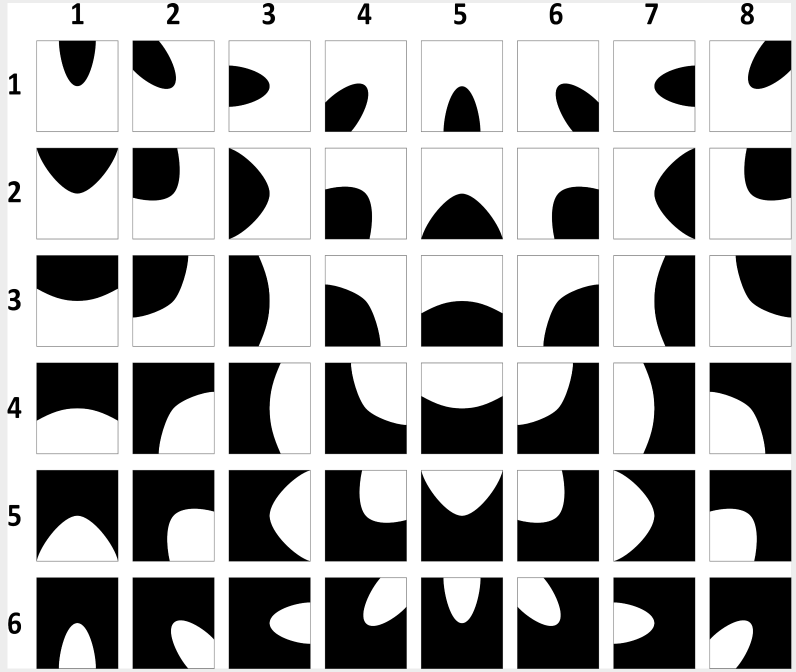
no change in all directions

no change along edge

significant change in all directions

Classification of HCs

Manually designed code chart for HC types

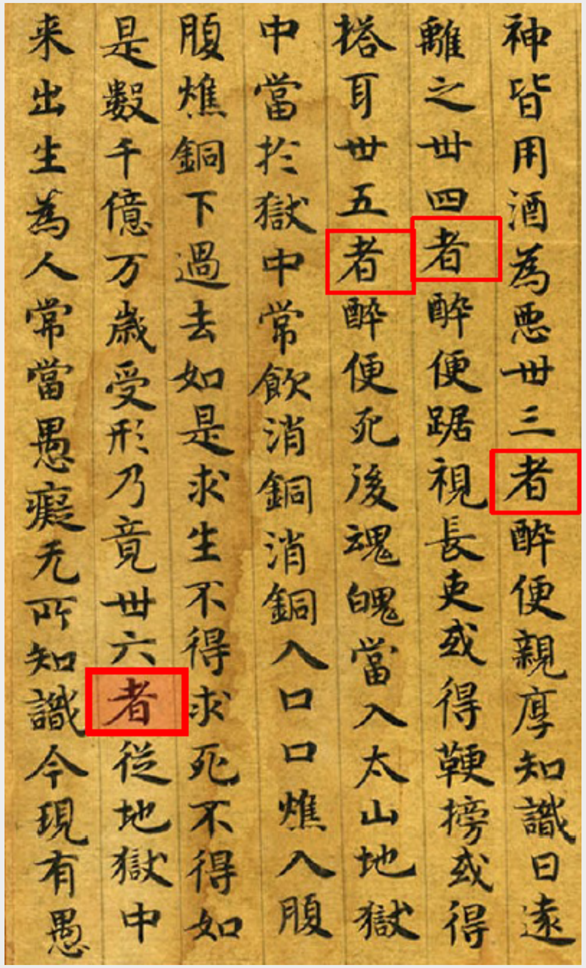


HCs are classified using a Support Vector Machine (SVM) trained with manually selected examples.

Example Database (1)

retrieved characters

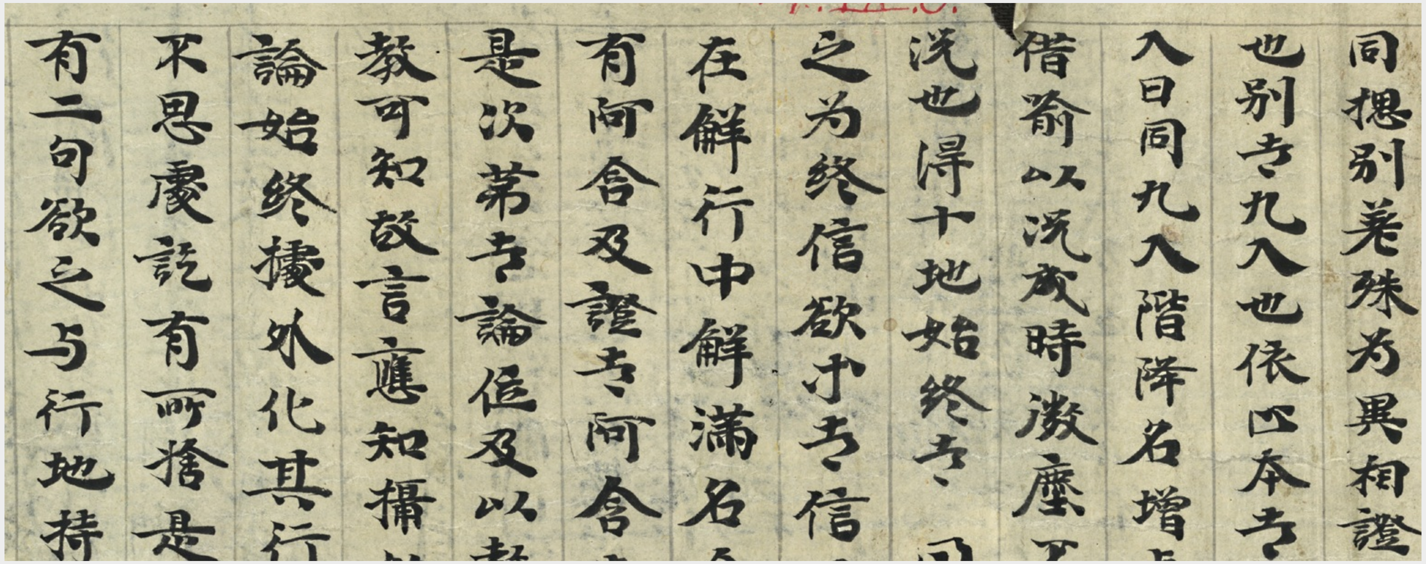
query character


神皆用酒為惡卅三者醉便親厚知識日遠
離之卅四者醉便踞視長吏或得鞭搒或得
塔耳卅五者醉便死後魂魄當入太山地獄
中當於獄中常飲消銅消銅入口口燋入腹
腹燋銅下過去如是求生不得求死不得如
是數千億万歲受形乃竟卅六者從地獄中
來出生為人常當愚癡无所知識今現有愚

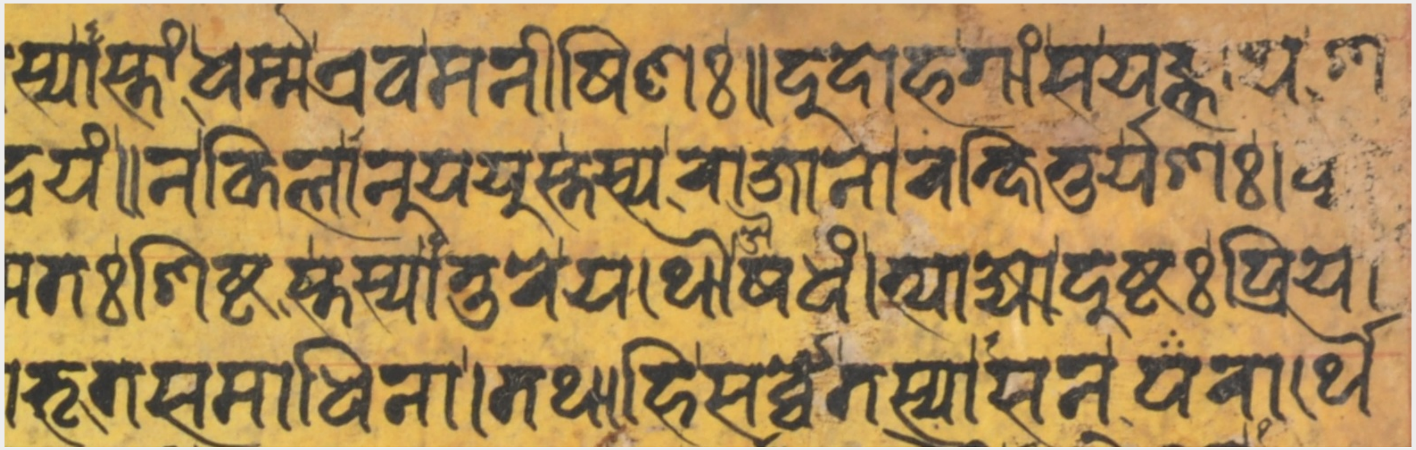
Database A:
Ca. 2000 Chinese characters

Example Databases (2)

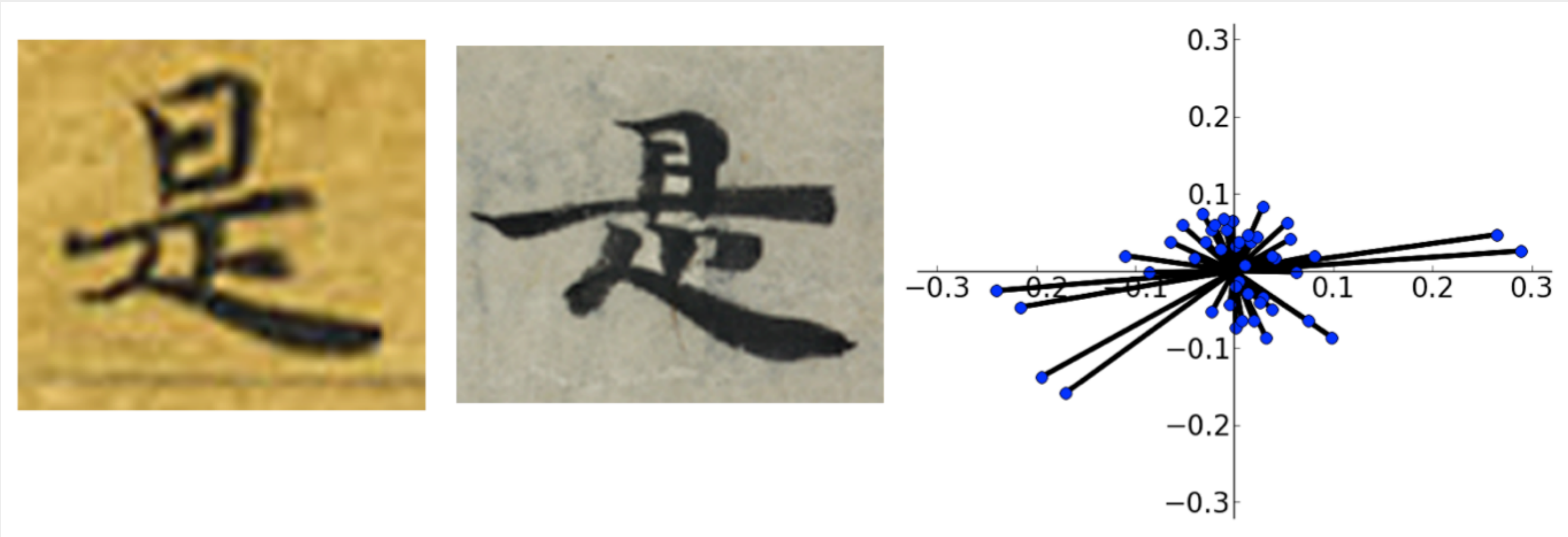
Database B: Ca. 2000 Chinese characters



Database C: Ca. 1800 Newari (Sanskrit) characters

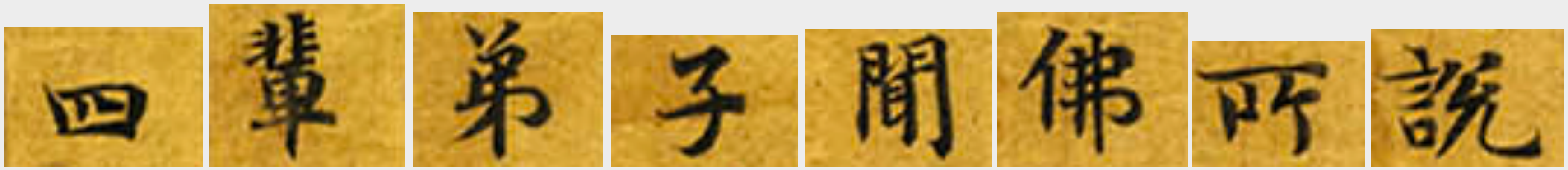


Displacements of Harris Corners



Displacements of corresponding HCs relative to character width, normalized to zero mean

Retrieval Results for Database A



1 2 3 4 5 6 7 8

9 10 11 12 13 14 15 16

Character	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
True Positives	13	2	0	5	?	10	28	2	16	2	0	7	4	0	5	1
False Positives	5	0	0	0	?	0	1	0	10	0	0	4	0	0	1	0
False Negatives	0	0	0	0	?	0	0	0	0	0	0	0	0	0	0	0

100% recall, 94% precision without warping.

Local Elastic Deformation

query pattern

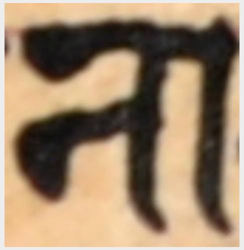
target pattern

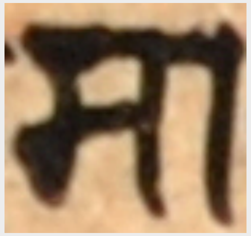
matching regions before warping

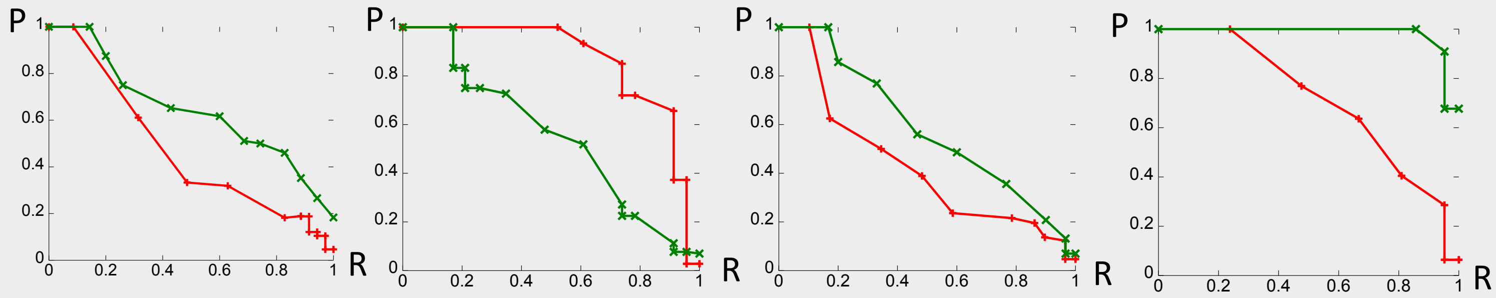
matching regions after warping

- **Binarization required**
- **Local warping with Gaussian radial basis functions**
- **Hill-climbing for better match**
- **Mismatching HC pairs are ignored**

Retrieval Results for Database B





Precision-Recall plots without warping (red) and with warping (green)

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Basic Stroke Finding Procedure

- **Determine character contours (or silhouette)**
  - Compute gradient magnitude image
  - Sub-pixel watershed segmentation
- **Identify strokes**
  - Constrained Delaunay Triangulation
  - Merge partial strokes at junctions
- **Compute stroke features**
  - Location of medial axis, length, orientation, width
  - Relational properties

Determining Character Contours

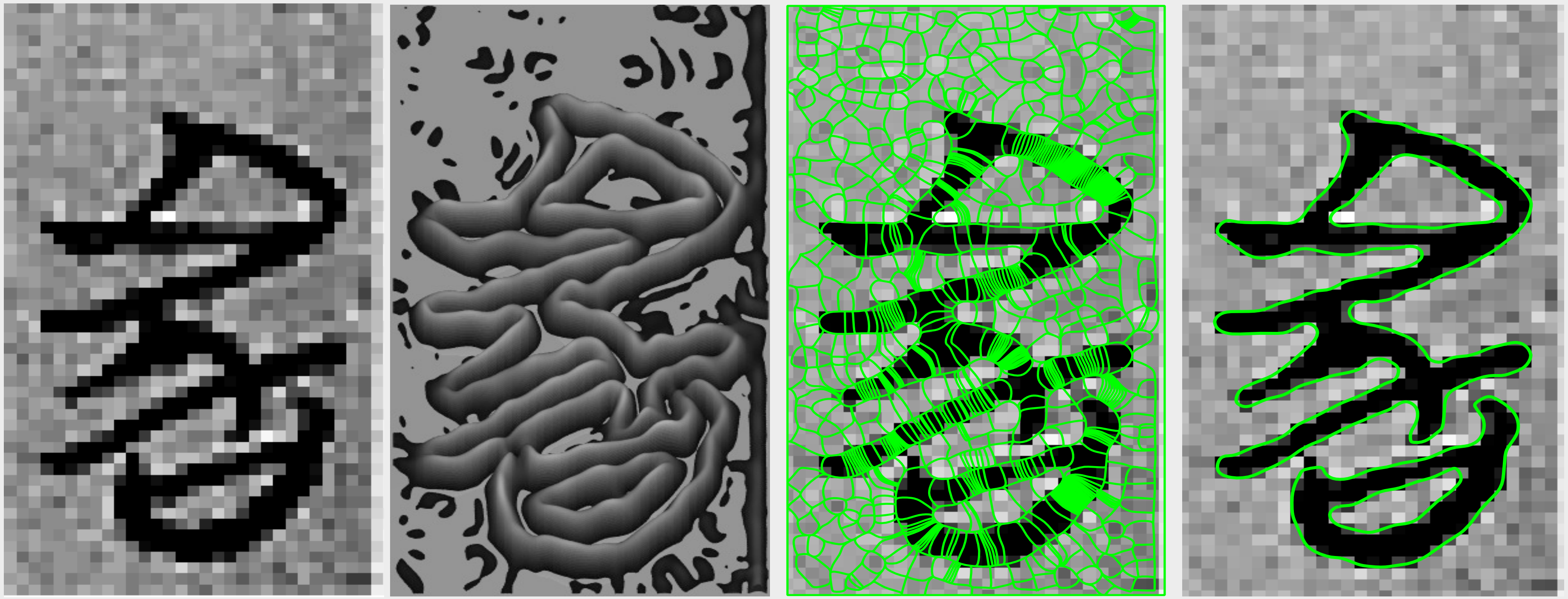


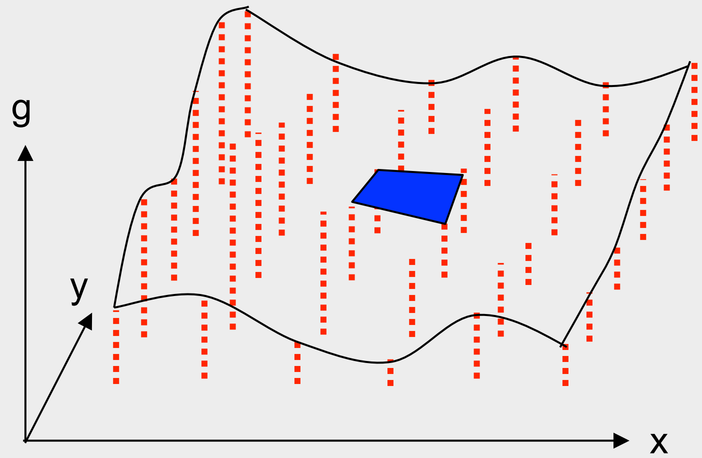
Image of Chinese character | Gradient magnitudes after interpolation | Watershed edges | Final contour after removing insignificant edges

Subpixel Watershed Segmentation

A **Determine continuous image by Spline interpolation between pixels of discrete image**

B **Determine watershed lines (mathematically: lines connecting maxima and saddle points)**

C **Remove insignificant lines**



5-th Order Spline interpolation

There exist numerous methods for determining object boundaries.
Nice properties of watershed lines:

- closed boundaries

- no artefacts at junctions

Constrained Delaunay Triangulation (CDT) for Stroke Analysis

CDT is defined for points on a polygonal boundary such that no edge of a triangle crosses the boundary.

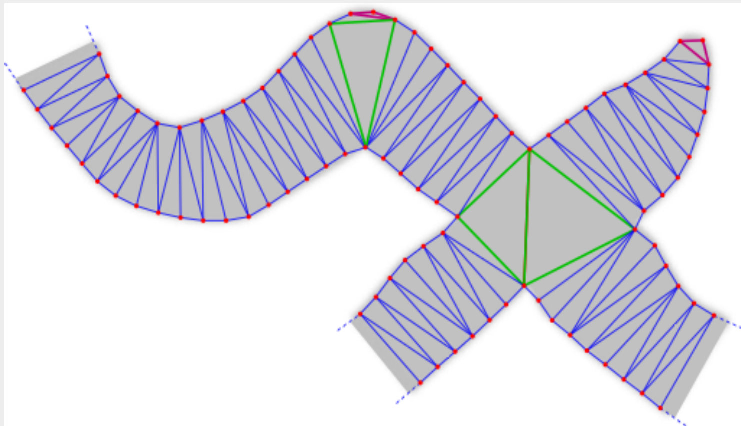
The density of boundary points can be chosen as fit for the application.

Three types of triangles according to the number of *chords* (edges not coinciding with the contour):

- *junction* triangles (3 chords, green)

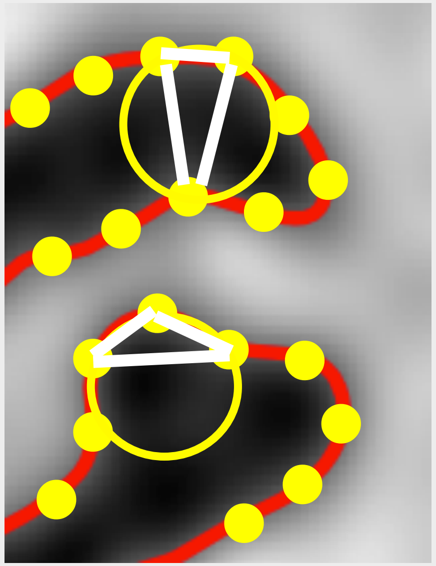
- *sleeve* triangles (2 chords, blue)

- *terminal* triangles (1 chord, red)

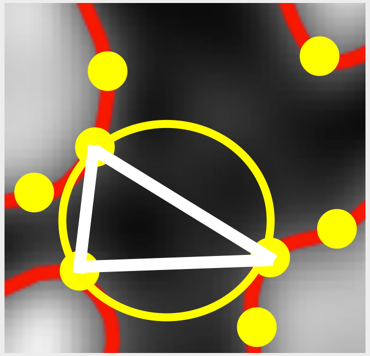


Stroke analysis amounts to collecting the connections from terminal or junction triangles via sleeve triangles to other terminal or junction triangles.

Examples of Delaunay Triangles



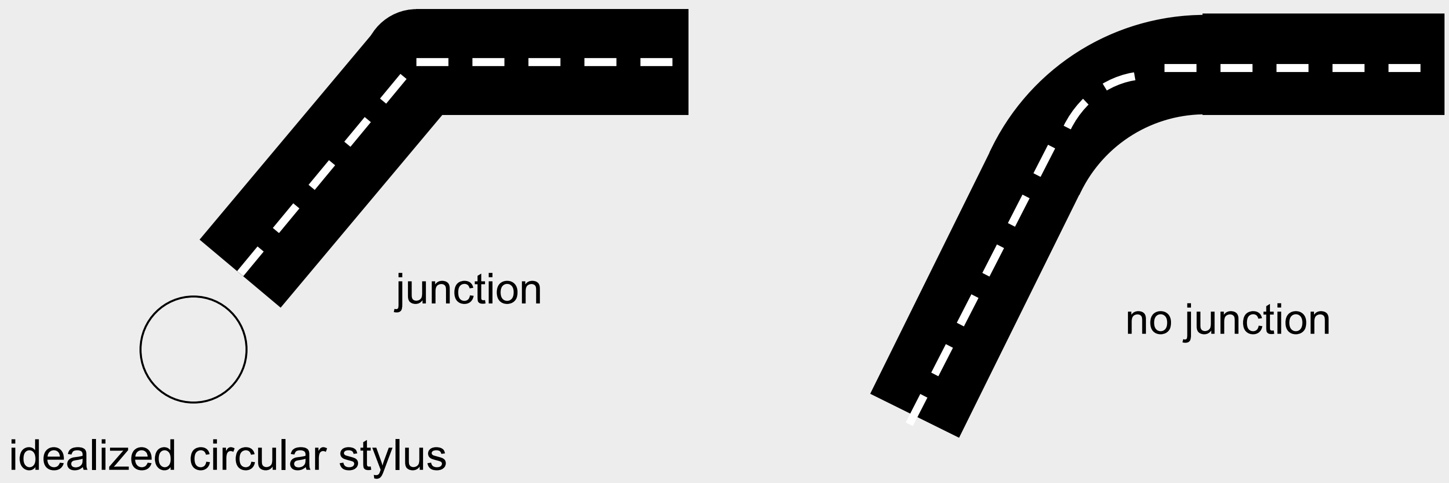
sleeve triangle (top)
terminal triangle (bottom)



junction triangle

Corners vs. Curves

Junction triangles are generated within a curve, if the stylus has performed a sudden (discontinuous) orientation change.



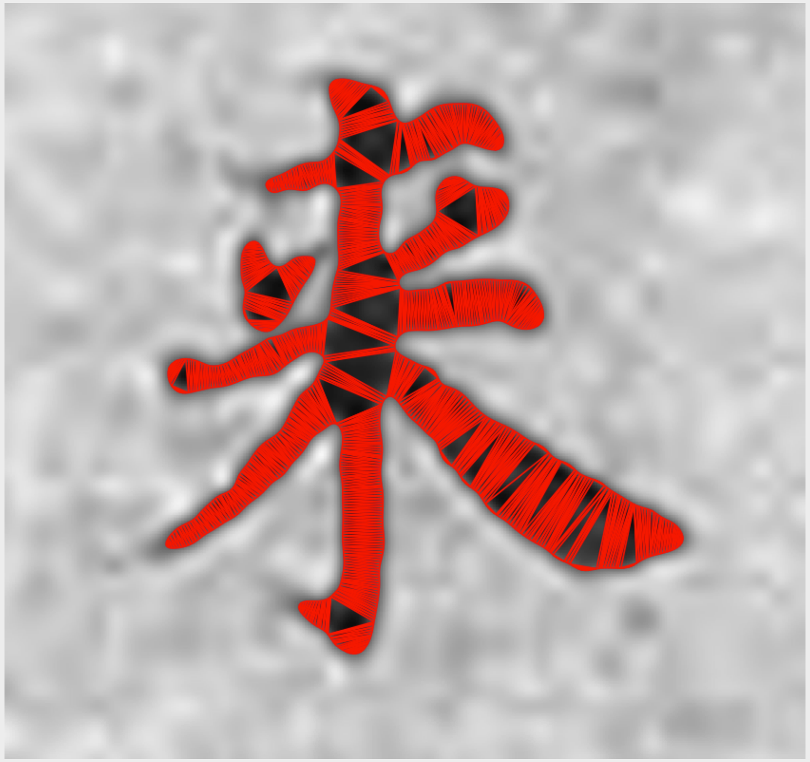
Exact conditions for junction:

- **Dense boundary points**
- **Stylus radius S, center line curve radius R, and angle α meet inequality**

$$R < S \frac{1 - \cos(\alpha/2)}{1 + \cos(\alpha/2)}$$

Triangulation Example

Chinese character for "come"
with computed contour



Constrained Delaunay
Triangulation

Universität Hamburg
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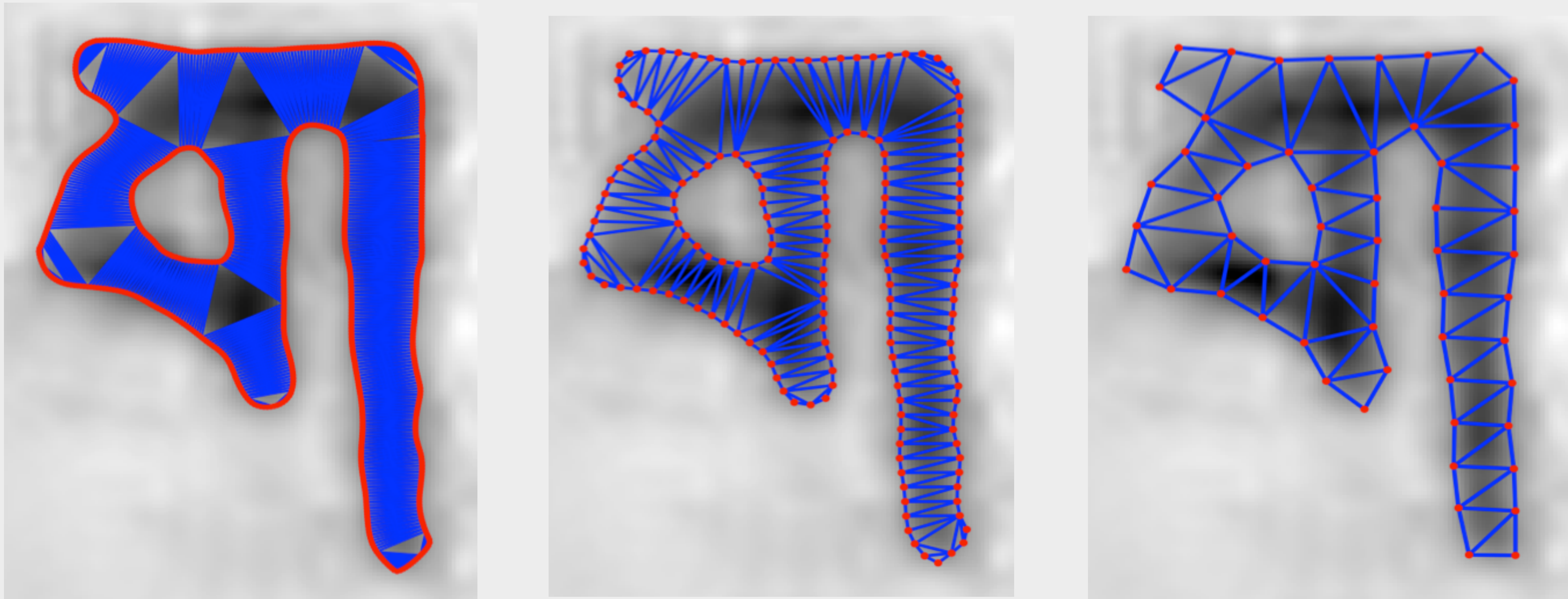
Collaborative Research
Centre for the Study of Manuscript Cultures
Manuskriptkulturen in Asien, Afrika und Europa
Sonderforschungsbereich 950

Influence of Contour Point Density

The spacing of boundary points must be chosen according to the details to be captured.

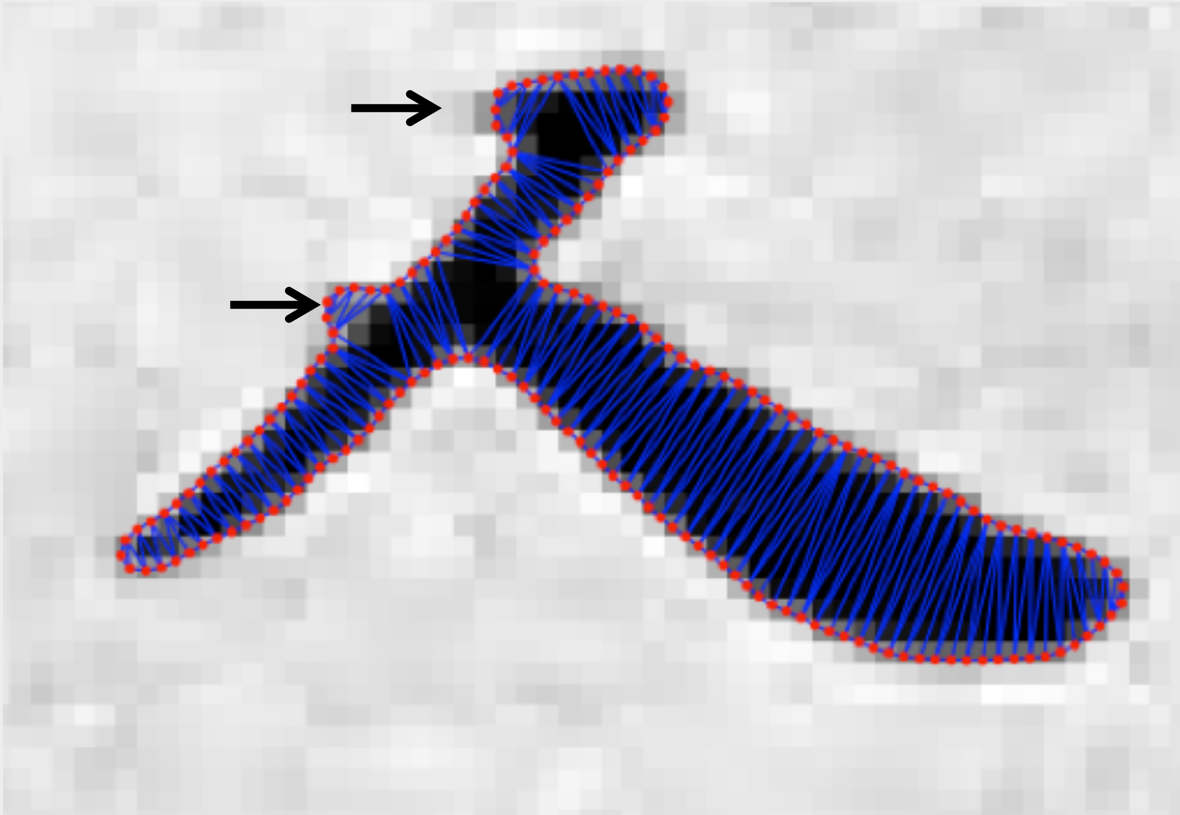


no junction triangles at upper left and right corners due to wide spacing

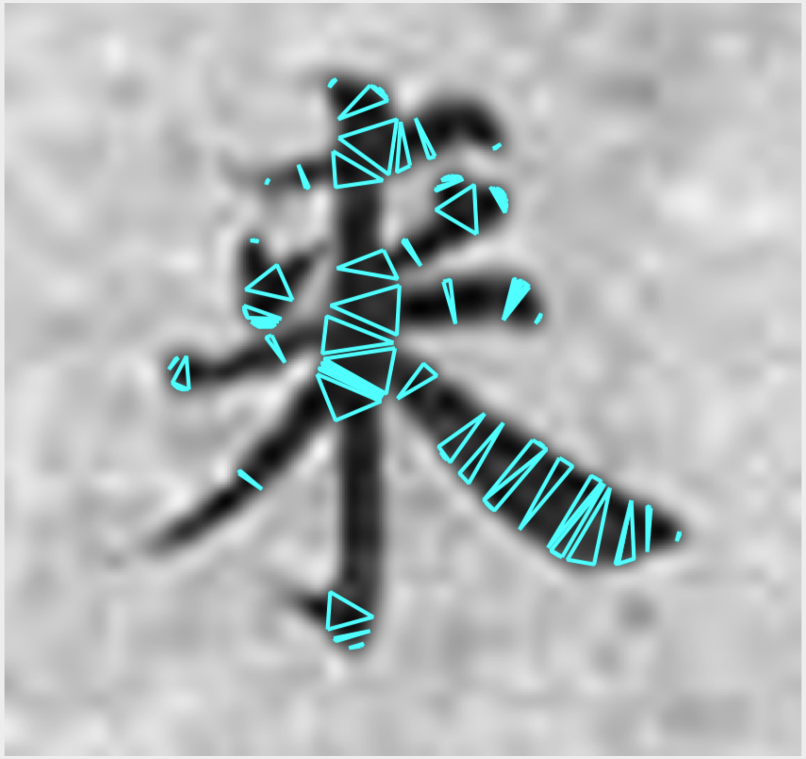
Influence of Distortions

"Distortions" may naturally arise from handwriting irregularities or background noise.

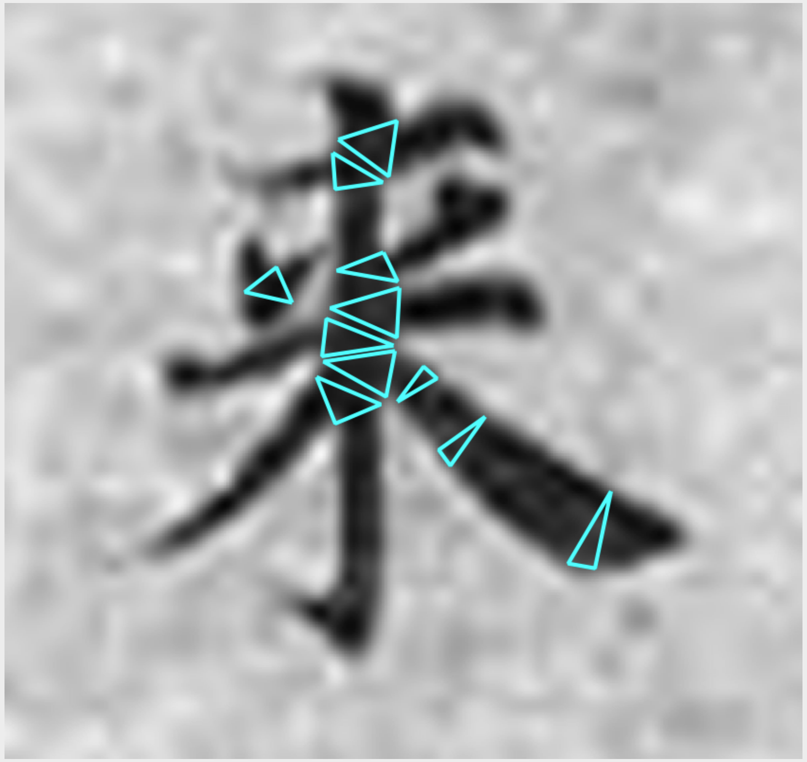
terminal and junction triagles at "distortions"



Junction Triangles



Junction triangles including spurious junctions due to handwriting irregularities



Cleaned up junction triangles

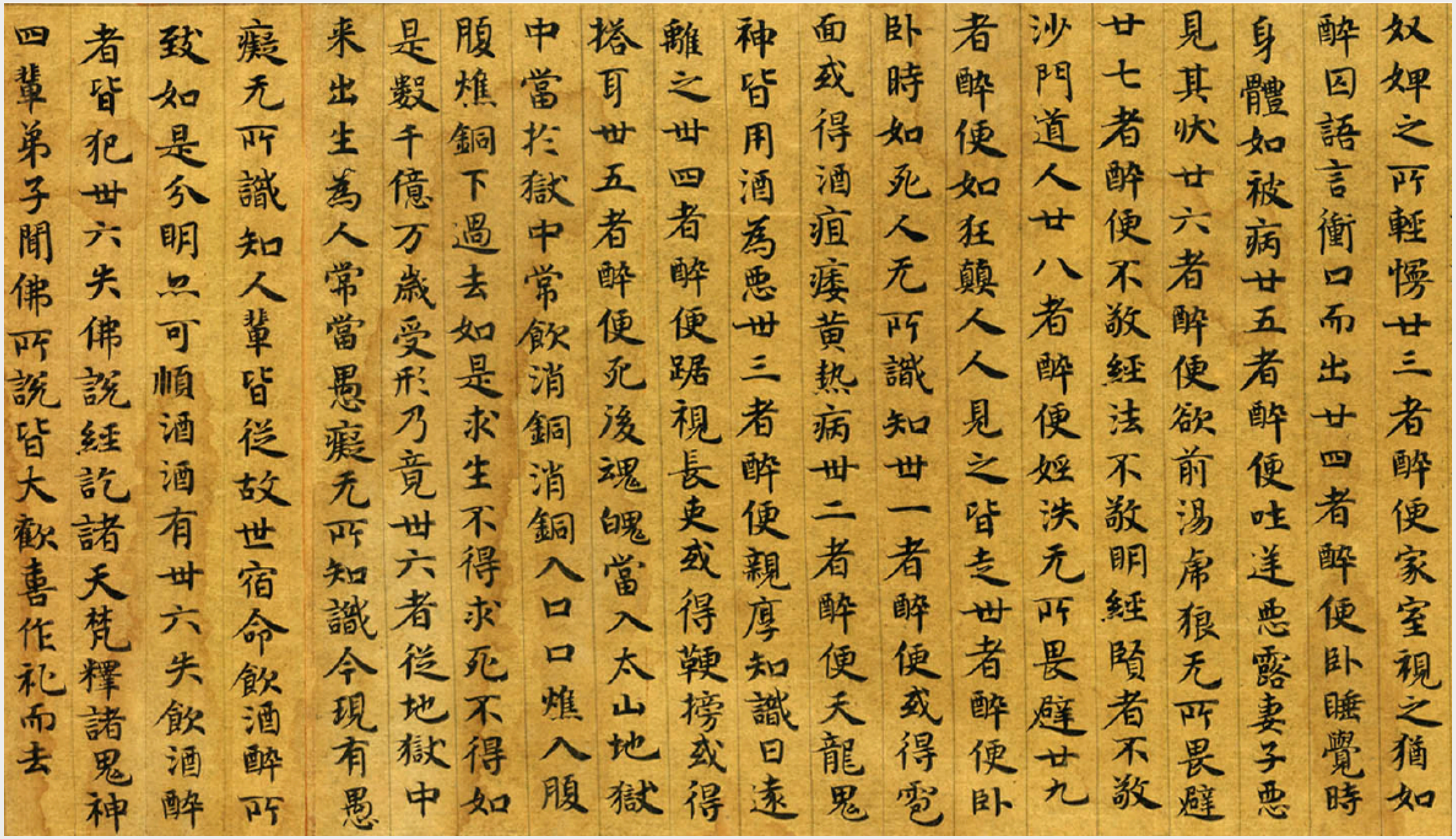
Merging Partial Strokes

Partial strokes are merged by searching for an optimal stroke configuration:

- **smooth individual continuation**
- **best overall result**

Evaluation (1)

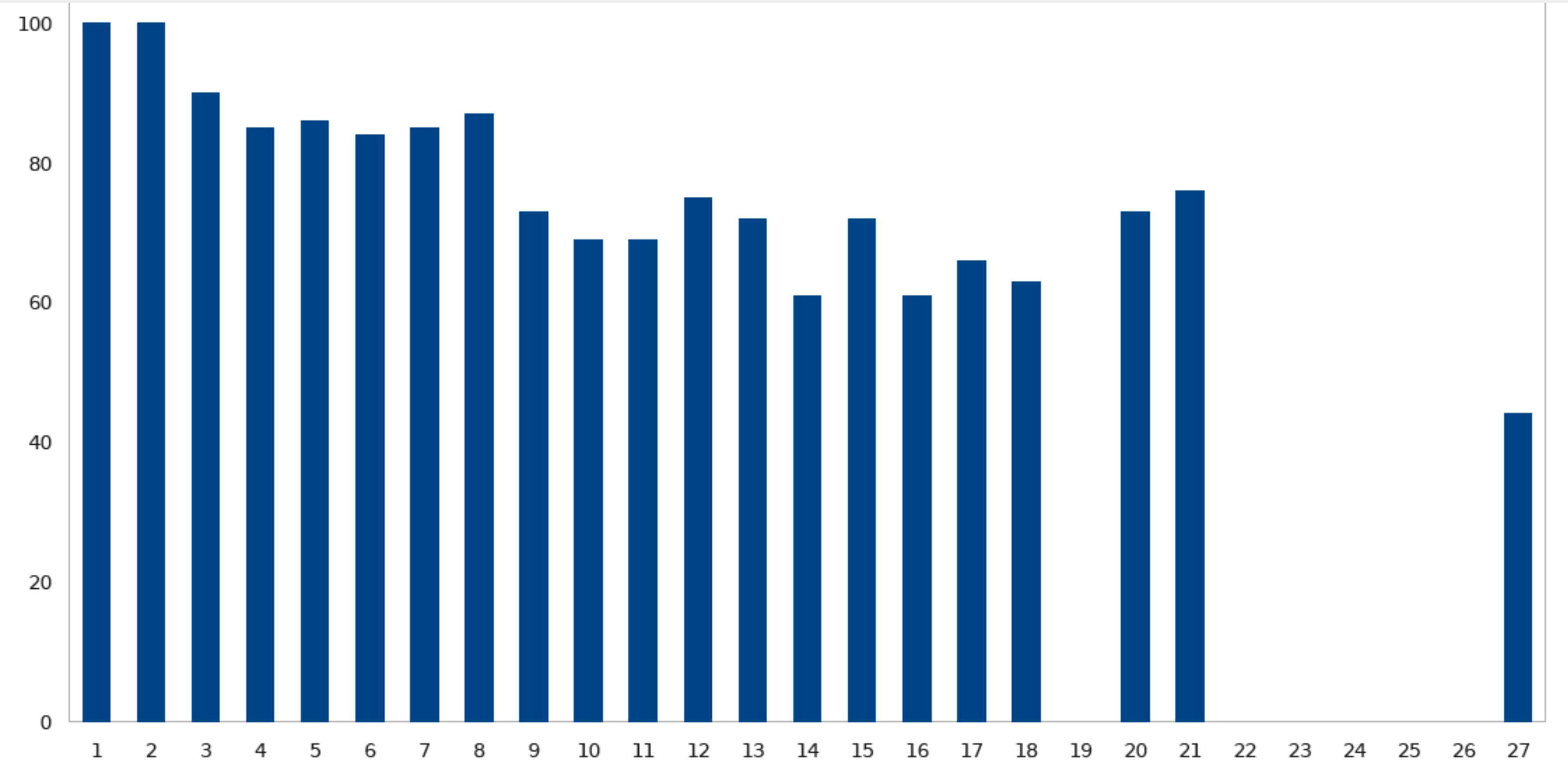
339 Chinese characters, ca. 60 x 60 pixels each



奴婢之所輕慢卅三者醉便家室視之猶如
醉因語言衝口而出卅四者醉便臥寤覺時
身體如被病卅五者醉便吐逆惡露妻子惡
見其狀卅六者醉便欲前湯鼐狼无所畏避
廿七者醉便不敬經法不敬明經賢者不敬
沙門道人廿八者醉便婬泆无所畏避廿九
者醉便如狂顛人人見之皆走卅者醉便臥
卧時如死人无所識知卅一者醉便或得電
面或得酒疱瘻黃熱病卅二者醉便天龍鬼
神皆用酒為惡卅三者醉便親厚知識日遠
離之卅四者醉便踞視長吏或得鞭榜或得
捲耳卅五者醉便死後魂魄當入太山地獄
中當於獄中常飲消銅消銅入口口燋入腹
腹燋銅下過去如是求生不得求死不得如
是數千億万歲受形乃竟卅六者從地獄中
来出生為人常當愚癡无所知識今現有愚
癡无所識知人輩皆從故世宿命飲酒醉所
致如是分明只可順酒酒有卅六失飲酒醉
者皆犯卅六失佛說經訖諸天梵釋諸鬼神
四輩弟子聞佛所說皆大歡喜作禮而去

Evaluation (2)

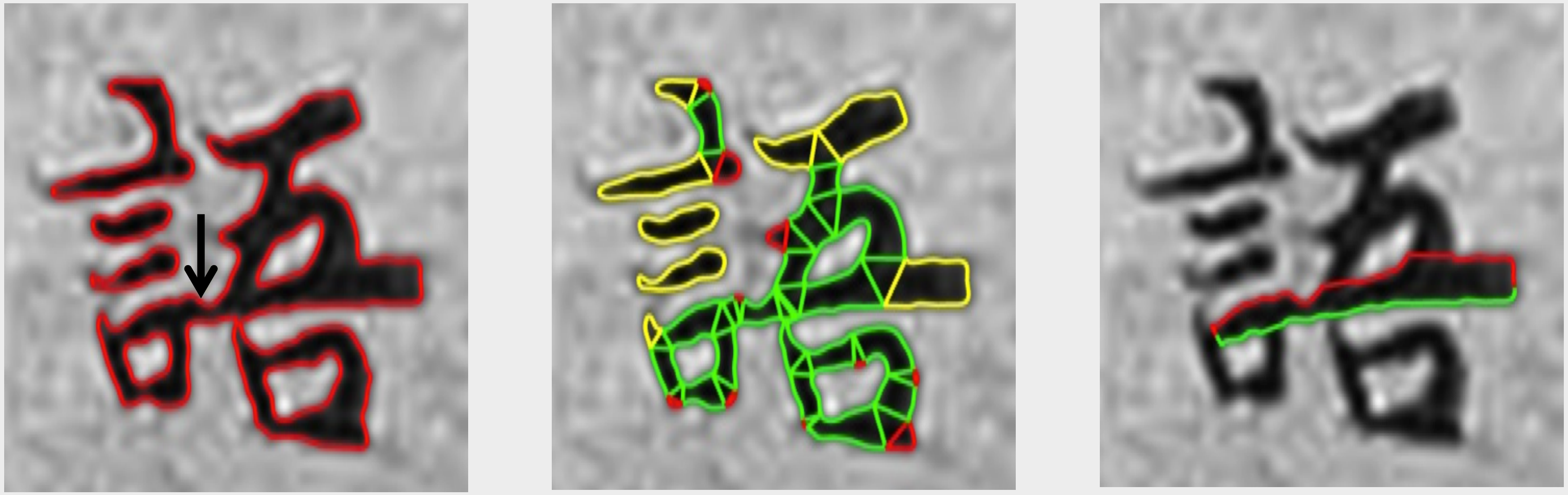
Stroke recognition rate decreases with character complexity



Faulty Stroke Reconstruction Due to Rounded Corners

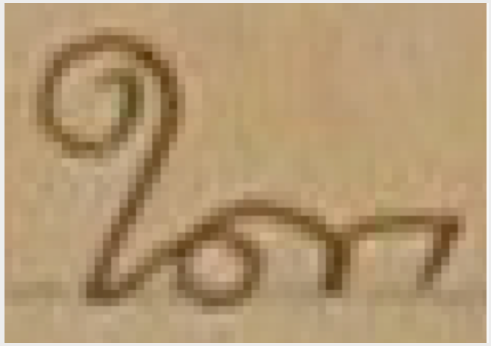
The square-shaped contours actually consist of four strokes, only one has been identifies due to missing junction triangles at rounded corners.

Faulty Stroke Reconstruction Due to Segmentation Error

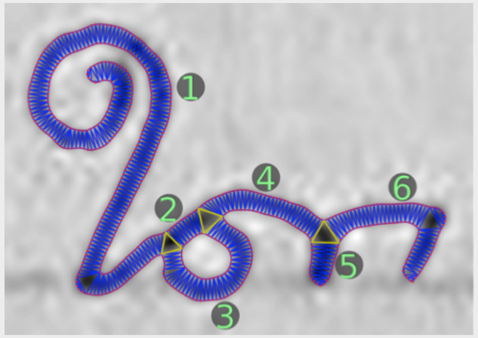


Two separate strokes were merged due to touching strokes in the image.

Application to Cursive Scripts



Tamil syllable *lai*



Triangulation resulting in six stroke segments

Three high-ranking reconstructions

Agenda

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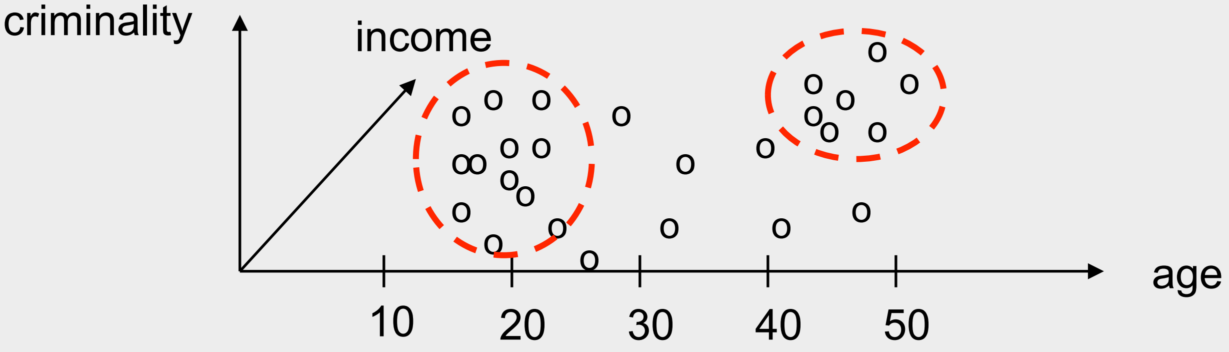
Discovering Clusters in Data

"Clusters" of data objects are hypothetical classes based on similarities and distances. Data objects should be as similar as possible within clusters and as distinct as possible between clusters.



Cluster 1: age 15 - 25, low income, high criminality ("youth criminality")
Cluster 2: age 45 - 55, high income, high criminality ("white-collar criminality")

Data objects are viewed as points in a multi-dimensional feature space. Similarity of data is judged by distance measures.

Clustering in Manuscript Analysis

Grouping of manuscrips / sections based on a similarity measure

How does one measure the similarity of e.g.
- letters?
- layouts?
- writing style?

Quantitative features in feature space
Symbolic features in relational structures

There exist numerous clustering procedures in commercial systems.

<u>Warning</u>: Results depend on *weights* assigned to different features

Metrical Distance Measures

A distance measure is required to judge the difference between two samples.

Mathematical definition of a metric d for points x, y, z must meet conditions:

$d(x, x) = 0$	points have distance 0
$d(x, y) \neq 0$	different points have distance different from 0
$d(x, y) = d(y, x)$	symmetry
$d(x, y) + d(y, z) \geq d(x, z)$	triangular inequality

Metrics cannot always be easily defined:

- Angles
- Colors
- Shapes
- Texts

Examples for Distance Measures

- **Euclidean distance for numerical values**

$$d^2 = \sum_i (x_i - y_i)^2$$

e.g. for length, width and orientation of two shapes

Normalization may be required for a meaningful comparison

$$b' = \frac{b}{\sigma_b} \qquad h' = \frac{h}{\sigma_h} \qquad \alpha' = \frac{\alpha}{\sigma_\alpha}$$

- **Absolute distance** $d = \sum_i \left|(x_i - y_i)\right|$

- **Maximal distance** $d = \max_i \left|(x_i - y_i)\right|$

- **Hamming Distance** $d = \sum_i d_i \quad \text{with} \quad d_i = \begin{cases} 0 & \text{for } x_i = y_i \\ 1 & \text{for } x_i \neq y_i \end{cases}$

k-means Algorithm

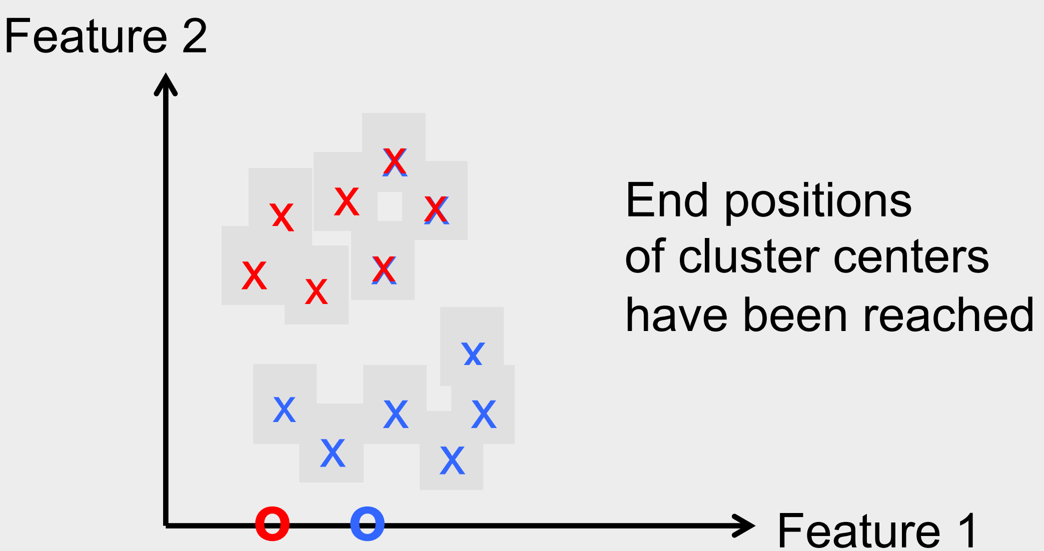
Samples are represented as points in an N-dimensional feature space.

A **Choose arbitrary initial cluster centers**

B **Determine cluster assignments of points according to distance to cluster centers**

C **Move cluster centers to mean of assigned points**

D **Repeat B and C until no further changes occur**



Structural Distance Measures

- **Levenshtein Distance ("Editing Distance")** of symbol sequences (e.g. texts)

  How many operations for
  - replacing a character / symbols
  - removing a character / symbols
  - inserting a character / symbols

  are minimally necessary to concert one sequence into the other

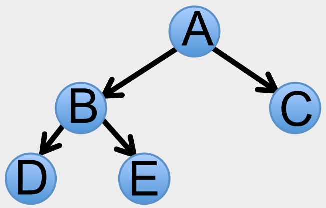
  Example: L E V E N S H T E I N ⟷ L E W E N S T E I N → d = 2

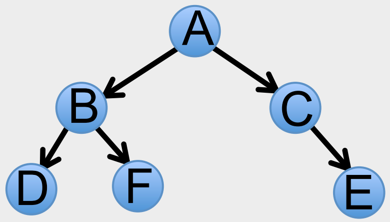
  There exist efficient algorithms to determine the Editing Distance.

- **Structure Distance**

  Generalization of Editing Distance to relational structures

edges often express compositional information





→ d = 3

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Datamining and Knowledge Discovery

Classical statistics

Machine Learning

Pattern Recognition

Data Mining and Knowledge Discovery are considered parts of AI (1990)

Identification of new, potentially useful patterns in large data sets

Data Mining:
Analysis, hypothesis generation

Knowledge Discovery:
Evaluation and interpretation

Datamining for Manuscript Analysis

Discovery of visual features to determine commonalities between manuscripts

Potential evidence for

- **common region of origin**
- **common cultural epoche**
- **common writing style**
- **common hands**

Thesis:

Computers may discover features and feature associations, which may have been overlooked or which are difficult to discover by humans.

Association Rules

Datamining offers mature and efficient procedures, developed e.g. for purchase analysis:

"Customers who purchase beer and pizza also tend to buy potatoe chips"

Transfer to manuscript analysis:

"Scribe A tends to use a smaller stroke angle in character Y more often than scribe B"

"There is a group of manuscripts

- ***where the cross bar in character X tends to be shorter than elsewhere, and***
- ***where the strokes in the characters Y1, Y2 and Y3 tend to be slimmer than normal, and***
- ***where the height of the signs is unusually constant"***

Preparing Manuscripts for Datamining

- **Select objects (characters, words) for comparison**

o1 o2 o3 o4 o5 o6 o7 o8 o9 o10 o11 012

- **Determine features of large repertoire for each object**

o1	angle4	angle2	length4	compact3	size2	size2	relation3
o2	angle5	angle2	length3	compact1	size1	size3	relation2
o3	angle3	angle2	length4	compact2	size1	size3	relation3
o4	angle4	angle2	length4	compact3	size2	size2	relation1
o5	angle3	angle2	length4	compact3	size1	size2	relation3
. . .							

- **Start datamining with APRIORI Algorithm**

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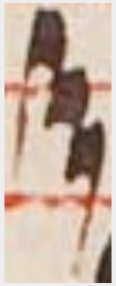
Compositional Patterns in Medieval Music Notation

What is the significance of square and rhomb note ligatures?



Is there any meaning to different stem lengths?

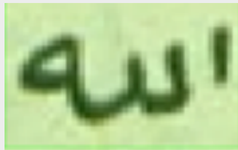
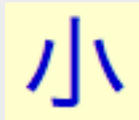
Large data volume of > 1200 pages must be analyzed!

Challenging Pattern Recognition Problem

ligatures of same type have significantly different appearances

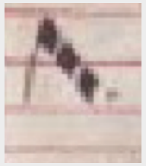
Search for *compositional structures*: patterns of parts related to each other by certain constraints.

Many examples of compositional structures in manuscripts:

Diacritics  **Words**  **Stroke radicals** 

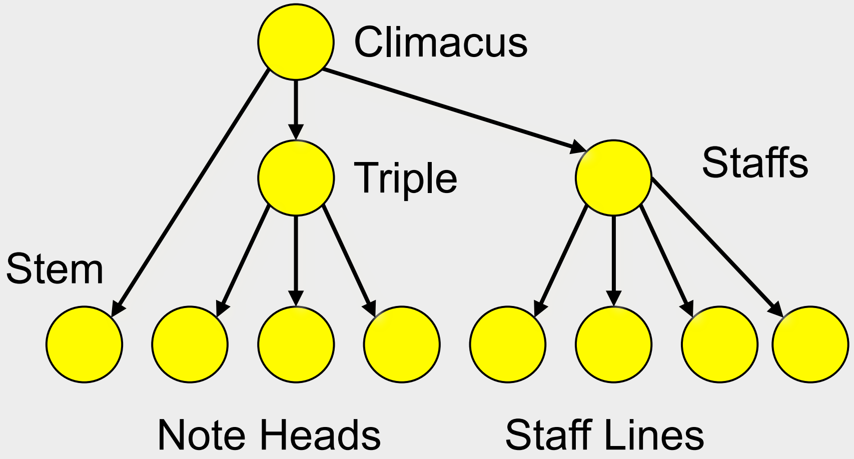
How does one recognize a compositional structure in a standardized way?

Models for Compositional Structures

A compositional structure  **can be visualized as a graph:**

Nodes represent image parts or aggregates

Edges represent the relation "composed-of" (or "has-part")



Each aggregate node is described by

- **aggregate name**
- **parent concepts**
- **aggregate properties**
- **parts**
- **constraints between parts**

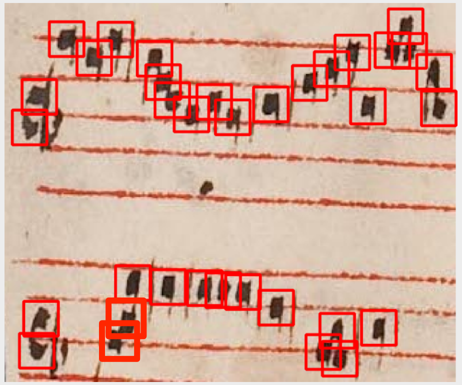
Name:	Climacus
Parent:	Ligature
Bounding Box:	< 150 x 200
Parts:	Staffs, Triple, Stem
Constraints:	Triple matches Staffs
	Stem touches upper left of Triple

Climacus model

Recognition of Primitive Parts

"Primitive parts" = elements of a compositional structure which cannot be decomposed further

Here: staff lines, note heads, stems



Standard recognition procedures:

- **Template matching**
- **Normalized Cross Correlation**
- **Feature-based Classification**
- **Specialized methods**

Here: Distinguishing between

- square notes
- rhomb notes
- noise

by template matching.

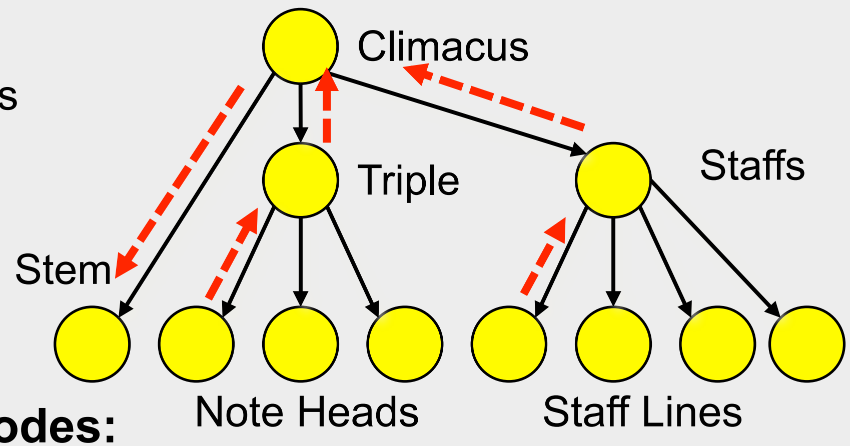
Recognition of Compositional Structures

There exist several standardized algorithms:

- **Constraint Satisfaction**
- **Top-down Search**
- **Bottom-up Search**
- **Mixed Bottom-up Top-down Search**

We used Mixed Bottom-up Top-down Search for ligature recognition:

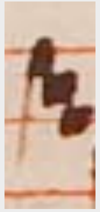
- Find staff lines
- Find staff system, check staff system constraints
- Find note heads
- Find triples, check triple constraints
- Find stem
- Find ligature, check stem constraint

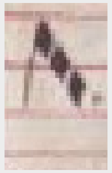


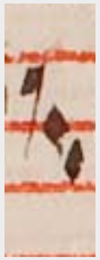
Standard bottom-up steps for aggregate nodes:

- Check constraints on parts
- Compute aggregate properties
- Assign aggregate to parent aggregates

Result Statistics







Manuscript	W1	W2	F
# Pages	379	508	798
# Ligature Type 1	2703	1089	3891
# Ligature Type 2	2	4	6
# Ligature Type 3	1398	549	1364
Ratio Type 1:Type 3	~2:1	~2:1	~3:1
Accuracy Note Classification	89,41%	96,44%	79,11%

W1 = Scottish Manuscript 1 (Herzog August Bibliothek Wolfenbüttel)
W2 = Scottish Manuscript 2 (Herzog August Bibliothek Wolfenbüttel)
F = French Manuscript (Notre Dame)

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Summary

Computer Vision and Artificial Intelligence provide powerful methods which can be harvested for palaeographic applications.

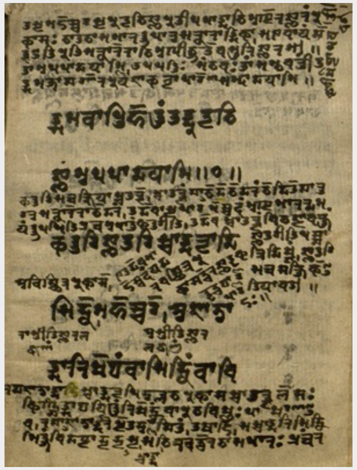
Computer support may range from sped-up palaegraphical methods to specially designed "black boxes".

You saw examples of

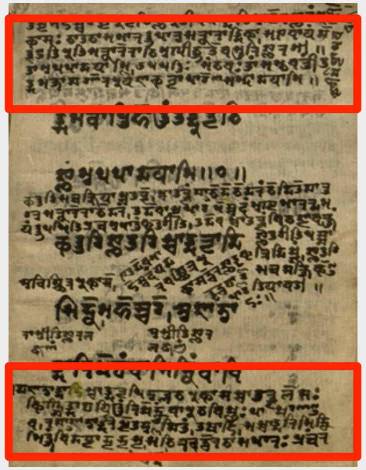
- **Restoration**
- **Retrieval**
- **Feature Extraction**
- **Grouping and Classification**
- **Interpretation**

There are numerous methods for Digital Palaeography, how choose?

"Models" for Computer Support



Tool box of computer methods



"Different scribes!"

It is useful to understand the "idea" (model) of a computer method:

- **What information is exploited, what is neglected?**
- **What are inherent limitations?**
- **How certain is a result?**


Thank you for your interest!