Perceptual Simplification of Paper-Based Scribbles for 3D Form Generation

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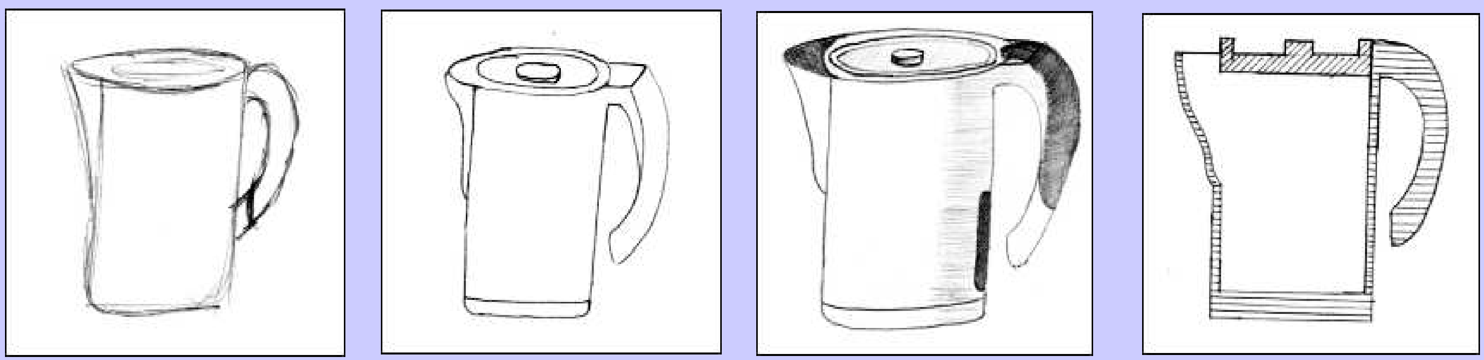
Introduction

- Traditional pen-and-paper is often the first drawing medium on which graphic ideas are expressed
- Paper-based drawings vary in detail according to the different stages of form design.



Rough Scribble | Neat Sketch | Manually Rendered Drawing | Cross-sectional Drawing

Freehand → Drawing Tools

Conceptual Design | Embodiment Design | Detailed Design

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Raster-to-Vector Conversion

- Paper-based drawings cannot be used directly with CAD tools.
- Vectorization algorithms are generally used to convert the raster information into vector form.

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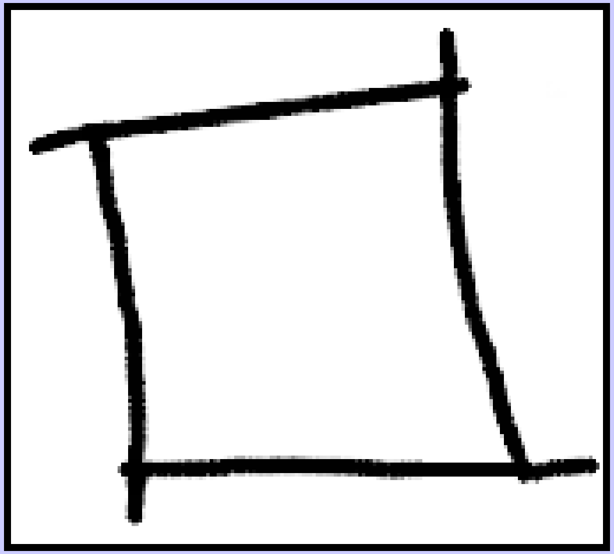
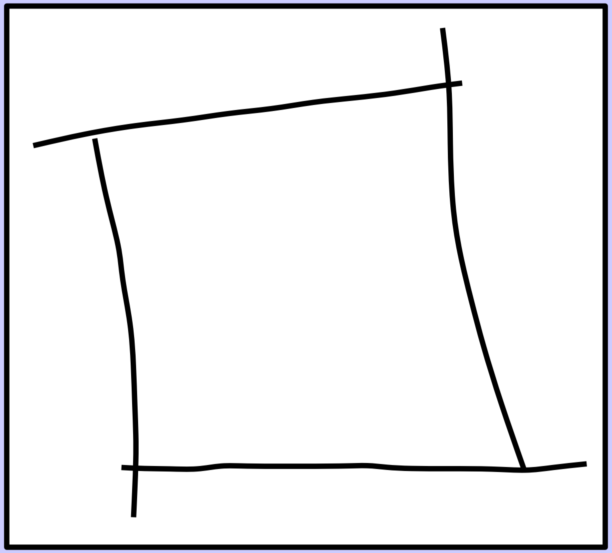


Raster Image



Line Location

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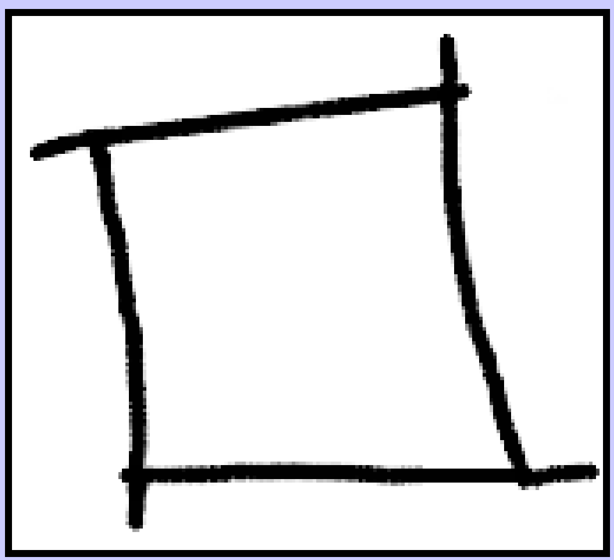
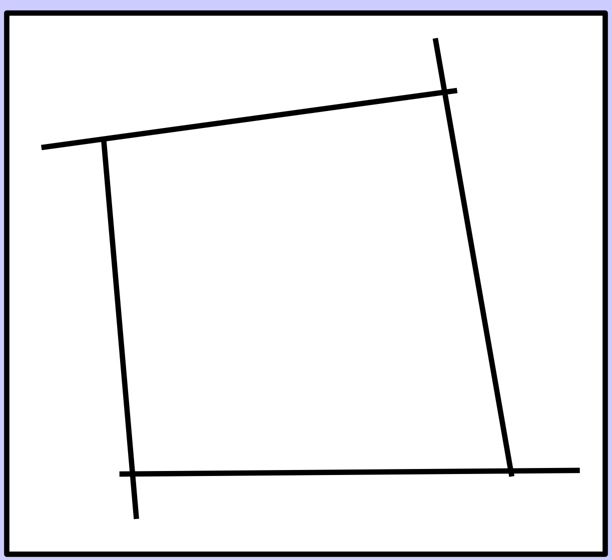


Raster Image



Line Fitting

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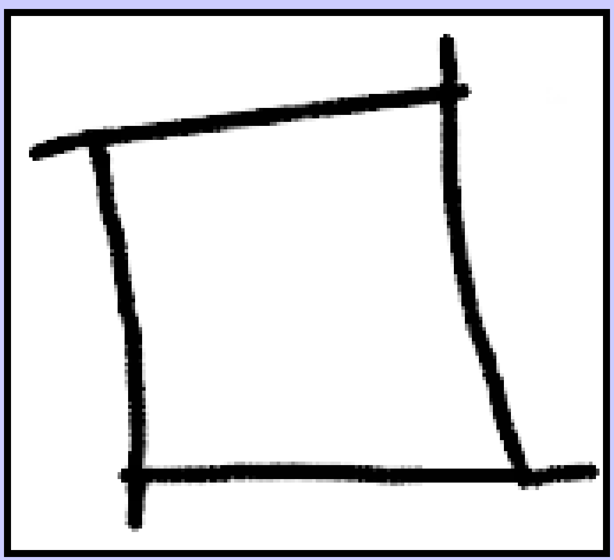
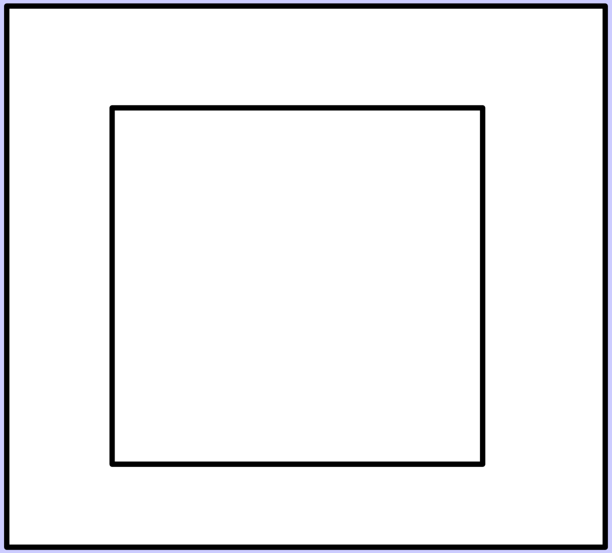


Raster Image



Beautification

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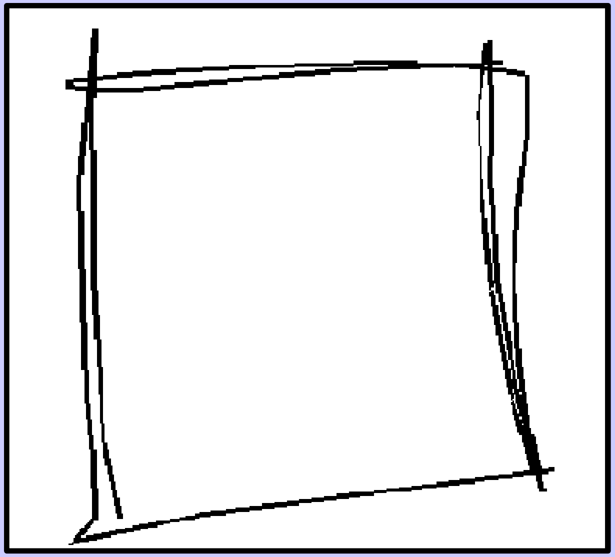
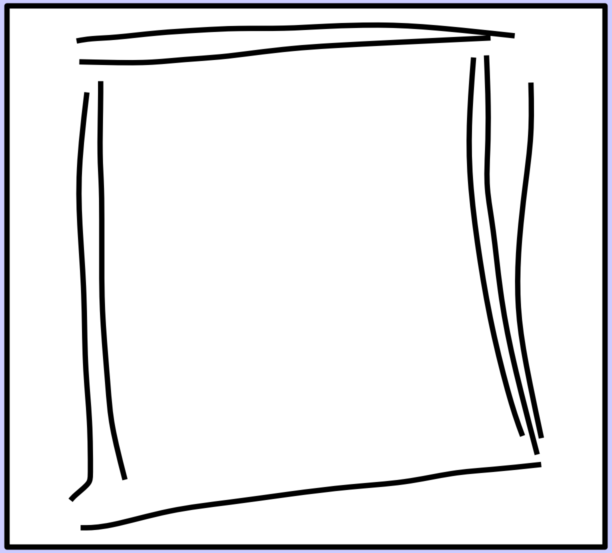
Raster-to-Vector Conversion

- Paper-based drawings cannot be used directly with CAD tools.
- Vectorization algorithms are generally used to convert the raster information into vector form.
- Scribbled objects **do not** have single-line edges.



Scribbled Drawing



Line Location

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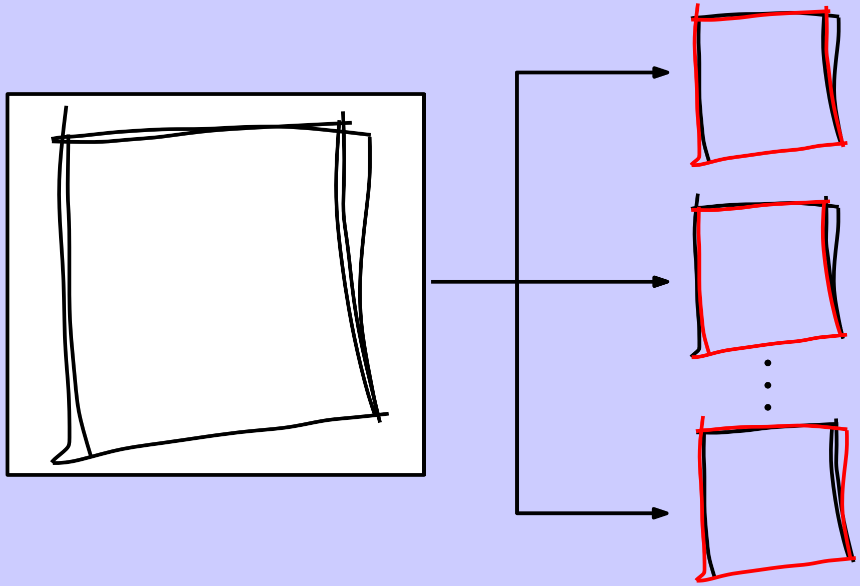
Research Problem



- There is no grouping algorithm that successfully groups paper-based scribble strokes.
- Existing scribble interpretation algorithms require that the scribble is drawn using 'digital ink'
  - simplifies the interpretation problem
  - digital tablets are not the designer's preferred drawing medium

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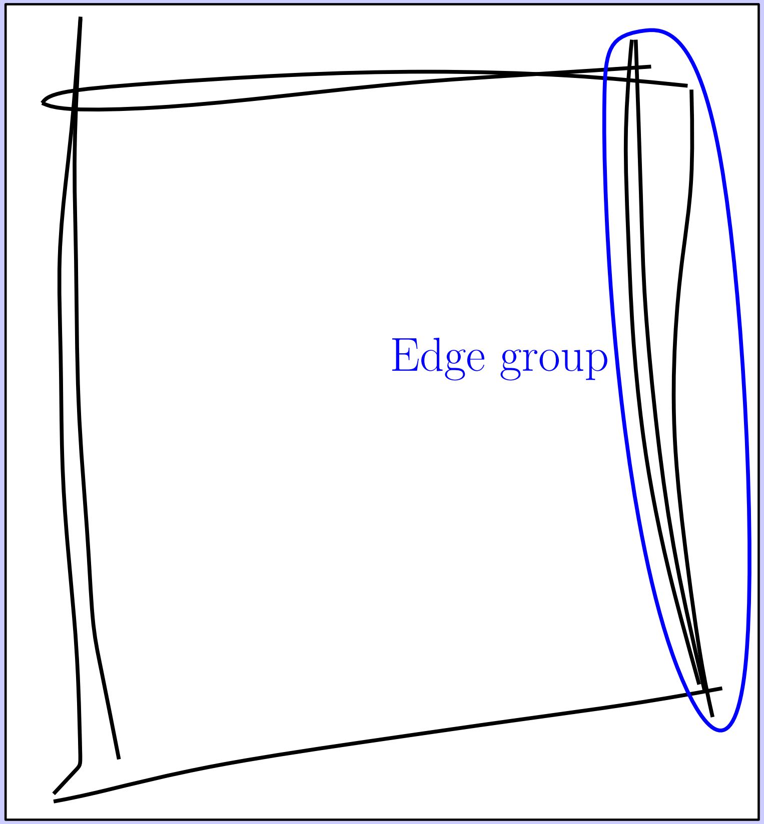
The Scribble Characteristics

- **Edge-group:** collection of strokes forming an object edge
- **Intra-group gap:** gap separating strokes within an edge group
- **Inter-group gap:** gap separating different edge groups



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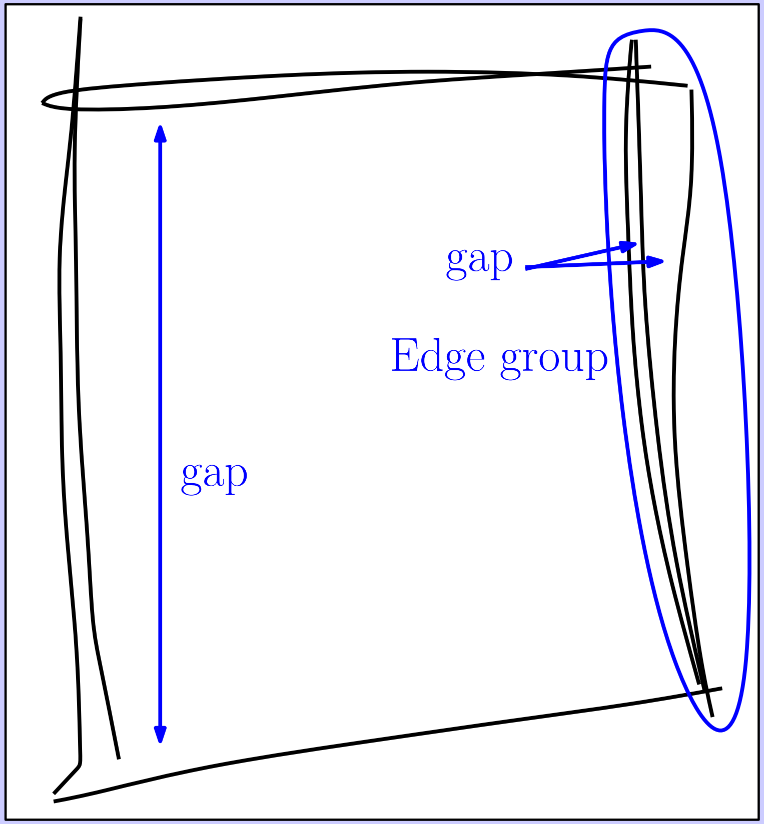

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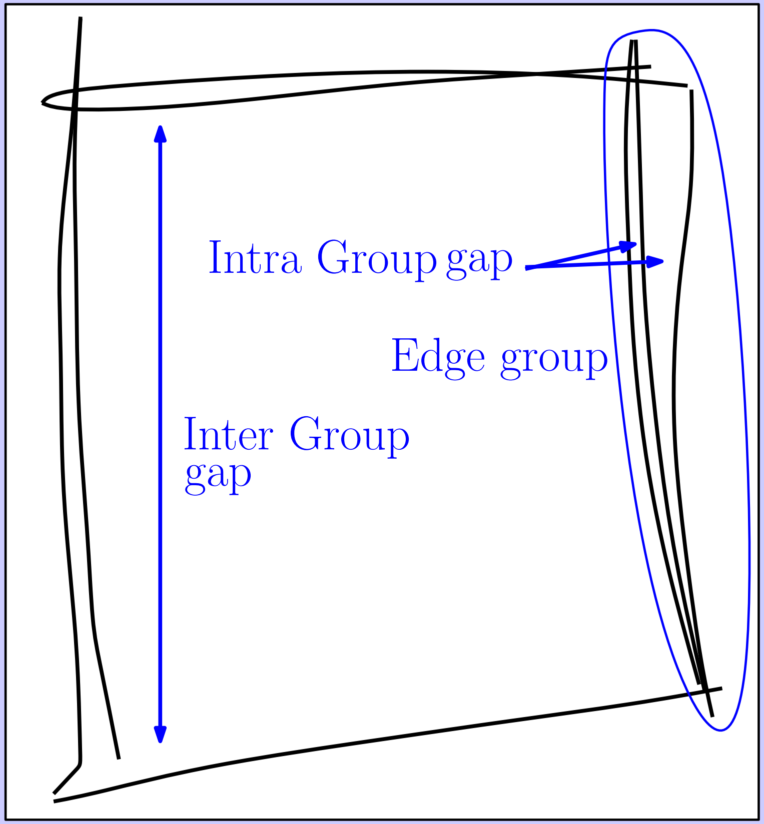

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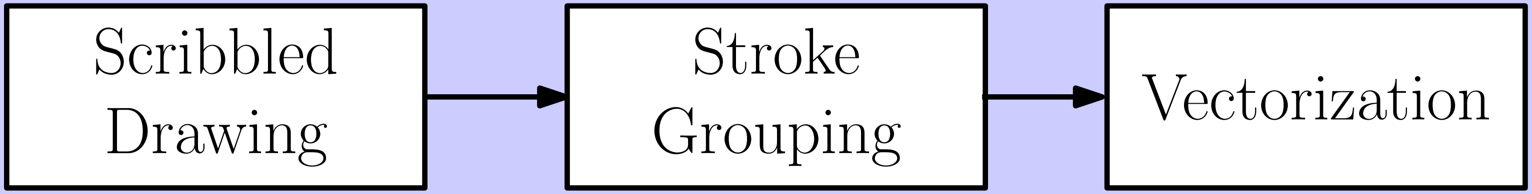
Our Scribble Simplification Algorithm

- Individual scribbled strokes gain significance only when interpreted as part of a stroke group.
- Over-strokes are grouped into line strokes before performing vectorization.



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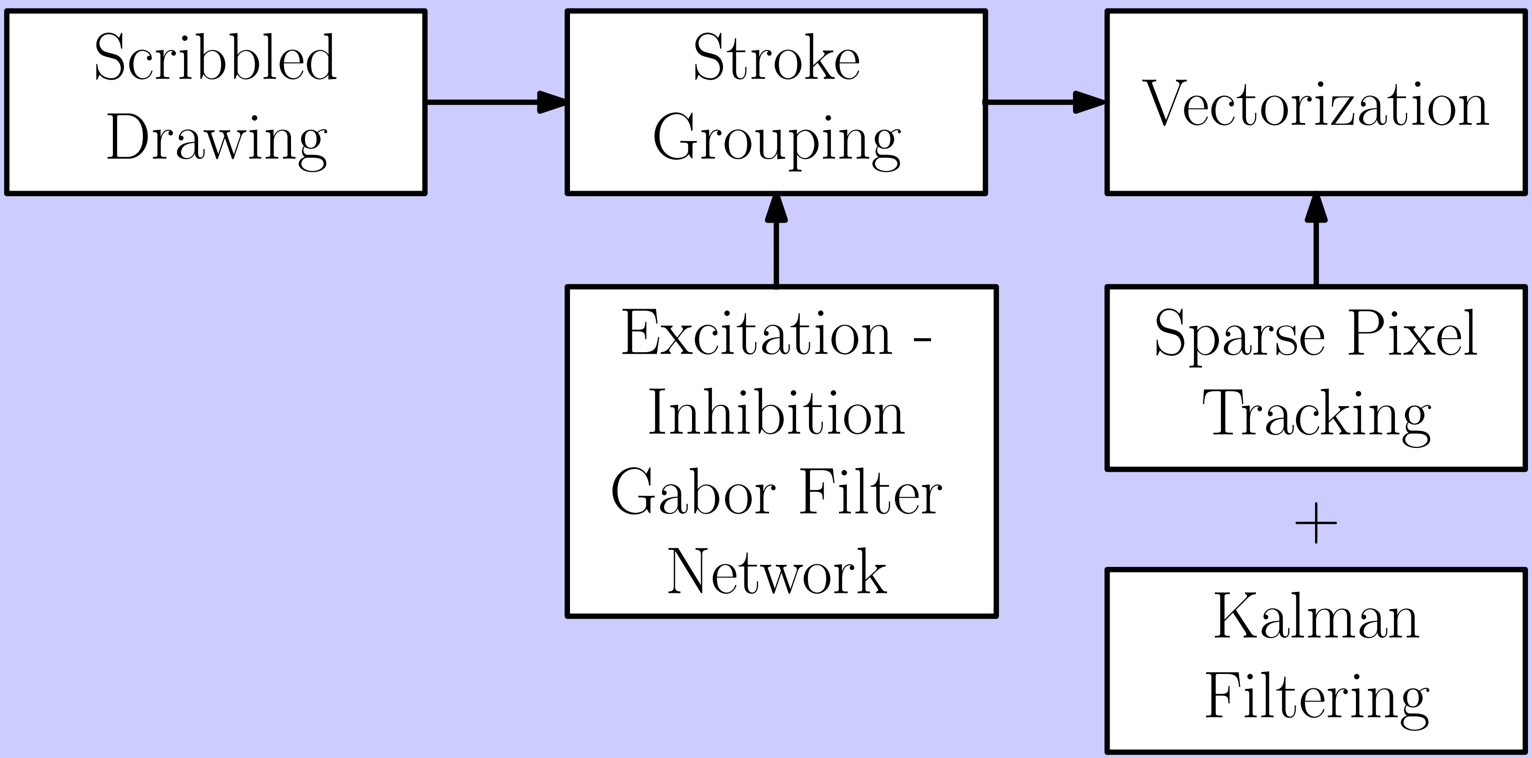

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Overview of the Gabor Filter

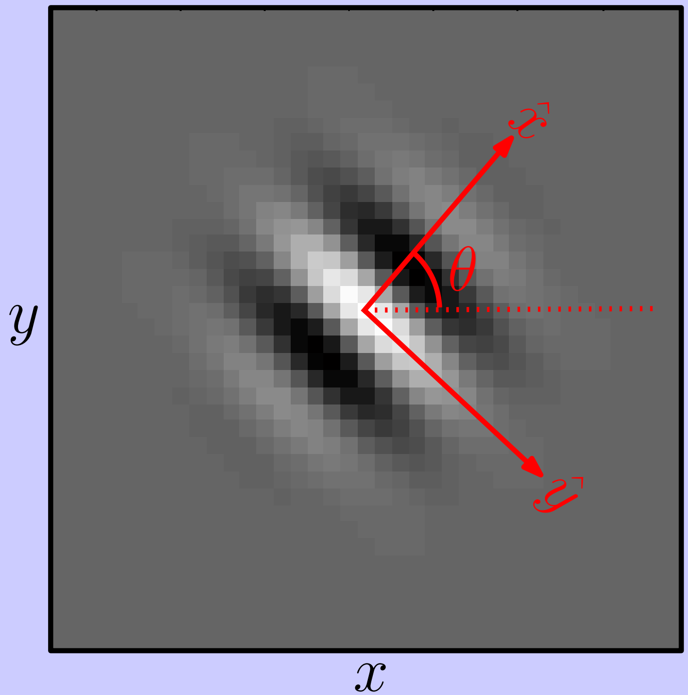
- The Gabor filter is defined by:

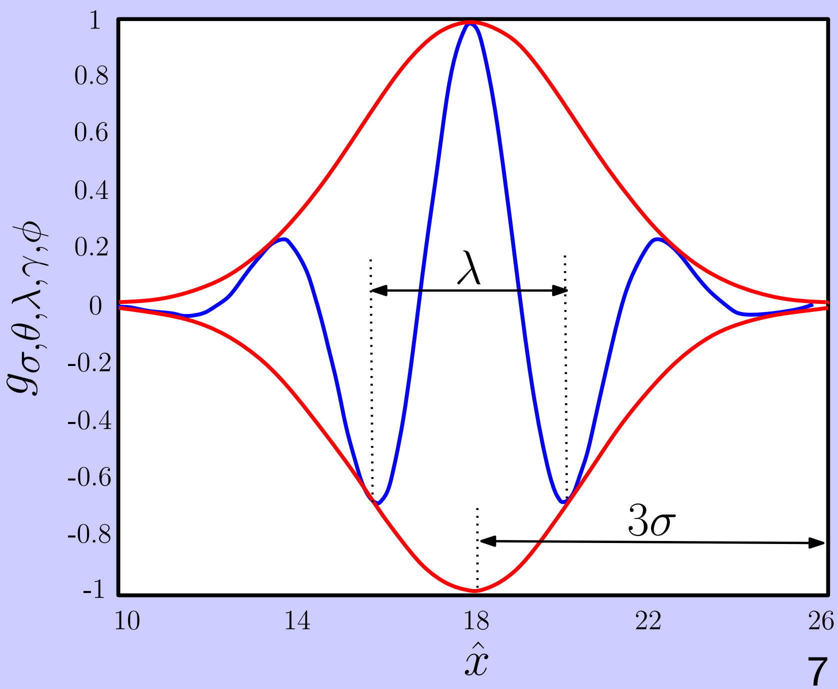
$$g_{\sigma,\theta,\lambda,\gamma,\phi}(x,y) = \exp\left\{-\frac{1}{2\sigma^2}\left(\hat{x}^2+\gamma^2\hat{y}^2\right)\right\}\cos\left(\frac{2\pi}{\lambda}\hat{x}+\phi\right) \quad (1)$$

$$\hat{x} = x\cos\theta + y\sin\theta \quad (2)$$

$$\hat{y} = y\cos\theta - x\sin\theta \quad (3)$$

- The filter has a bandwidth $b = \log_2\left\{\frac{\frac{\sigma}{\lambda}+\frac{1}{\pi}\sqrt{\frac{\ln 2}{2}}}{\frac{\sigma}{\lambda}-\frac{1}{\pi}\sqrt{\frac{\ln 2}{2}}}\right\}$





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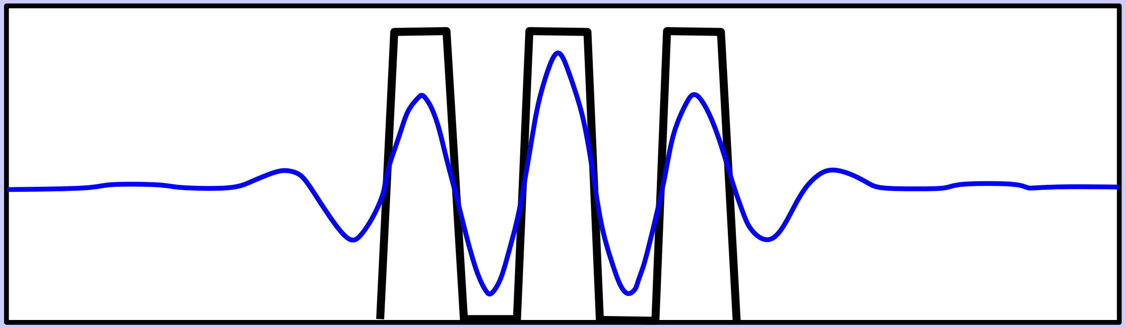
The Phase ϕ

- $\phi = 0$: filter responds to the stroke centers - ‘centre-on’ filter
- $\phi = \frac{\pi}{2}$: filter responds to the stroke edges
- $\phi = \pi$: filter responds to the intra-line gaps - ‘centre-off’ filter



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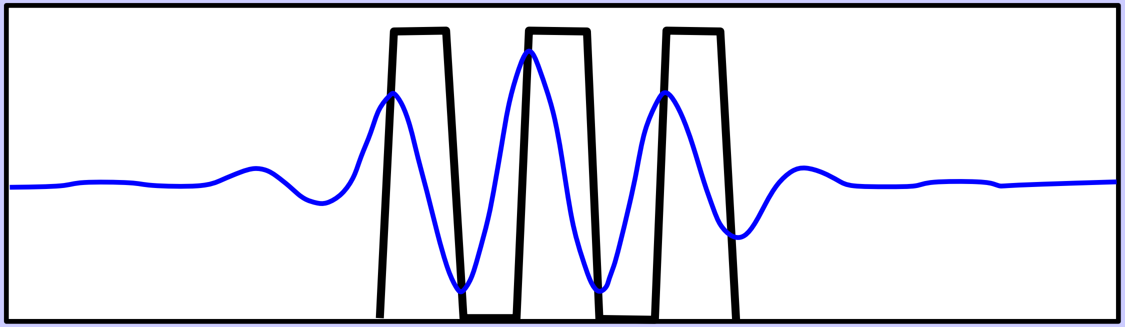

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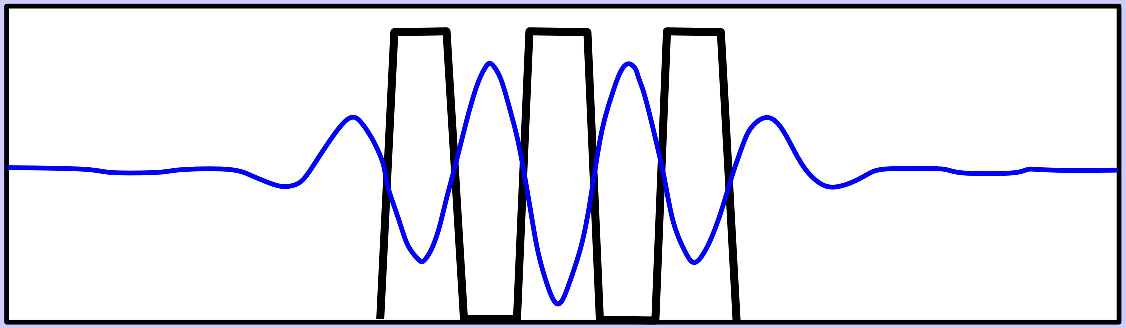

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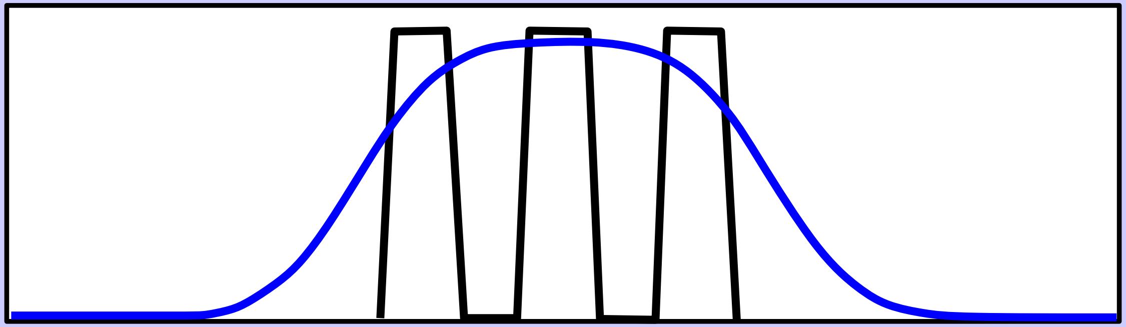

- The energy response $G_{\theta,\lambda,\gamma}$ of a quadrature filter pair is used to give a continuous response for the stroke group

$$G_{\theta,\lambda,\gamma}(x,y) = \sqrt{\hat{g}^2_{\theta,\lambda,\gamma,\phi=0}(x,y) + \hat{g}^2_{\theta,\lambda,\gamma,\phi=\frac{\pi}{2}}(x,y)} \tag{4}$$

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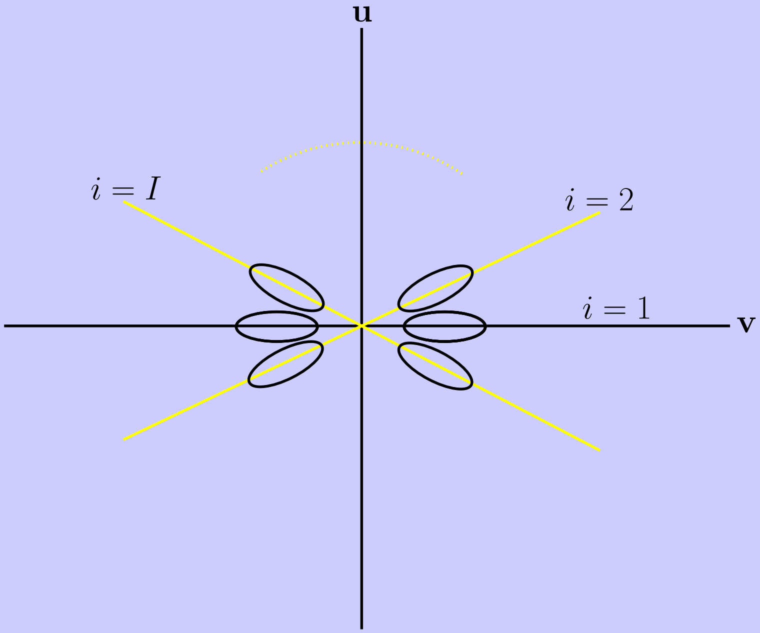
The frequency $\frac{1}{\lambda}$ and Orientation θ



- The Gabor filter bank has I orientation bands and J frequency bands which are selected such that the filter bank has complete coverage of the spatial-frequency domain
- The Gabor filter bank implemented has 10 equally spaced orientation levels and 7 frequency levels in the range $\left[\frac{1}{30}, \frac{1}{2}\right]$ cycles per pixel for a image resolution of 72dpi

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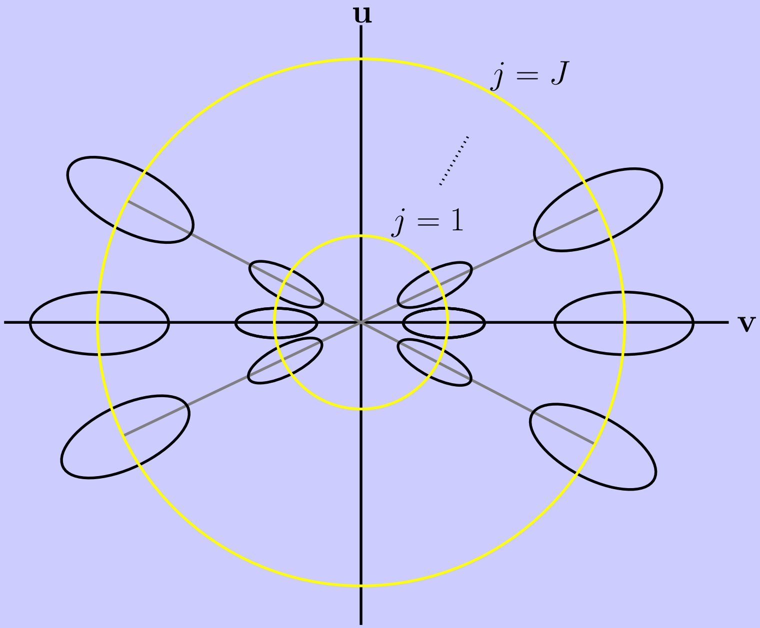

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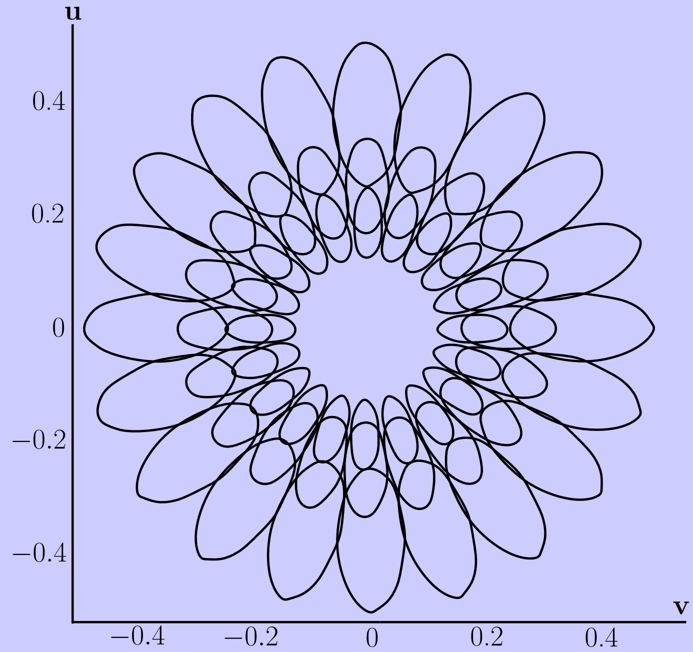

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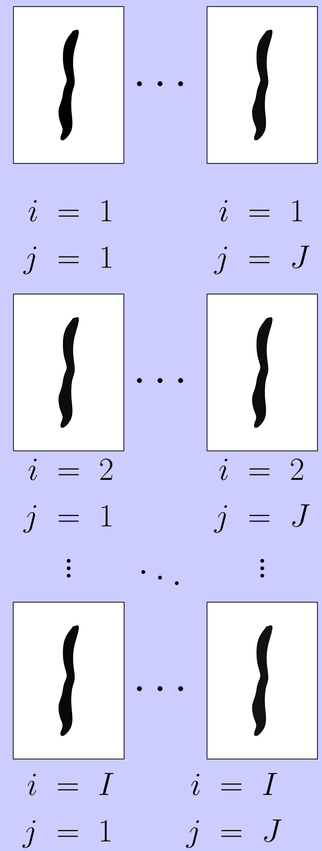
Stroke Grouping using the Gabor Filter



Response Images

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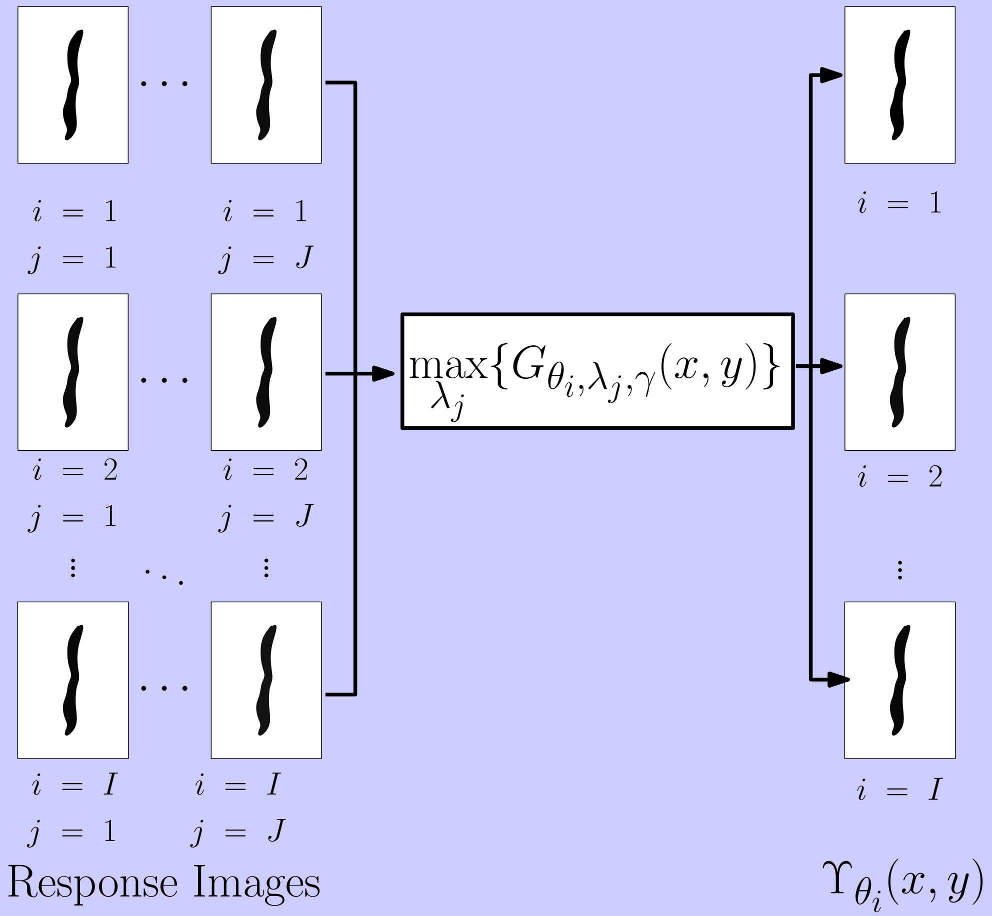

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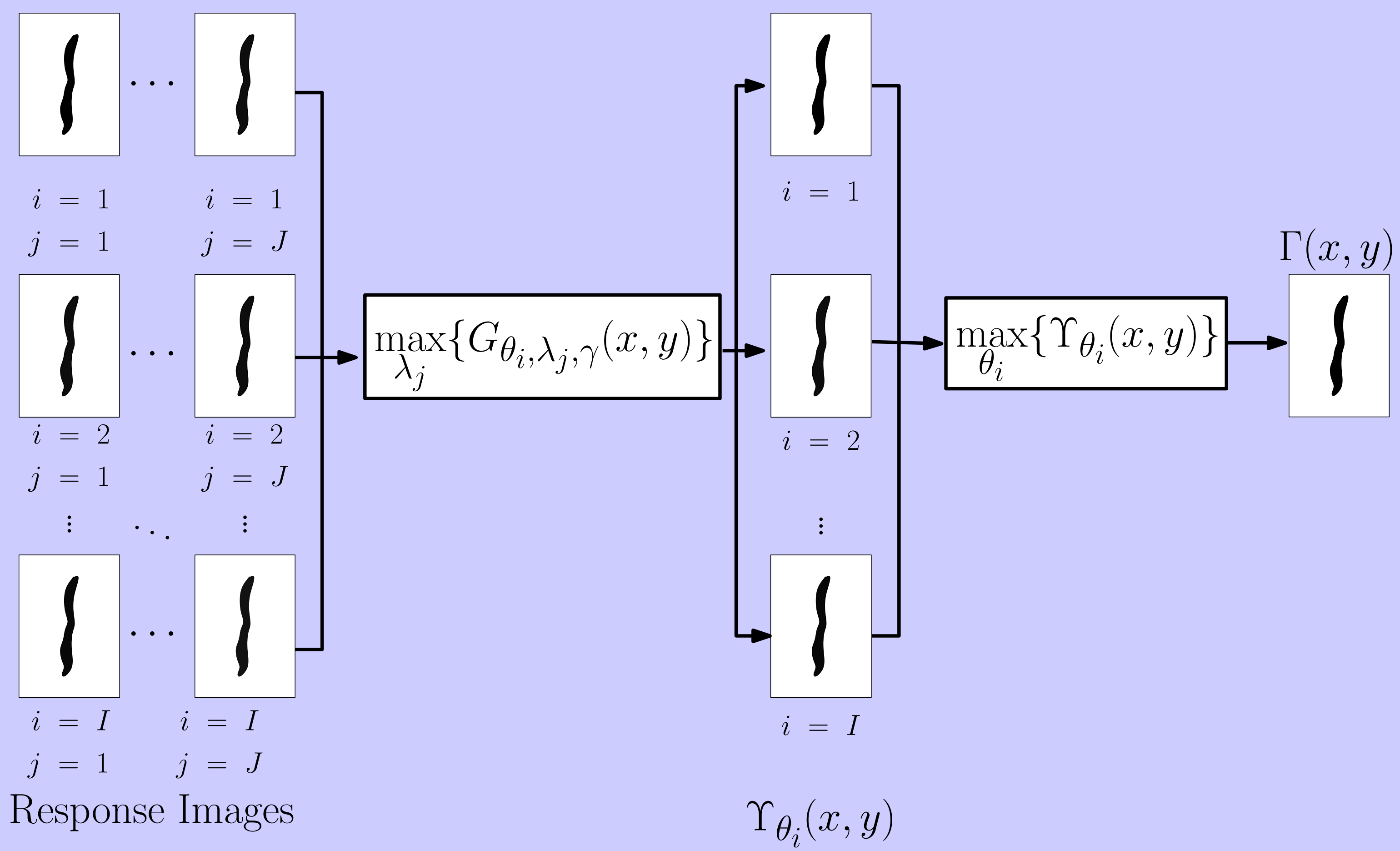

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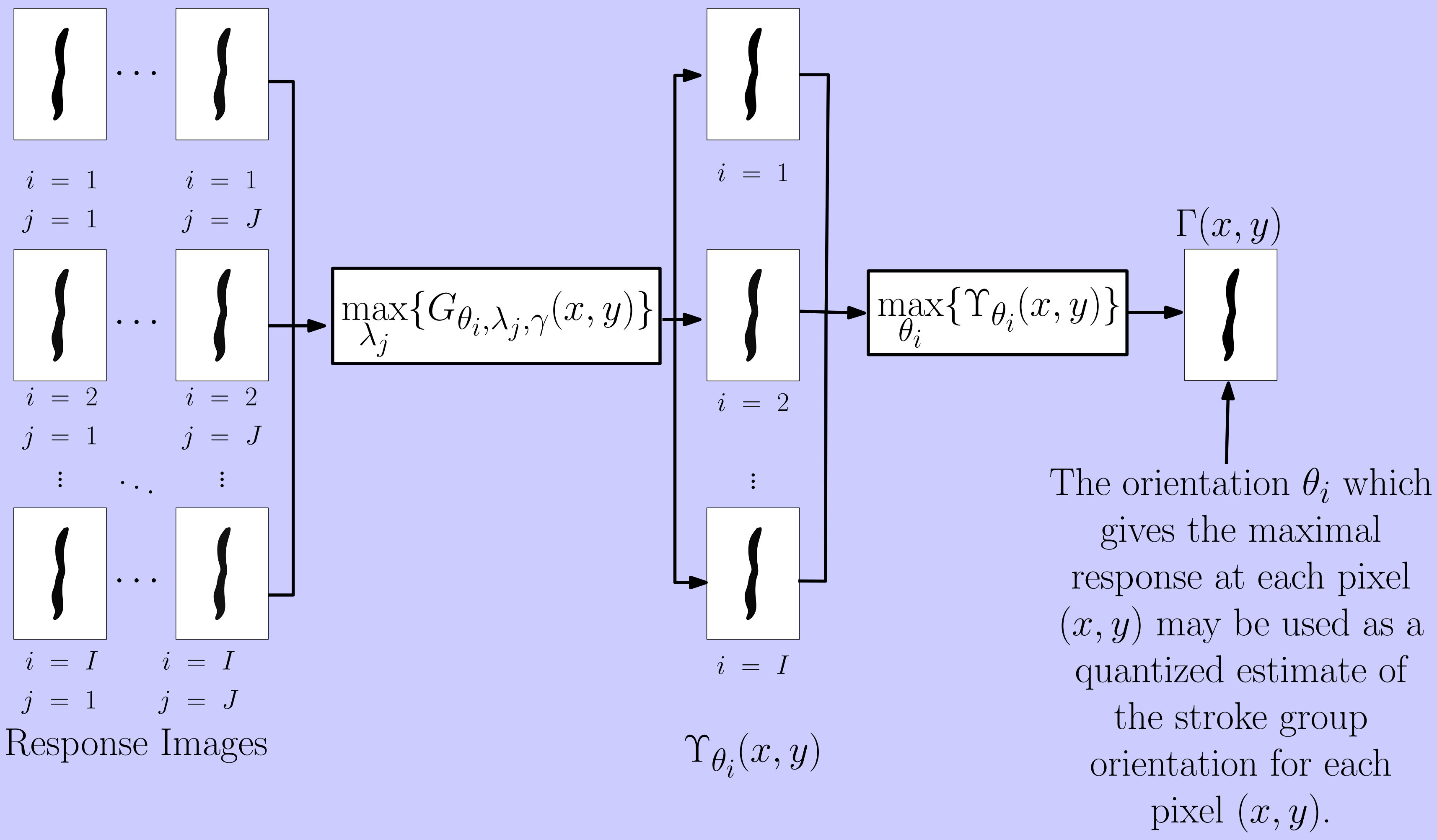

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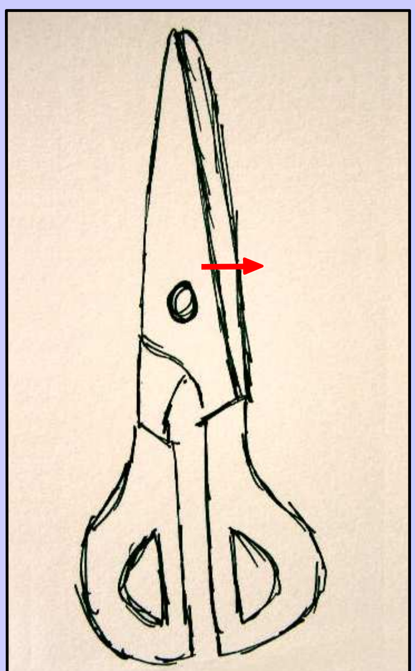
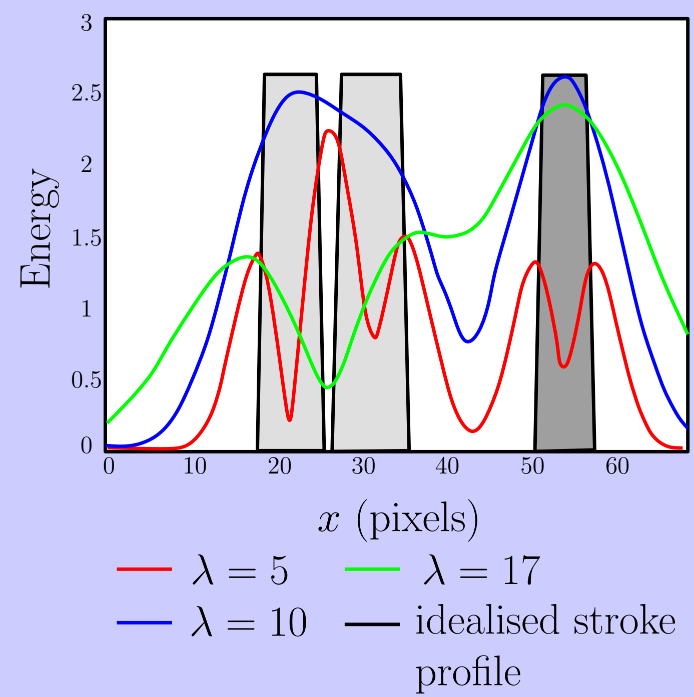
Limitations of the Grouping Scheme

- When two or more edge groups that have a fine pattern are close to each other, the coarser filters in the filter bank respond to the edge groups as a single coarse pattern.
- This will not allow the quadrature grouping scheme to make sufficient distinction between edge-groups.





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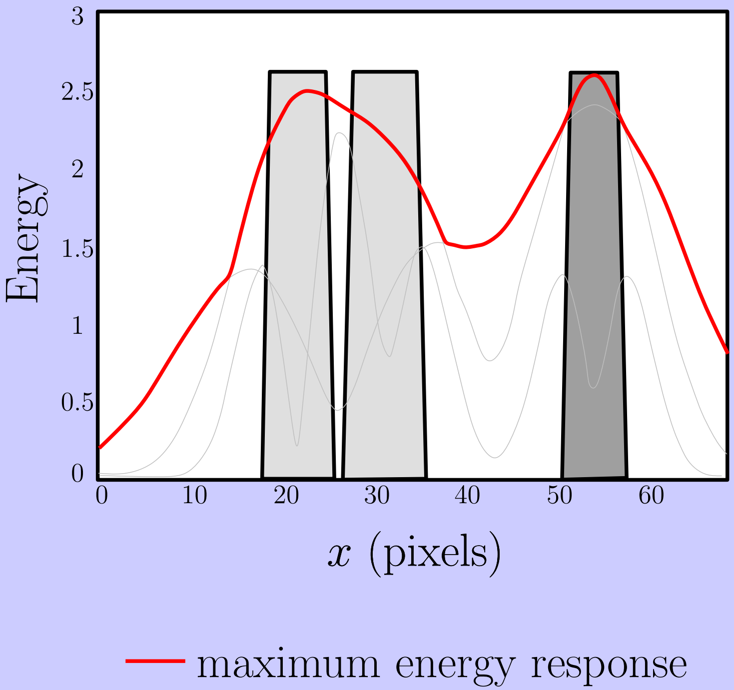

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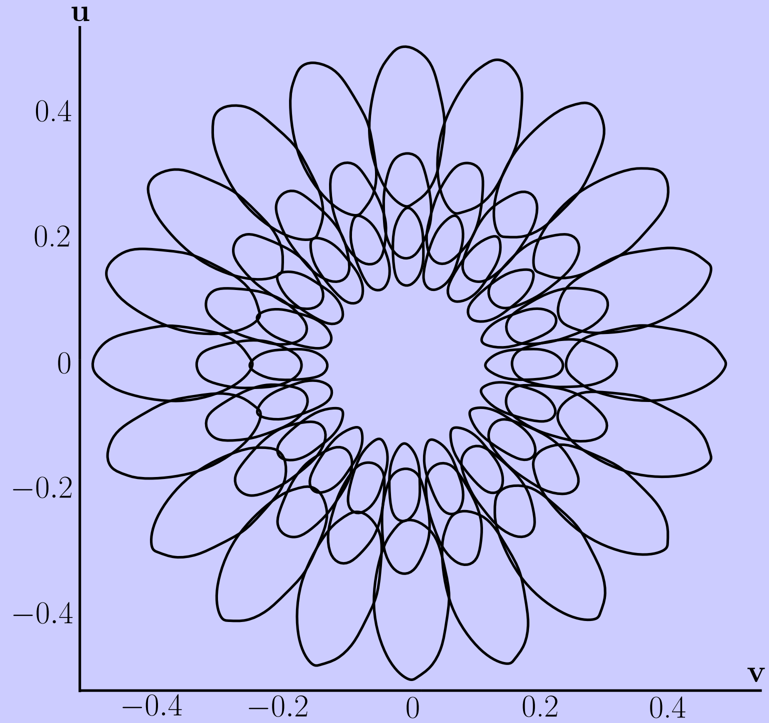
The Inhibiting Filter



- The visual pattern formed by two edge groups and the inter-group gap has a lower frequency than the pattern formed by the strokes within the edge groups.
- To inhibit the inter-group gaps the filter must give a positive response at the gaps, hence it requires a phase of $\phi = \pi$

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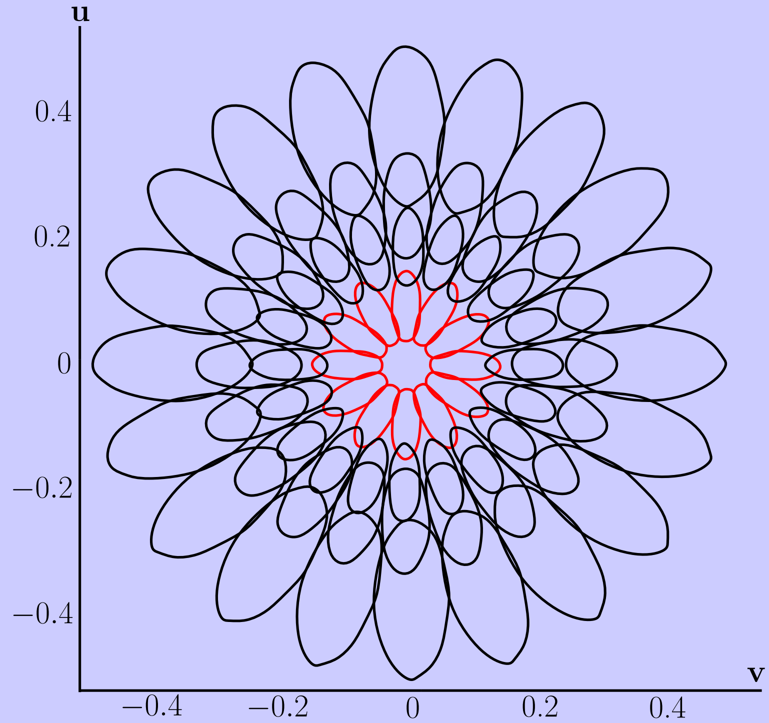

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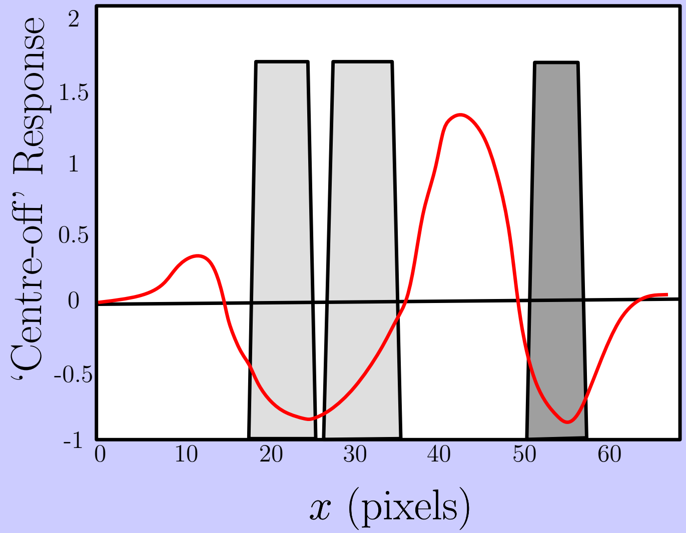
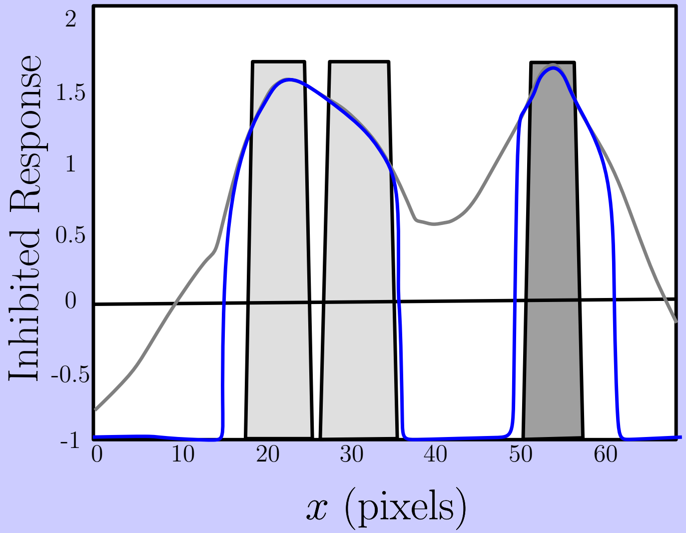
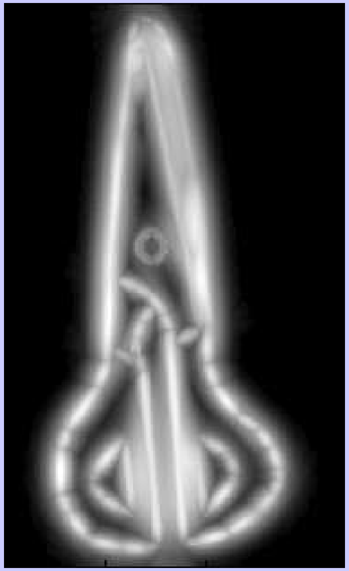
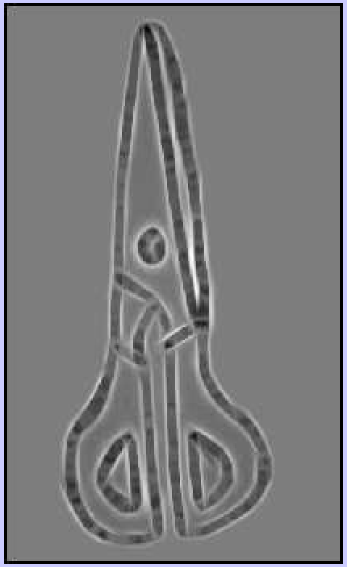
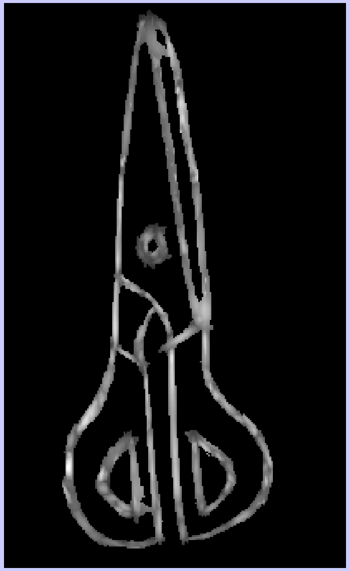





Energy Response


'Centre-off' Response


Inhibited Energy Response

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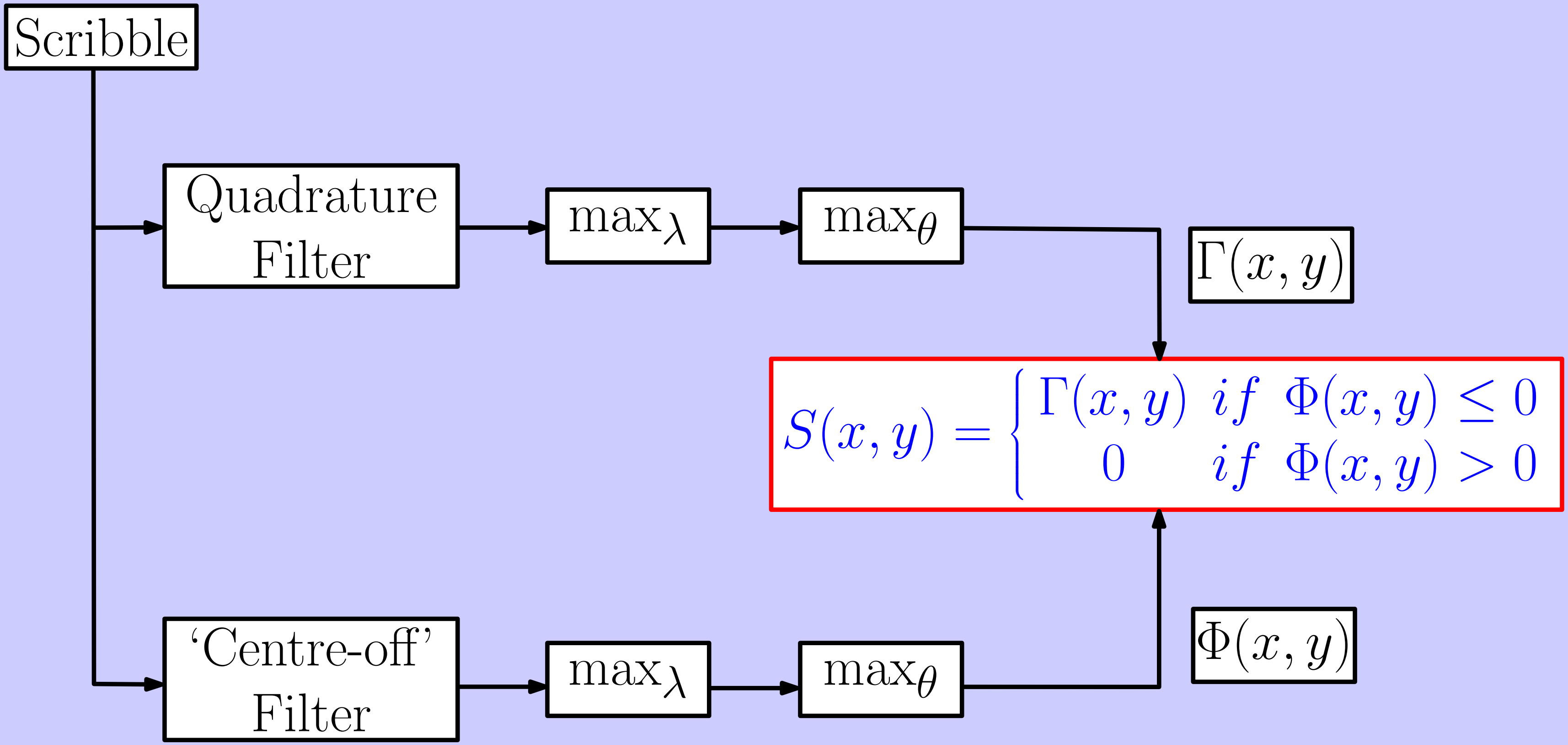
The Stroke Grouping Algorithm



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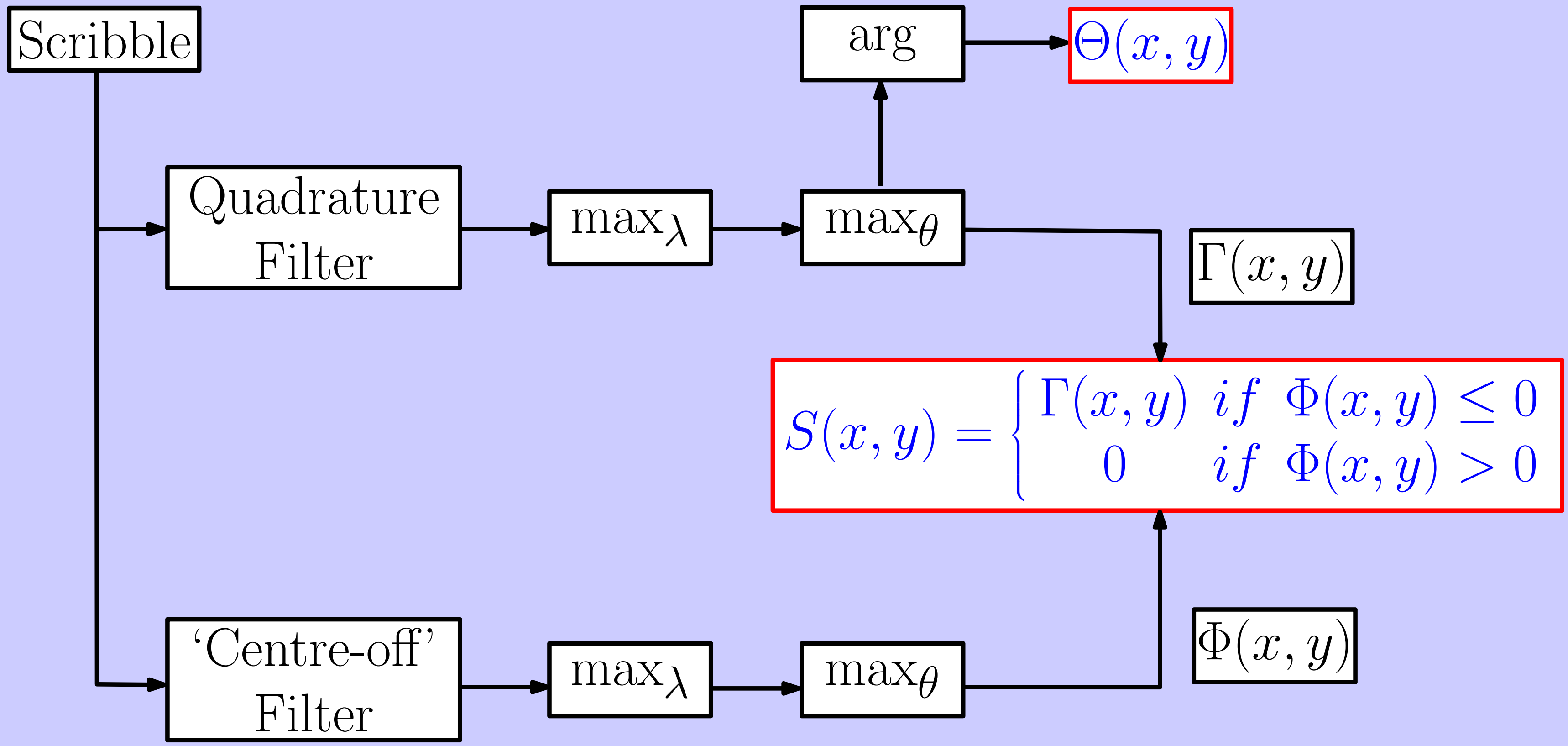

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New vs 'Off-the-Shelf' Vectorization

- The Gabor-grouping algorithm simplifies the scribbled drawing creating a new raster image in which
  - edge groups are represented by single lines
  - the edge groups have a line width greater than unity
- Therefore the simplified scribble must be processed with a vectorization algorithm similar to those proposed for neat paper-based drawings
- The Gabor-grouping algorithm augments the scribbled drawing with quantized estimates of the stroke orientations
- These orientations are used to guide a line tracking algorithm and hence replace the line location step used in these vectorization algorithms

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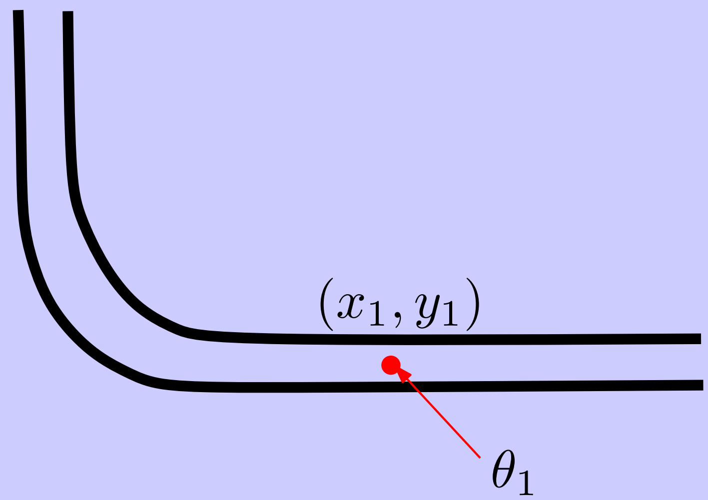
The Line Tracking Algorithm



- Using the orientation θ_k at a tracking instant k the position of the track point for the next tracking instant $k+1$ may be predicted using

$$x_{k+1} = x_k + D\cos(\theta_k) \tag{5}$$

$$y_{k+1} = y_k + D\sin(\theta_k) \tag{6}$$

  - D is the tracking step length

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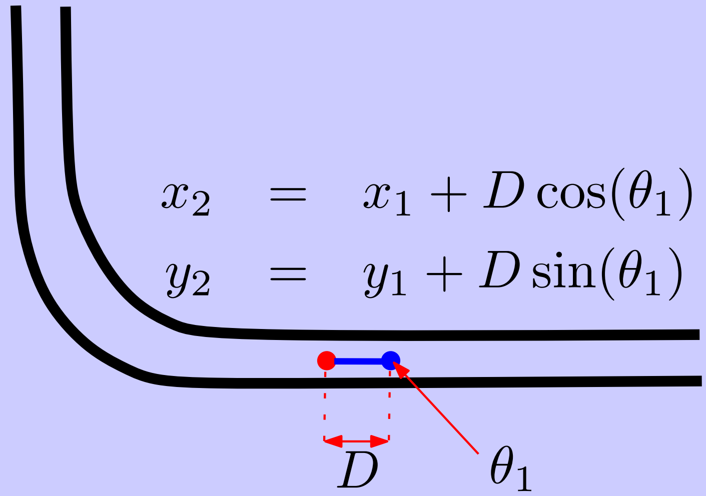

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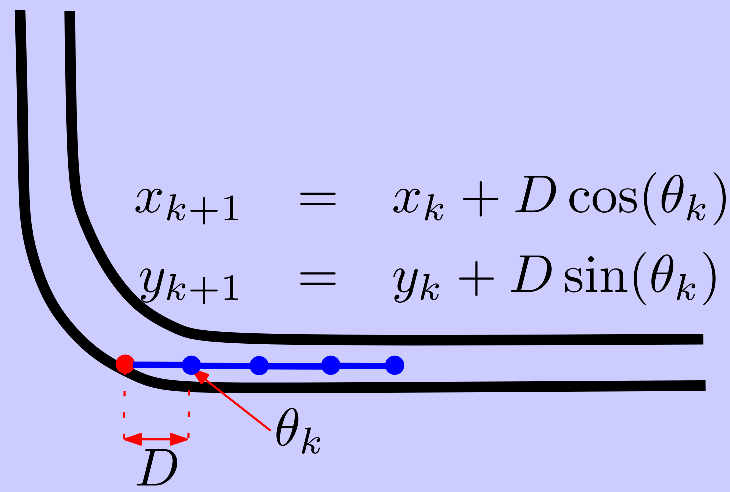

$$
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- This piece-wise linear tracking may be offset from the actual medial points

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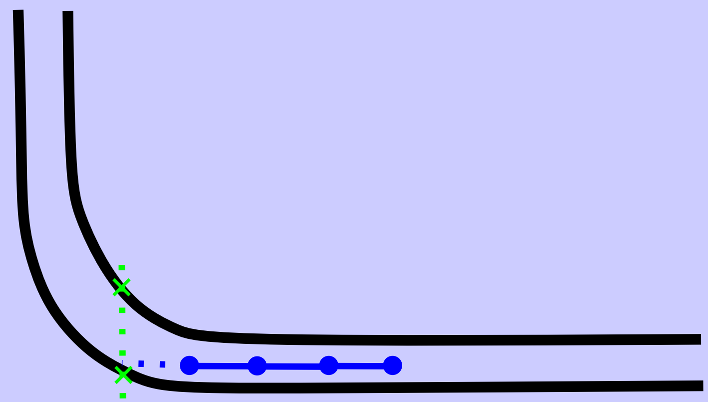

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- To compensate for this offset, an oriented scan line is taken at each new point to determine the contour boundaries of the line segment

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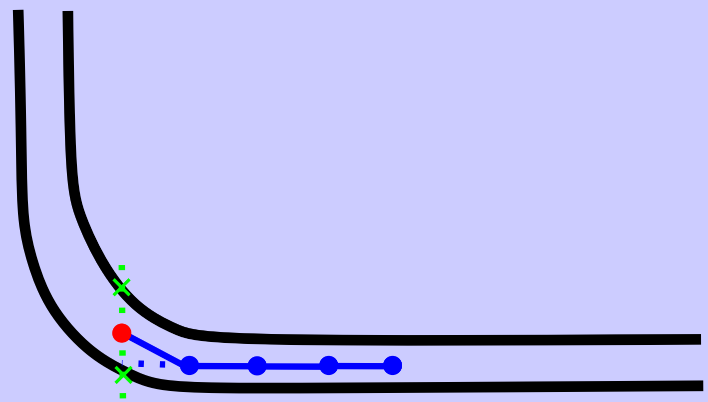

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- To compensate for this offset, an oriented scan line is taken at each new point to determine the contour boundaries of the line segment
- The midpoint of the scan line is used as a better estimate of the medial point

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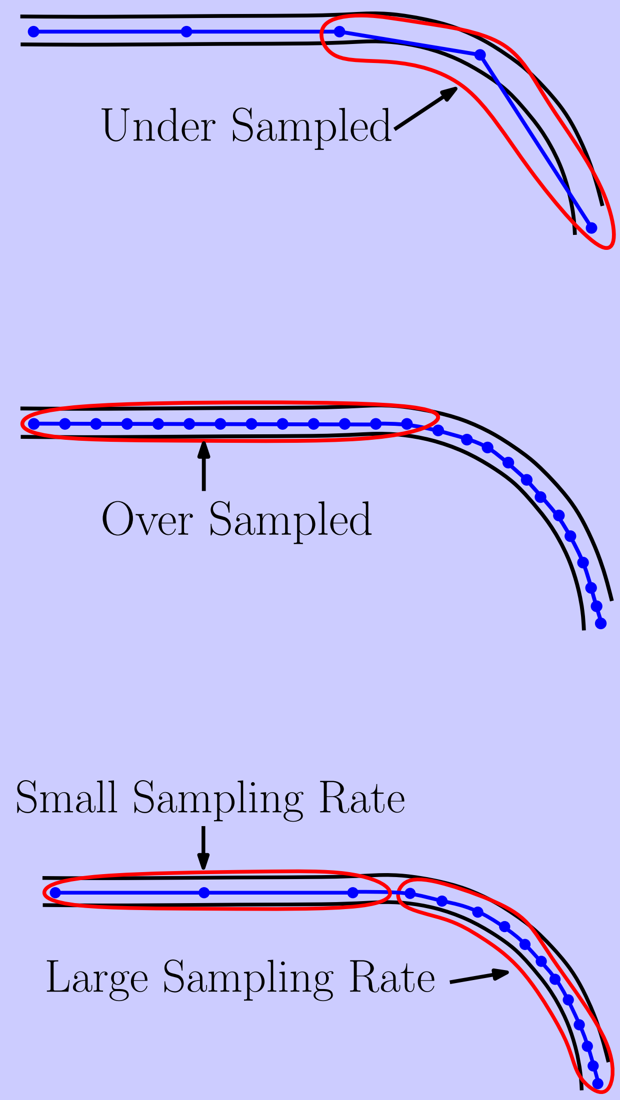
The Tracking Step Size D

- The tracking algorithm should not under sample or over sample the drawing
- Since the drawings may contain a mixture of straight line segments and curved segments an adaptive tracking step is required.
- A straight line segments are detected when the tacking point remains on the stroke foreground and the orientation remains constant
- Curved segments are detected when the orientation of subsequent tracking points changes



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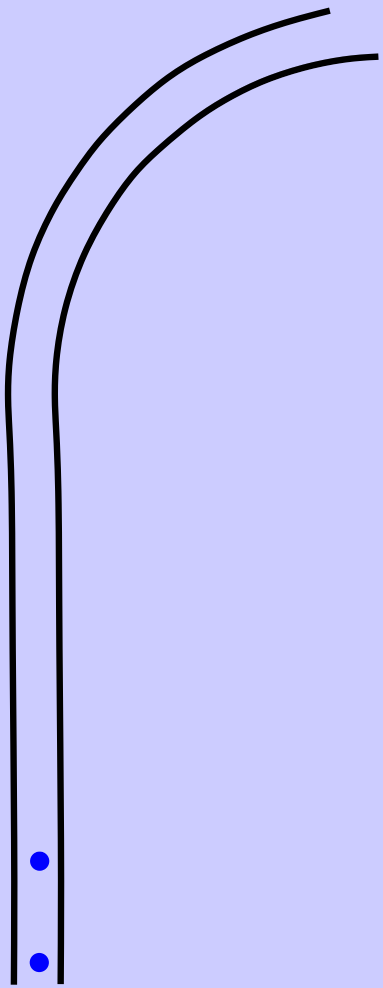

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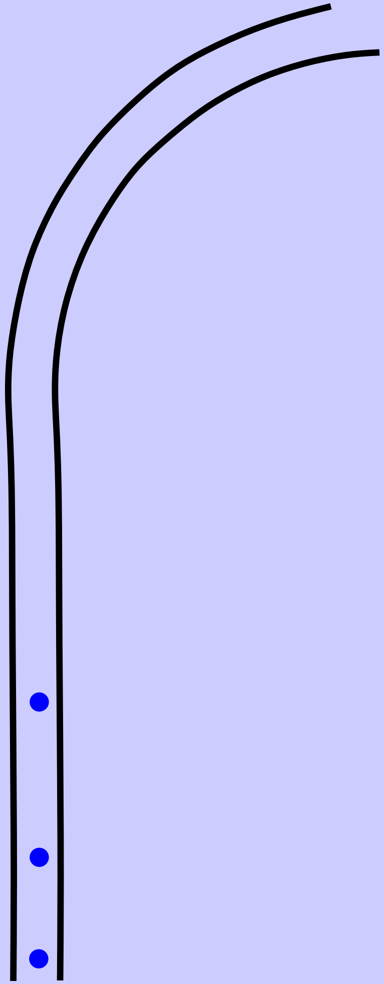

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The Tracking Step Size D

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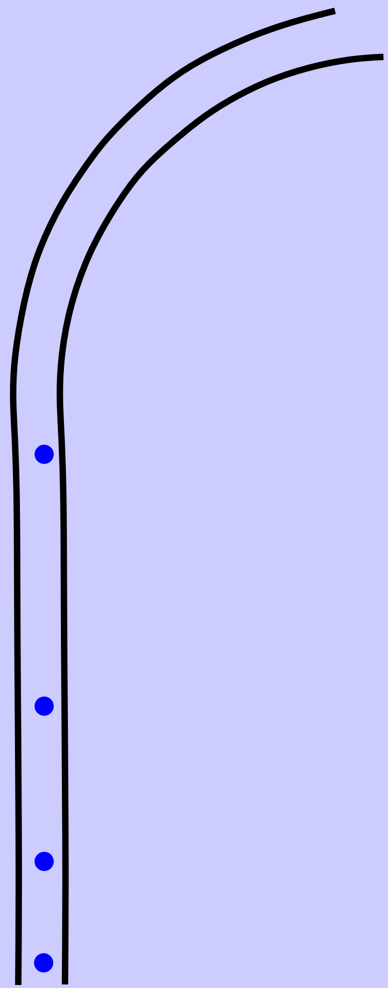

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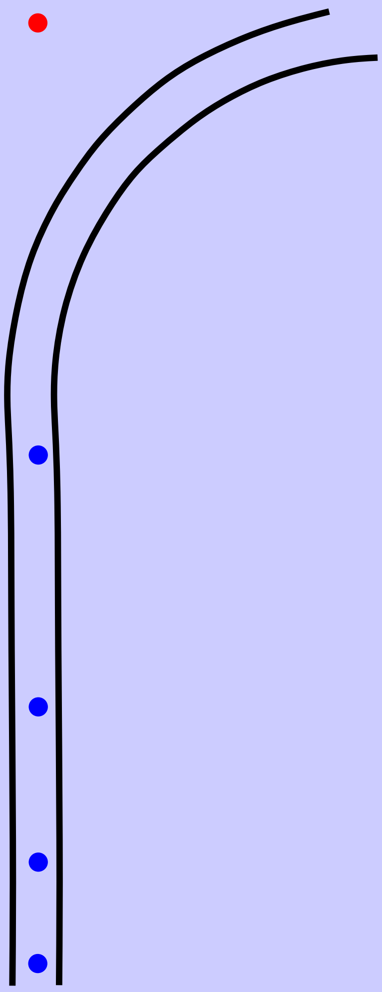

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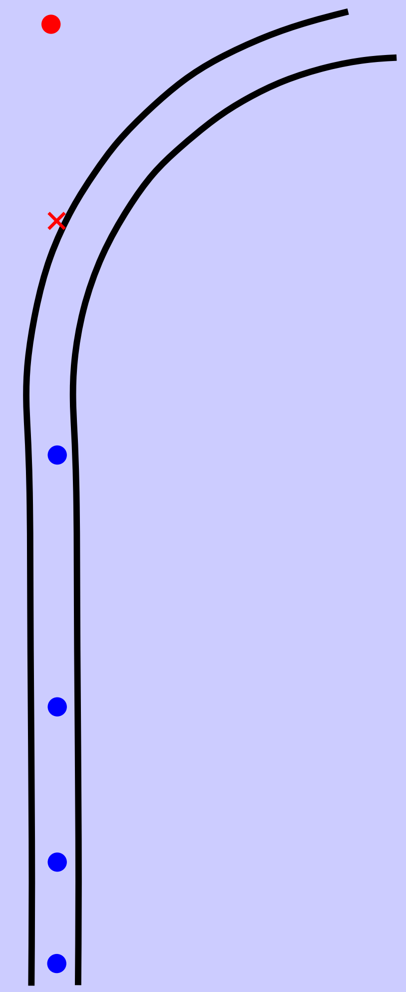

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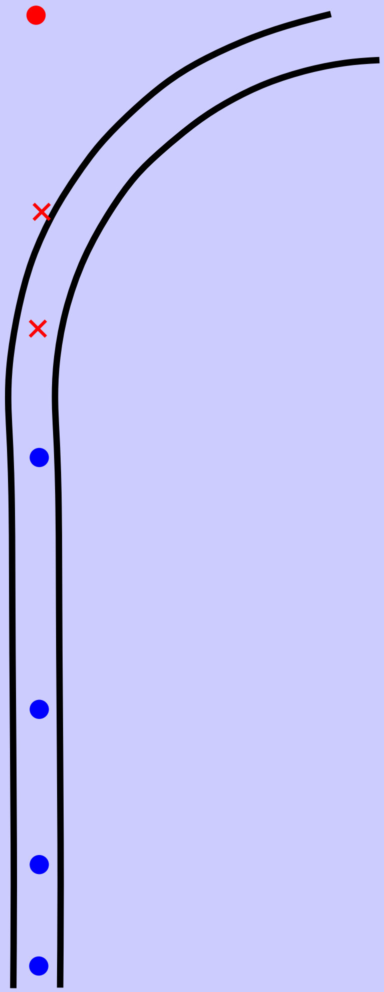

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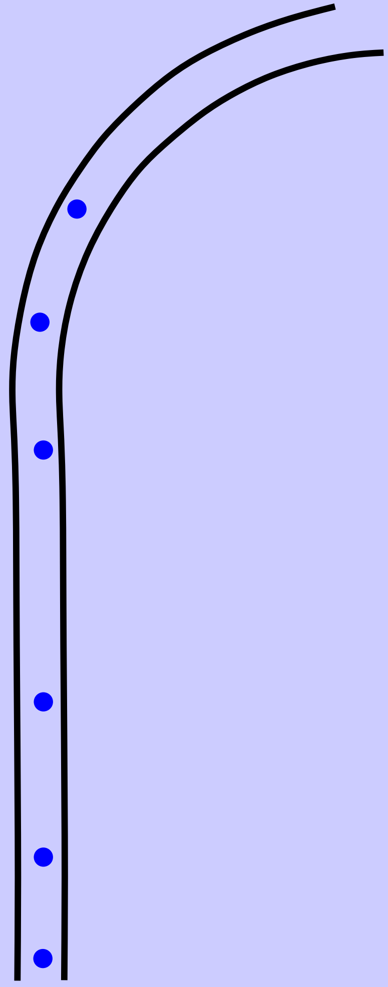

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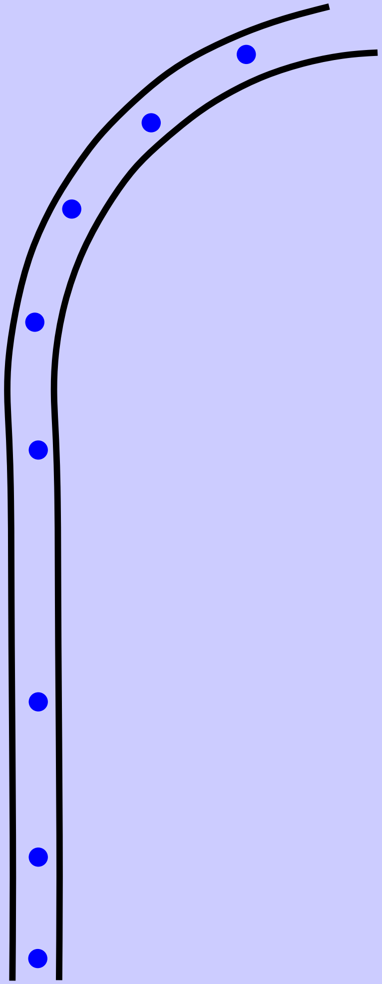

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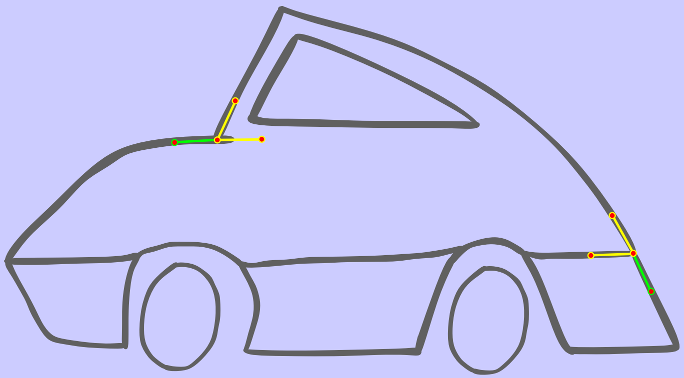
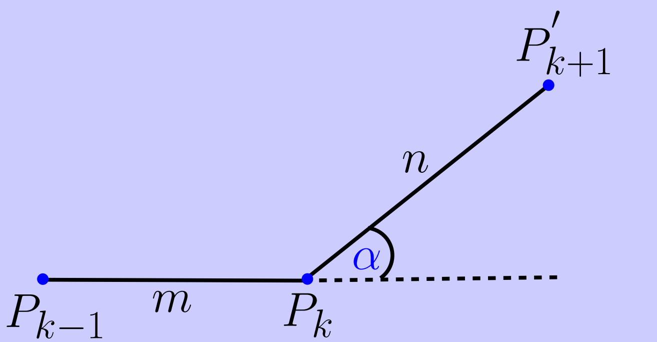
Salient Point Tracking at Junctions

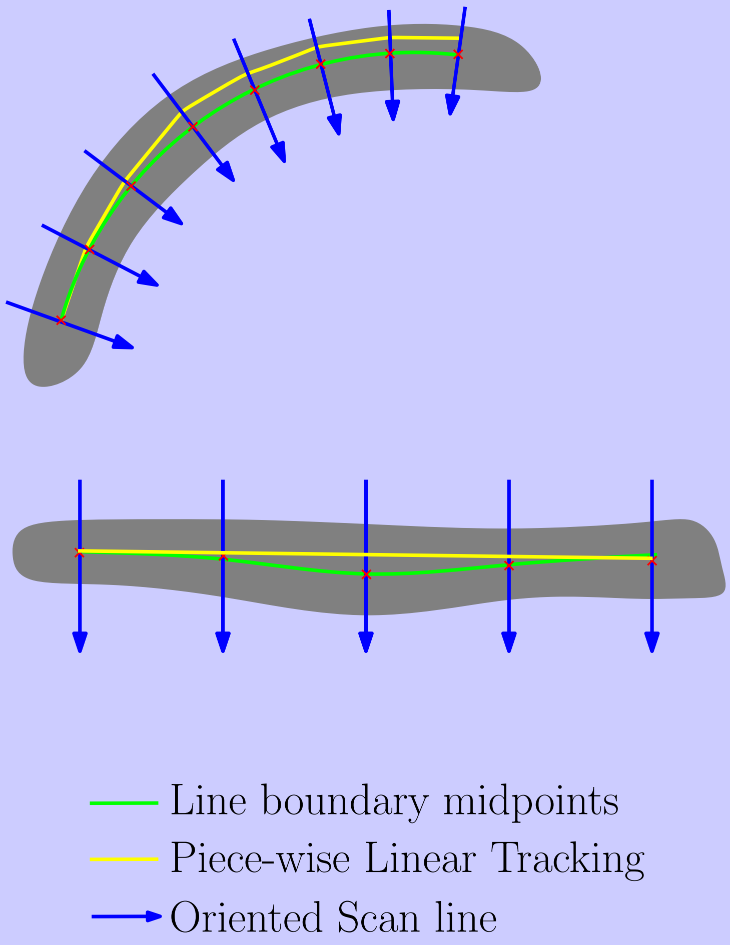




$$Saliency = S_{P'_{k+1}} \exp(-\frac{2\alpha \tan(\frac{\alpha}{2})}{D})$$

- At junctions, the tracking algorithm should select the path that gives maximum saliency
- The local saliency is measured by propagating the line path to a preliminary track point P'_{k+1}
- The change in direction α and the Gabor response $S_{P'_{k+1}}$ are used to define the saliency
- The direction which results in maximum local saliency is selected as the tracking direction

Introducing the Kalman Filter



- The tracking algorithm has two medial point estimates
- The piecewise linear tracking is not suitable for high curvatures
- The contour boundaries are not suitable for lines with contour boundary noise
- A mechanism that obtains a better estimate from these two estimates is required
- The Kalman filter is introduced to the line tracking algorithm to provide this mechanism

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The Kalman Filter

Process Model

$$\mathbf{x}_k = A\mathbf{x}_{k-1} + B\mathbf{u} + \mathbf{w}_{k-1}$$

- $\mathbf{x}$ is the system states
- $\mathbf{u}$ is an optional input
- $\mathbf{w}$ is the process noise
- A relates the $\mathbf{x}_{k-1}$ to $\mathbf{x}_k$
- B relates the input $\mathbf{u}$ to the state $\mathbf{x}$

Measurement Model

$$\mathbf{z}_k = H\mathbf{x}_k + \mathbf{v}_k$$

- $\mathbf{z}$ are the system's measurements
- H relates $\mathbf{x}$ to $\mathbf{z}$
- $\mathbf{v}$ is the measurement noise

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The Kalman Filter

Process Model

$$\mathbf{x}_k = A\mathbf{x}_{k-1} + B\mathbf{u} + \mathbf{w}_{k-1}$$

$$x_k = x_{k-1} + D\cos(\theta_{k-1})$$
$$y_k = y_{k-1} + D\sin(\theta_{k-1})$$

$$\begin{pmatrix} x \\ y \end{pmatrix}_k = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} x \\ y \end{pmatrix}_{k-1} + \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} D\cos\theta \\ D\sin\theta \end{pmatrix}$$

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Measurement Model

$$\mathbf{z}_k = H\mathbf{x}_k + \mathbf{v}_k$$

$$z_{x_k} = x_k$$
$$z_{y_k} = y_k$$

$$\begin{pmatrix} z_x \\ z_y \end{pmatrix}_k = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}_k$$

- $\mathbf{z}$ are the system's measurements
- H relates $\mathbf{x}$ to $\mathbf{z}$
- $\mathbf{v}$ is the measurement noise

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The Kalman Filter

Time Update Equations		*Measurement Update Equations*
$\mathbf{x}_{k\|k-1} = A\mathbf{x}_{k-1\|k-1} + B\mathbf{u}_{k-1\|k-1}$ $P_{k\|k-1} = AP_{k-1\|k-1}A^T + Q$	→ / ←	$K_k = P_{k\|k-1}H^T(HP_{k\|k-1}H^T + R)^{-1}$ $\mathbf{x}_{k\|k} = \mathbf{x}_{k\|k-1} + K_k(\mathbf{z}_k - H\mathbf{x}_{k\|k-1})$ $P_{k\|k} = (I - K_kH)P_{k\|k-1}$

- Q is the covariance of the process noise **w**
- R is the covariance of measurement noise **v**
- P is the error covariance
- K is a gain matrix which minimizes the *a posteriori* error covariance.
- K weights the difference between the predicted measurements and the actual measurements, hence updating the system states

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The Smoothed Kalman Filter

- Since the Kalman filter acts upon the system in a forward manner, the estimation of the system states using the Kalman filter is causal.

- To remove this causality, the forward estimation is augmented to include a Kalman smoothing step

$$
\begin{aligned}
J_{k|N} &= P_{k|k} A^T (P^{-1}_{k+1|k}) \\
\mathbf{x}_{k|N} &= \mathbf{x}_{k|k} + J_k(\mathbf{x}_{k+1|N} - A\mathbf{x}_{k|k}) \\
P_{k|N} &= P_{k|k} + J_k(P_{k+1|N} - P_{k+1|k}) J_k^{-1}
\end{aligned}
$$

  - N is the total number of measurements
  - The smoothed states $\mathbf{x}$ are estimated using backward recursions $k = N, N-1, \cdots, 1$ conditioned on all the measurement data $\mathbf{z}_{1:N}$

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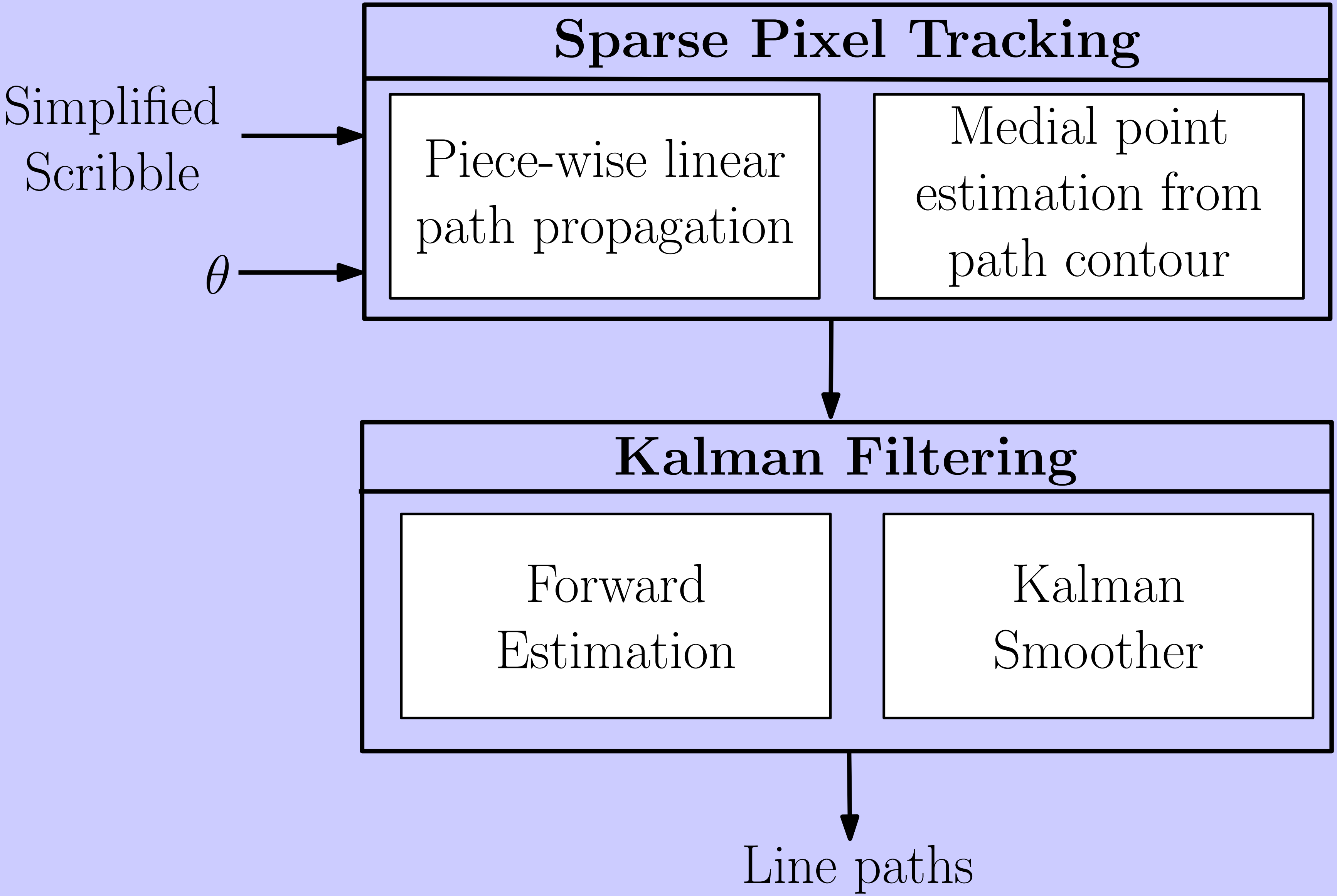
The Line Location Algorithm



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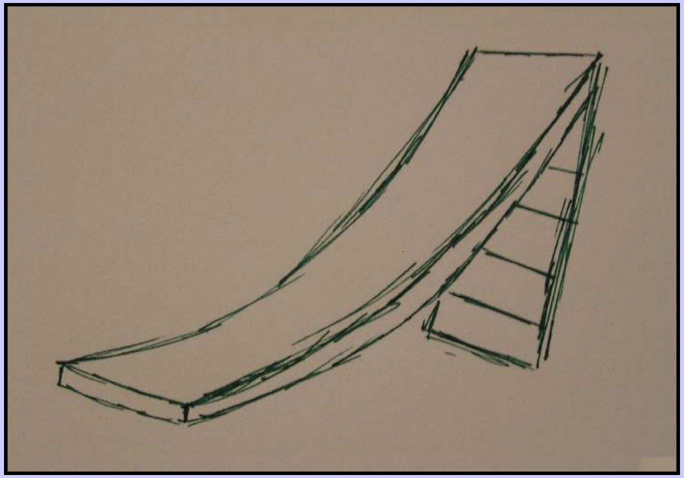
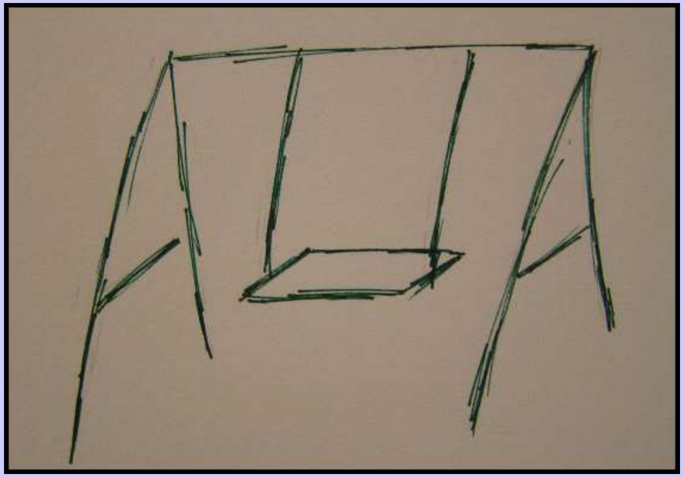
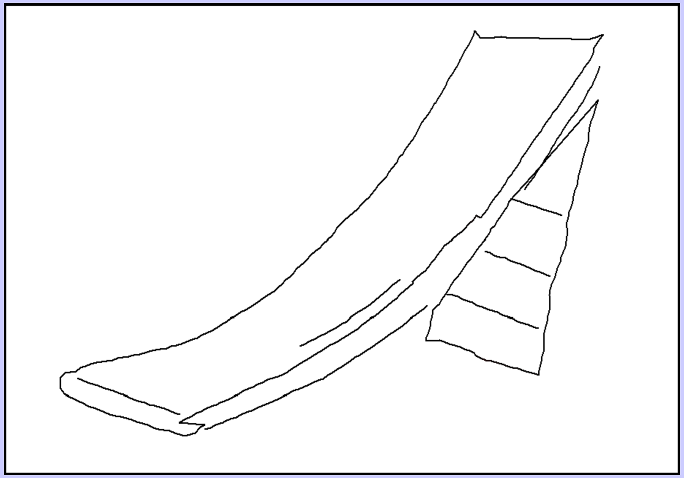
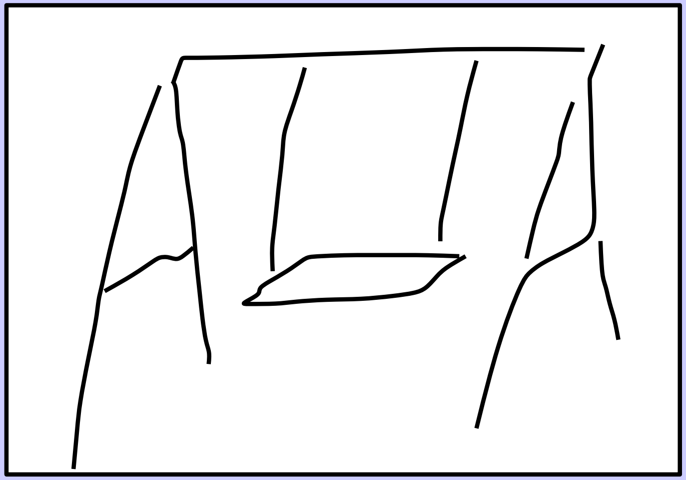
Results





Scribbled Drawing





Simplified Scribble

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Evaluation of Results

Comparison of the Gabor Grouping Algorithm with Morphology Operators

Image ID	Scribble Roughness	'Close' Operation			Gabor Filtering
		$W = 5$	$W = 9$	$W = 11$	
Test 1	49.94	39.89	35.59	**32.63**	21.22
Test 2	10.44	**23.57**	23.58	23.59	13.57
Test 3	45.66	34.31	**33.41**	33.97	19.46
Test 4	41.99	25.07	23.92	**23.43**	9.97
Test 5	40.04	28.52	**26.01**	26.03	22.88
Test 6	50.24	37.17	**32.42**	33.47	17.69
μ	43.68	32.13	29.87	28.95	18.48
σ	6.61	7.71	7.89	8.26	5.56

Comparing the total number of pixels that do not match with the ground truth drawing

as a percentage of the foreground pixels

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Evaluation of Results

Evaluating the Usefulness of the Gabor Grouping Algorithm

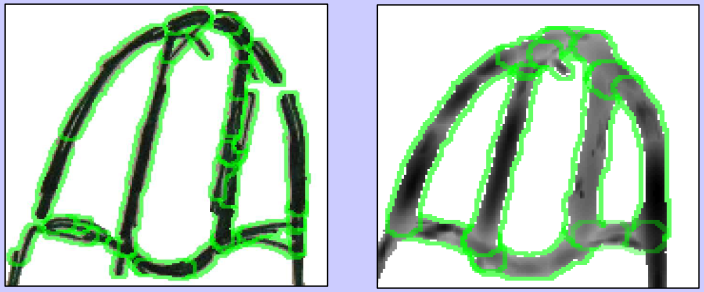

Image ID	Ground Truth	Scribble	Simplified Scribble
Test 1	18	53	18
Test 2	13	44	18
Test 3	14	44	15
Test 4	15	64	16
Test 5	9	50	13
Test 6	22	62	24

Comparing the number of segments obtained by the ScanScribe software for the ground truth drawing, the scribbled drawing and the simplified drawing

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Evaluation of Results

Comparison of the Proposed Line Tracking Algorithm and the Sparse Pixel Vectorization Algorithm on Neat Line Drawings

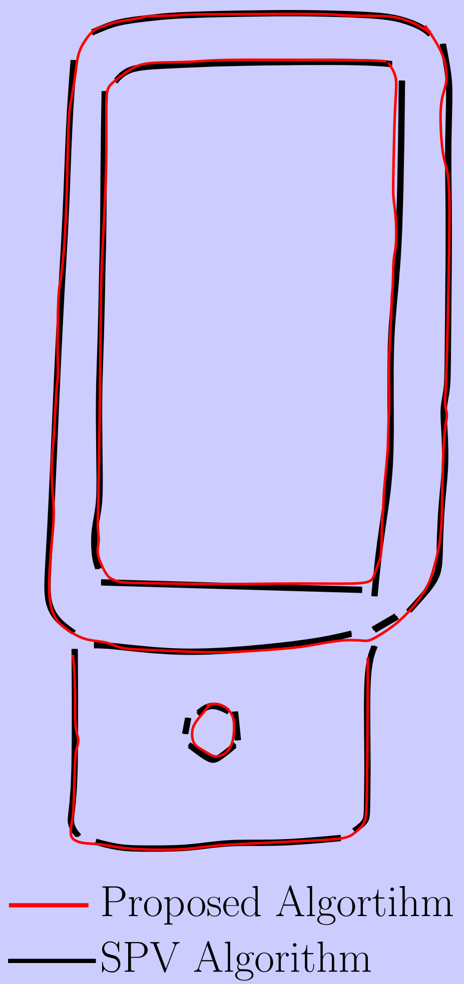

Image ID	**SPV**	**Kalman Tracking**
Test 1	0.87	0.90
Test 2	0.82	0.86
Test 3	0.81	0.92
Test 4	0.76	0.88
Test 5	0.80	0.87
Test 6	0.82	0.88
μ	0.82	0.87
σ	0.03	0.02

Comparing the Pixel Recovery Index (PRI) obtained by the SPV algorithm and the proposed line tracking algorithm

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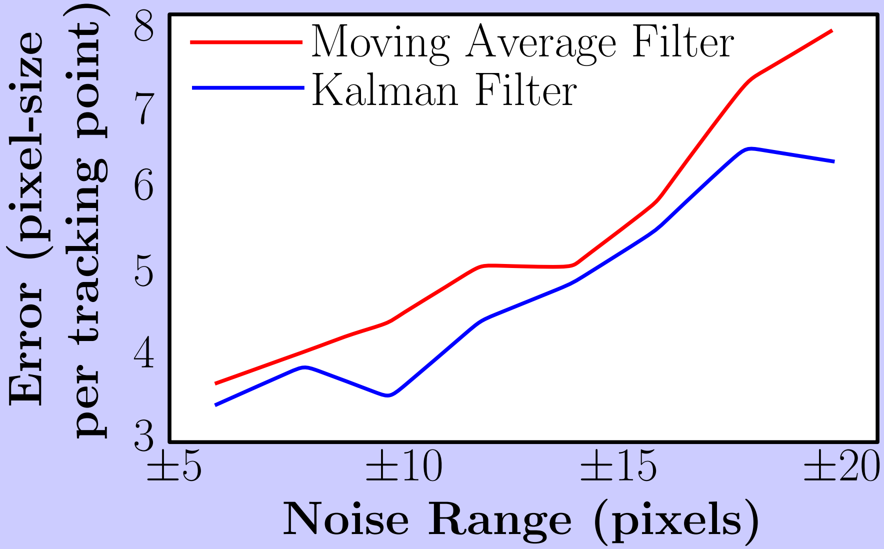
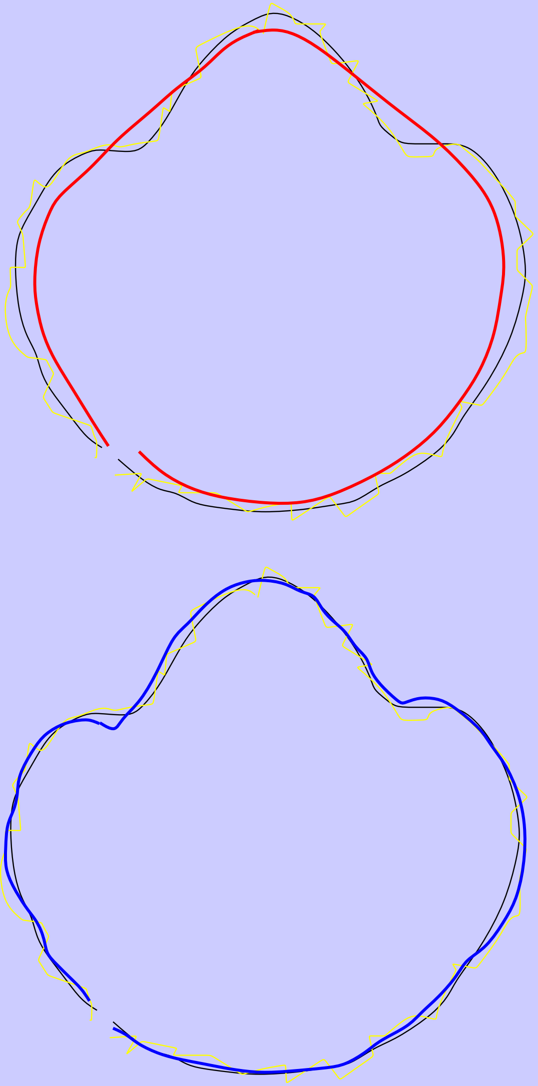
Evaluation of Results

Comparison of the Kalman Filtering with the Moving Average Filter





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Obtaining 3D Form from Scribbles

- The medial points obtained from our algorithm can be used directly in CAD tools. However, the CAD representation would still be a 2D representation and further CAD operations are required to obtain the 3D form.

- We have proposed an annotation language whereby the scribbled drawing can be annotated in an intuitive way so as to allow computer algorithms to automatically obtain the 3D form form the paper-based drawing.

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The Components of the Annotation Language

- A complete and annotated sketch will consist of

  Object profile: a sketch depicting a side view of the object

  Plane lines: lines that indicate planes of interest in the object

  Cross-sectional profiles: 2D sketches that indicate the cross-sectional shape of the object

- The object profile must be drawn in a different colour than the plane lines and cross-sectional profiles

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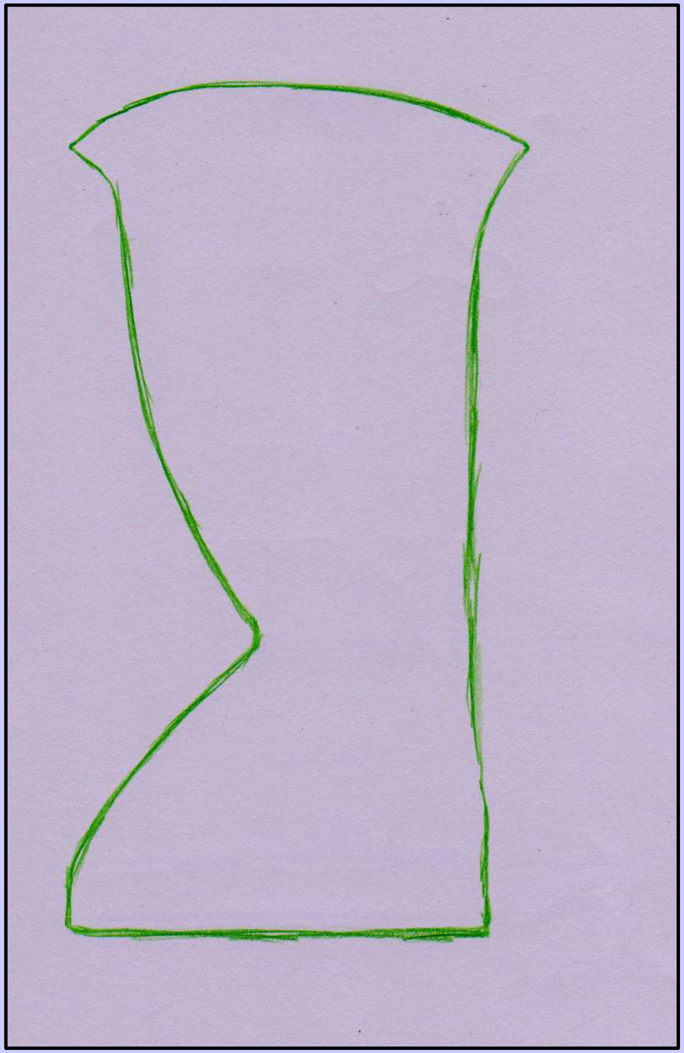
Case study 1: A Blender



1. Sketch the object profile.

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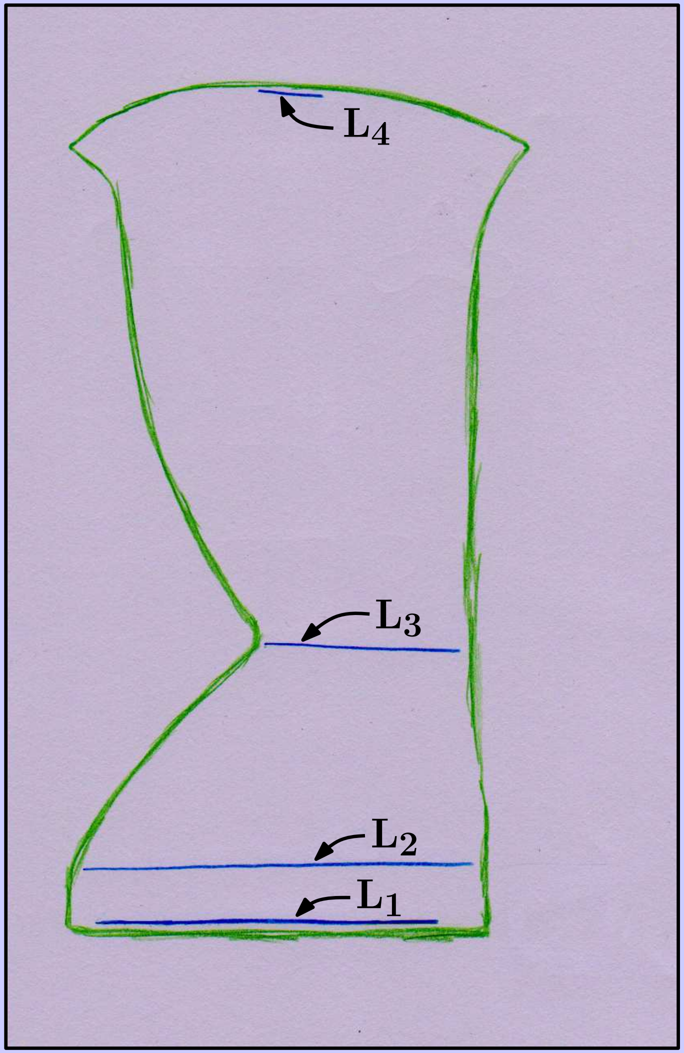
Case study 1: A Blender



2. Mark salient planes with a plane line.

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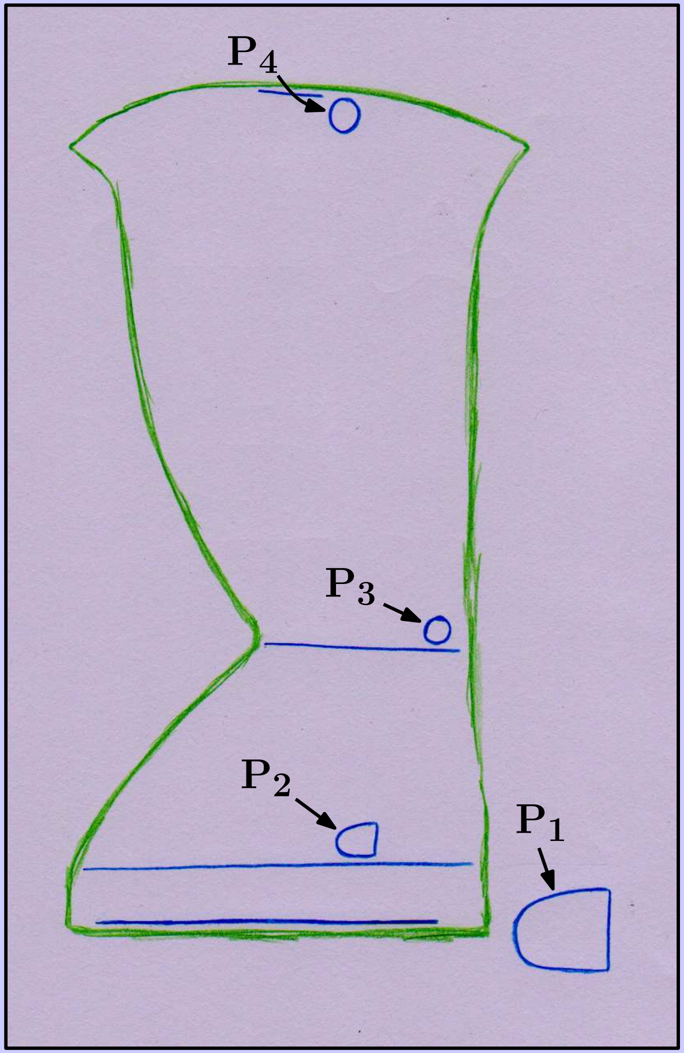

3. Use cross-sectional profiles to specify the cross-sectional shape at the plane lines.

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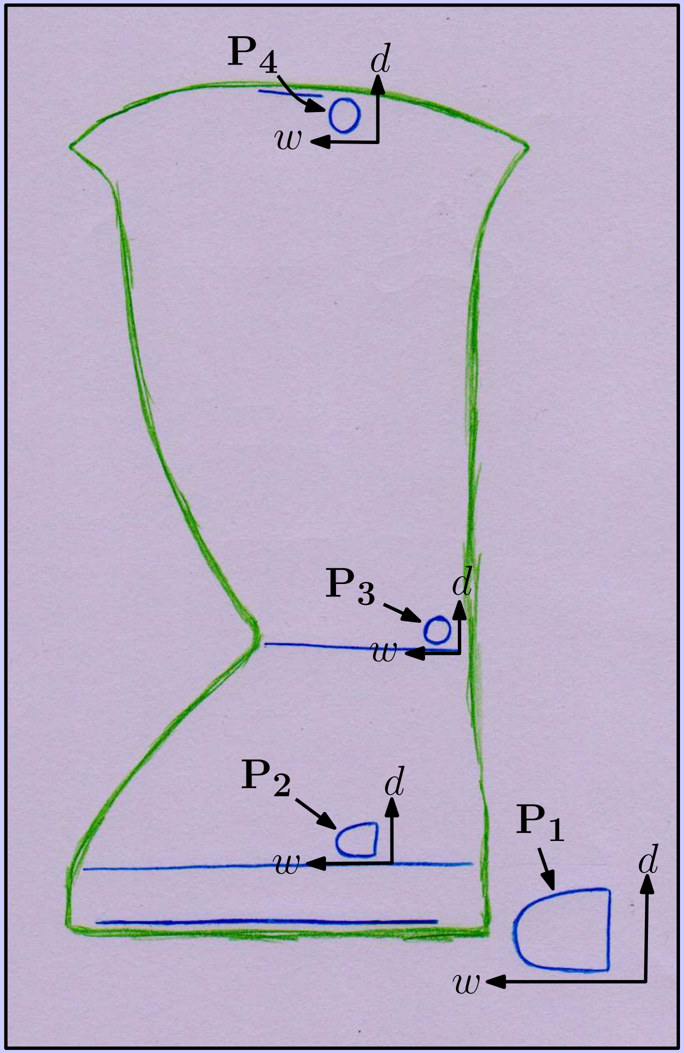
Case study 1: A Blender



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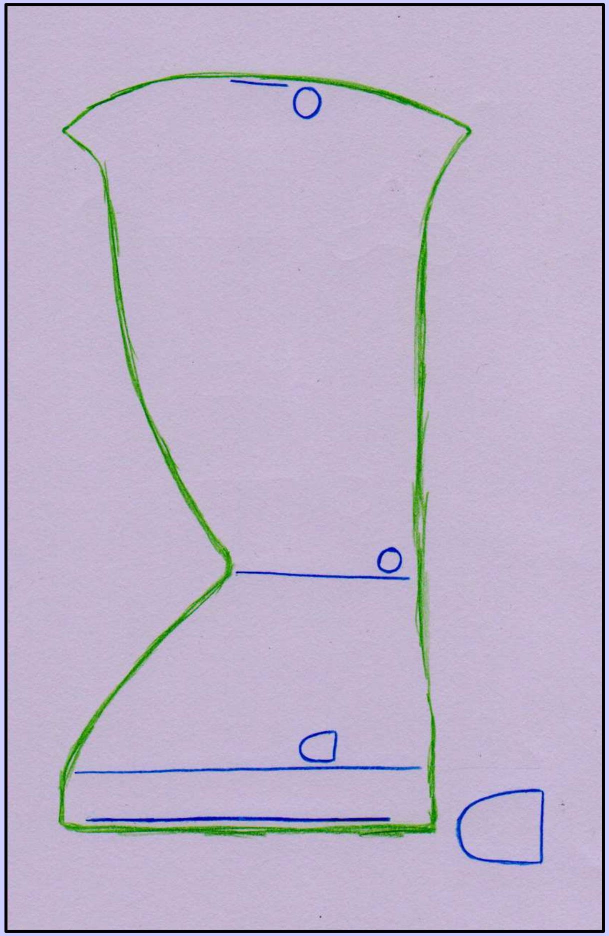
Case Study 1: Interpreting the Sketch



- Centre and scale the given cross-sectional profiles

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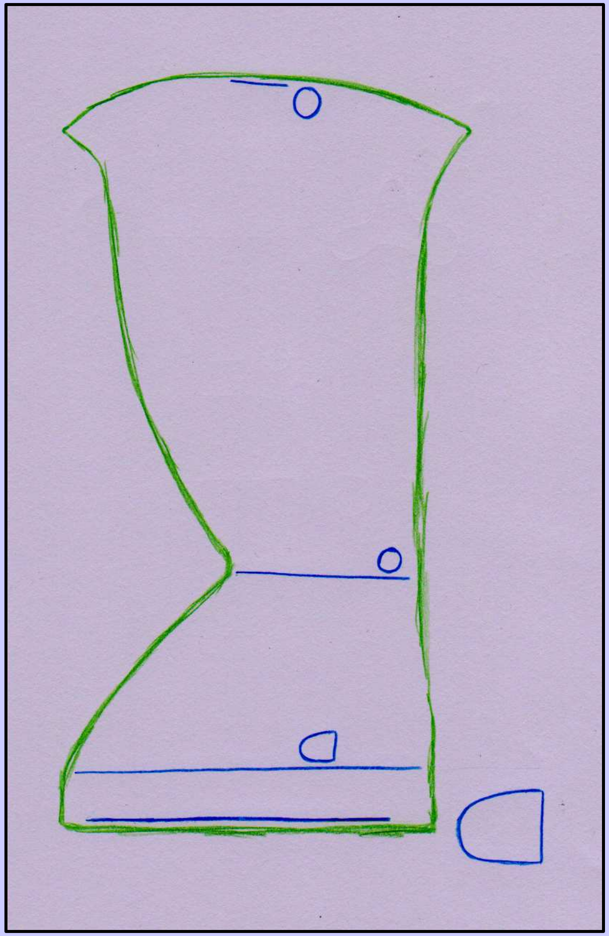

- Centre and scale the given cross-sectional profiles
- Create intermediary cross-sectional profiles to define the object form accurately

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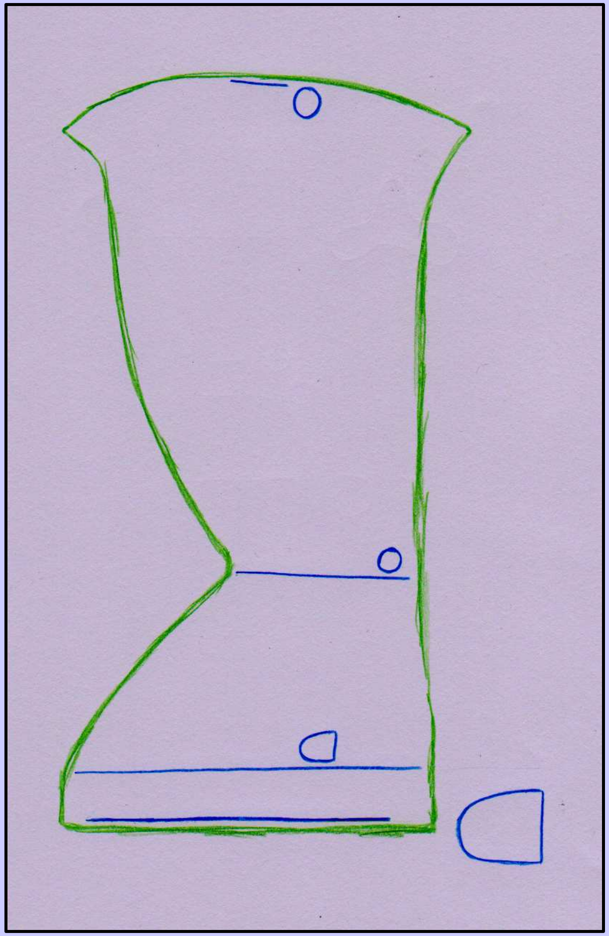
Case Study 1: Interpreting the Sketch



- Centre and scale the given cross-sectional profiles

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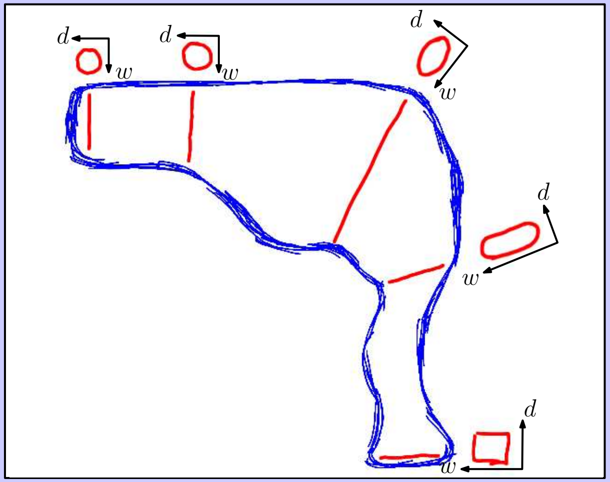
Shapes modelled using this annotation-language

A Hair Dryer



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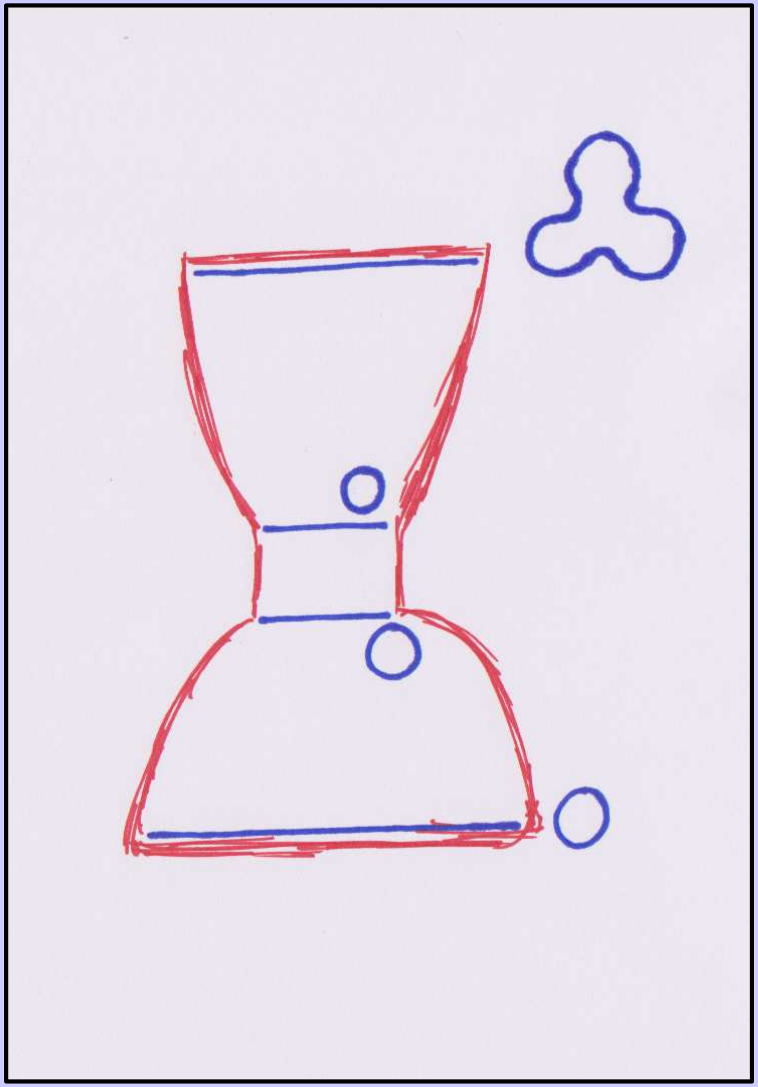
Shapes modelled using this annotation-language

A Bathroom Tap



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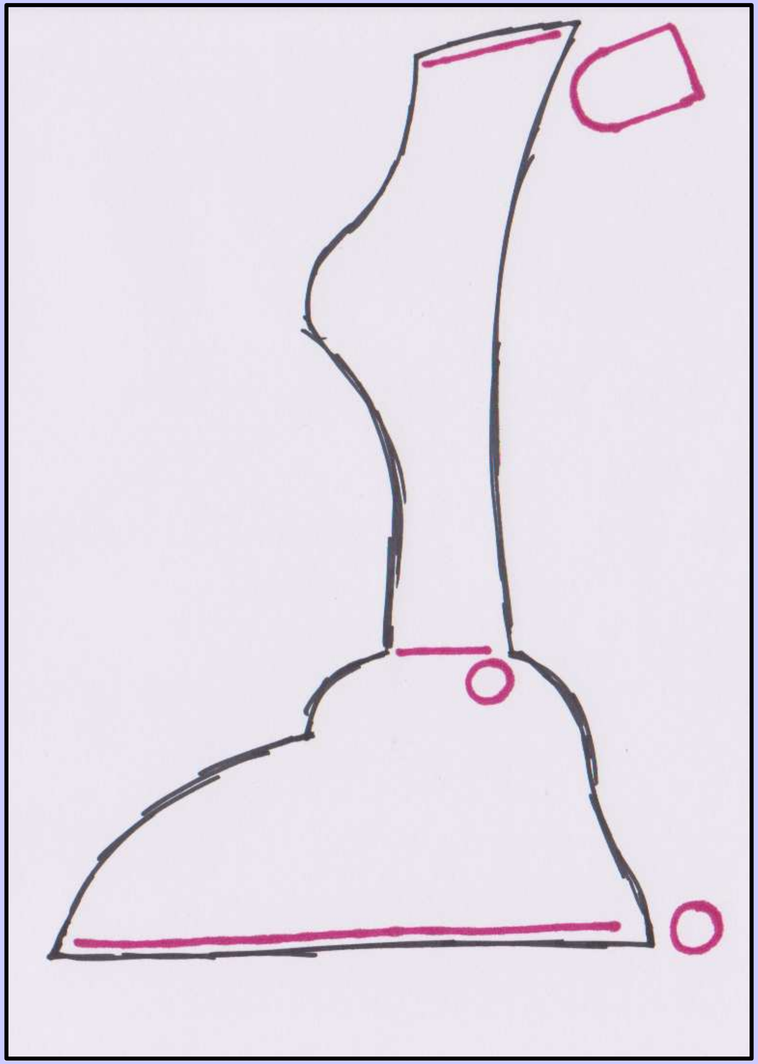
Shapes modelled using this annotation-language

A Joystick



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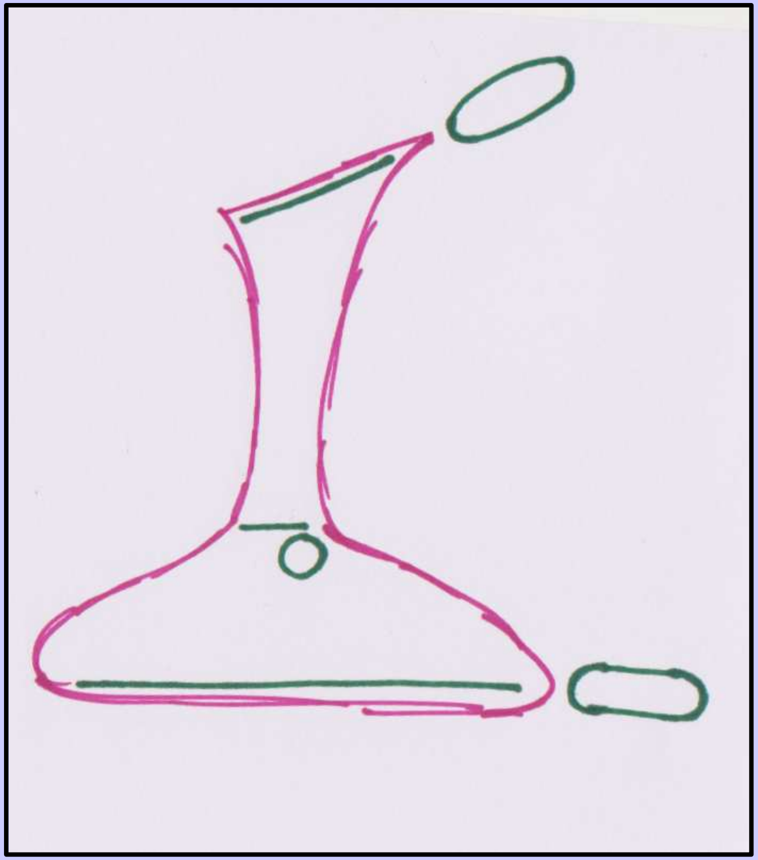
Shapes modelled using this annotation-language

A Nail Polish Bottle



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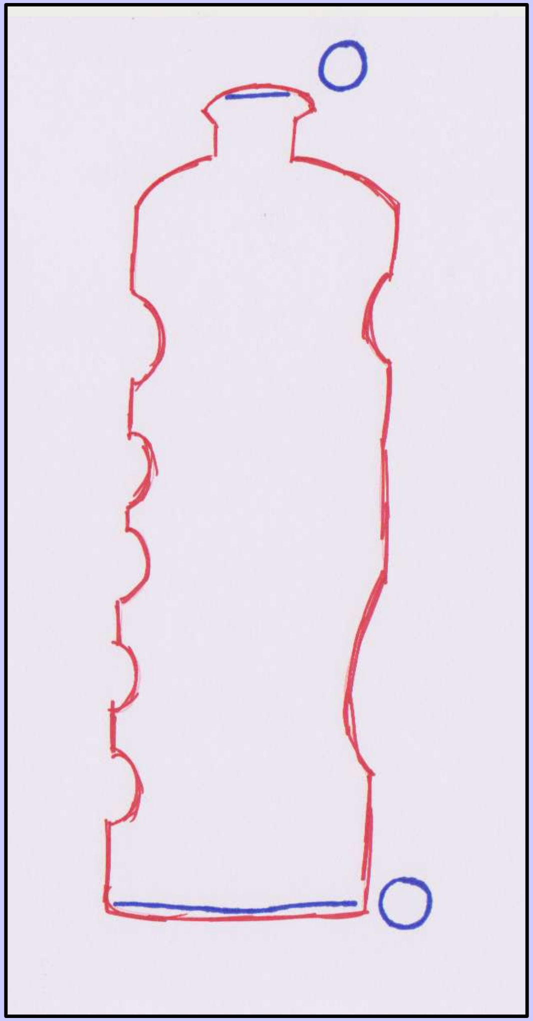
Shapes modelled using this annotation-language

An 'Easy Grip' Drinking Flask



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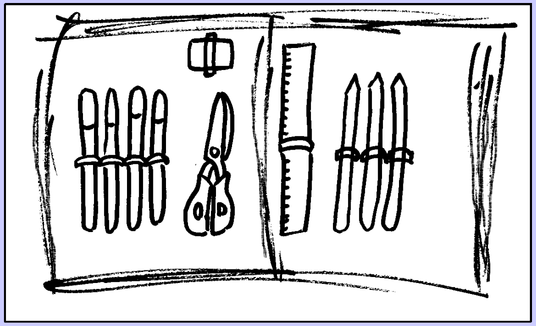
Conclusions

- These algorithms make CAD tools accessible from scribbled drawings, thus decreasing the time taken for a designer to obtain virtual prototypes from concept drawings.
- Our algorithms can be further improved in order to successfully interpret different genres of scribbles. This involves:
  - Simplification of scribbles having different stroke resolutions



  - Improving the annotation language to cater for more complex forms involving different parts

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List of Publications

1. Bartolo A., Farrugia P., Camilleri K. P., Borg J. C., A Profile-driven Sketching Interface for Pen-and-Paper Sketches in Proceedings of the Workshop on Sketch Tools for diagramming, Herrshing am Ammersee, Germany, 2008

2. Bartolo A., Camilleri K. P., Fabri S. G., Borg J. C., Paper-based Scribble Simplification: Where Do We Stand? in Proceedings of the Eurographics Workshop on Sketch-Based Interfaces and Modeling 2008, pg. 25-32

3. Bartolo A., Camilleri K. P., Fabri S. G., Borg J.C., Line Tracking Algorithm for Scribbled Drawings. In Proceedings of the 3rd International Symposium on Communications, Control and Signal Processing, 2008

4. Bartolo A., Camilleri K.P., Fabri S. G., Borg J.C., Farrugia P.J. Scribbles to Vectors: Preparation of Scribble Drawings for CAD Interpretation. In Proceedings of the Eurographics Workshop on Sketch-Based Interfaces and Modeling 2007.

5. Bartolo A., Cassar T., Camilleri K.P, Fabri S.G., Borg J. C. Image Binarization using the Extended Kalman Filter. Informatics in Control, Automation and Robotics II, pp 153-162, J. Filipe, J.L. Ferriera, J. A. Cetto and M. Carvalho editors, Springer 2006

6. Bartolo A., Camilleri K.P., Farrugia P.J., Borg J.C. A New Sketch Based Interface using the Gray-level Co-occurrence Matrix for Perceptual Simplification of Paper Based Scribbles. In Proceedings of the Eurographics Workshop on Sketch-Based Interfaces and Modeling, pp 91 - 98, 2006

7. Bartolo A., Cassar T., Camilleri K.P, Fabri S.G., Borg J. C. Image Binarization using the Extended Kalman Filter. In Proceedings of the 2nd International Conference on Informatics in Control, Automation and Robotics Vol. 2 pp 160-167, 2005

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- The application of the scribble interpretation algorithm and the development of the annotation language was carried out with the collaboration of the Department of Industrial and Manufacturing Engineering

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Further information on the research work carried out within the Department of Systems and Control Engineering can be accessed at http://www.um.edu.mt/eng/sce

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