Skeleton pruning by contour approximation and the integer medial axis transform

uOttawa

University of Ottawa

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Outline

Medial Axis of a shape (Digital Images)

- The locus of centers of all maximal discs tangent to the boundary in more than one point.
- A set of connected pixels that have at least two closest boundary points.
- Points with more than 2 closest points in the boundary are branching points.
- End points are the extreme pixels of the skeleton.

Blum's definition 1967.

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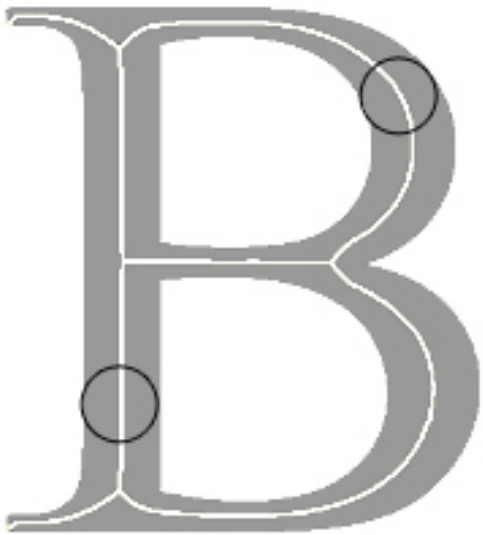

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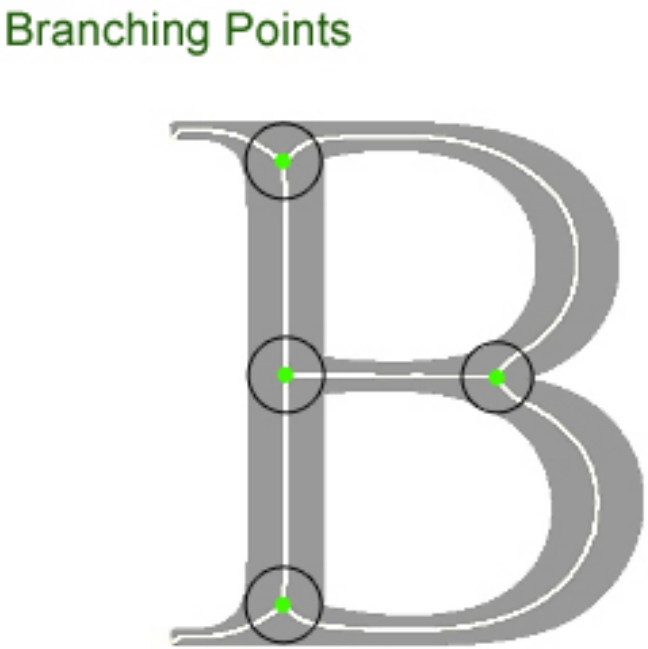

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Problem and Objective

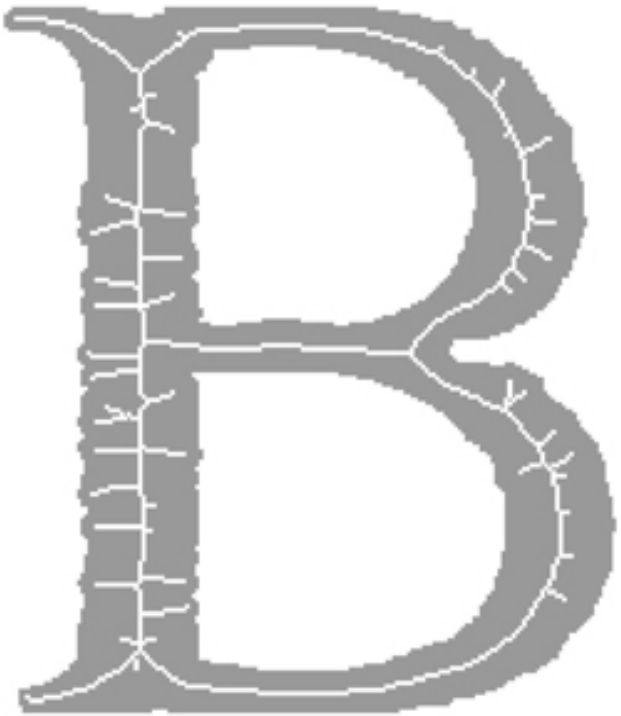
Problem

The digital medium (pixels) and boundary noise create unwanted branches.

Objective

A medial axis subset:

- conserves connectivity.
- removes undesired branches.
- reconstructs the original shape.
- is robust to image transformations.
- computes vectorial medial axis.
- used in real time applications.



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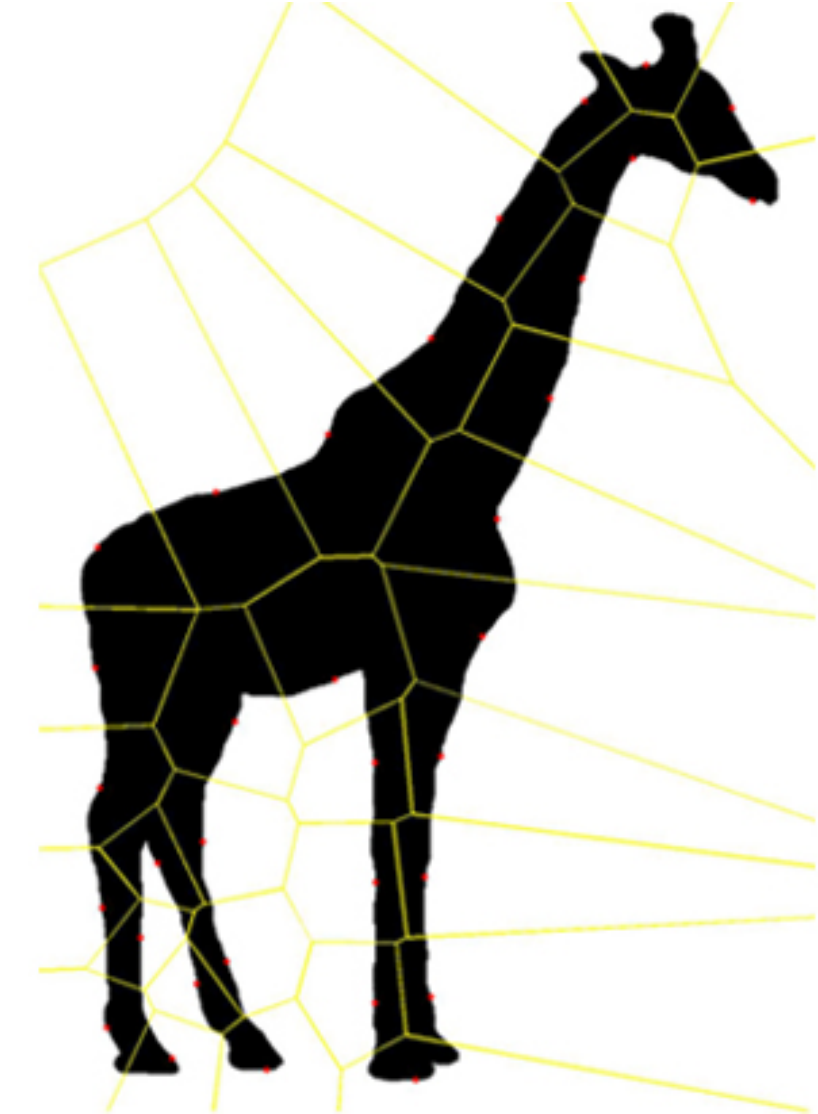
Contributions of our solution

Contributions

- Conserves connectivity.
- Outputs a subset of the integer medial axis.
- Fast and easy to implement.

Voronoi diagram.



- Computes voronoi regions of boundary points and pruning.
- As density of boundary points goes to infinity, diagram converges to medial axis.

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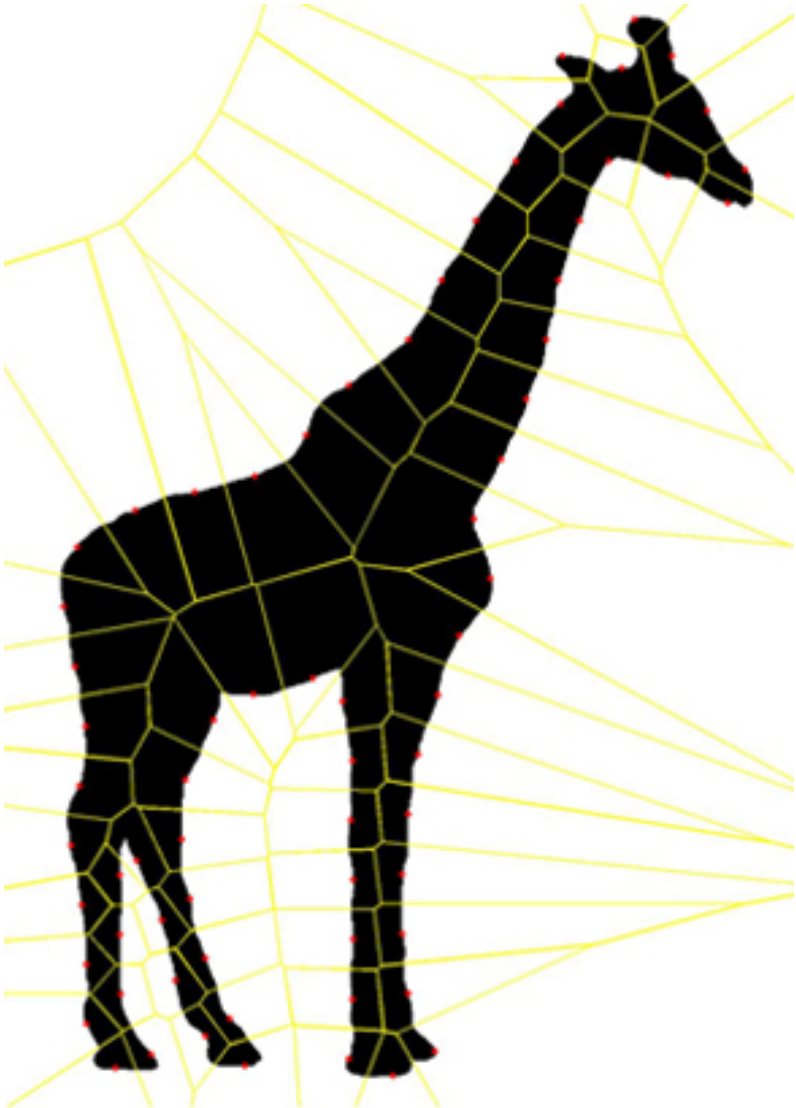

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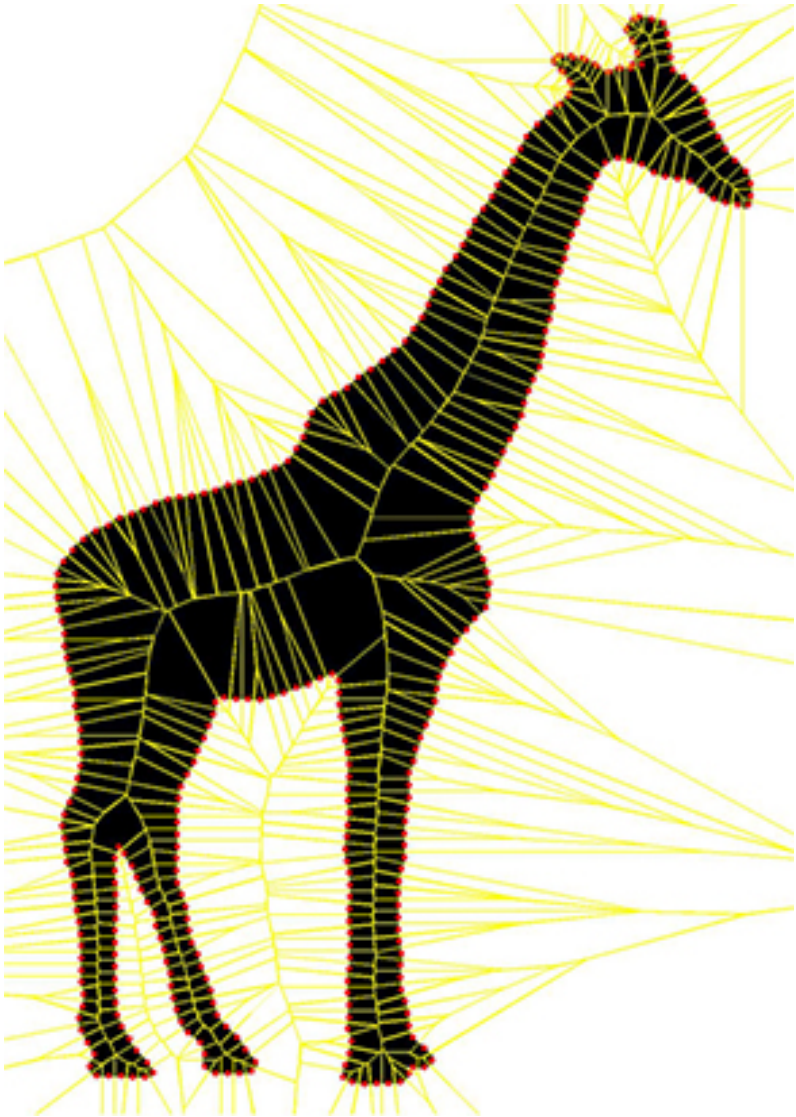

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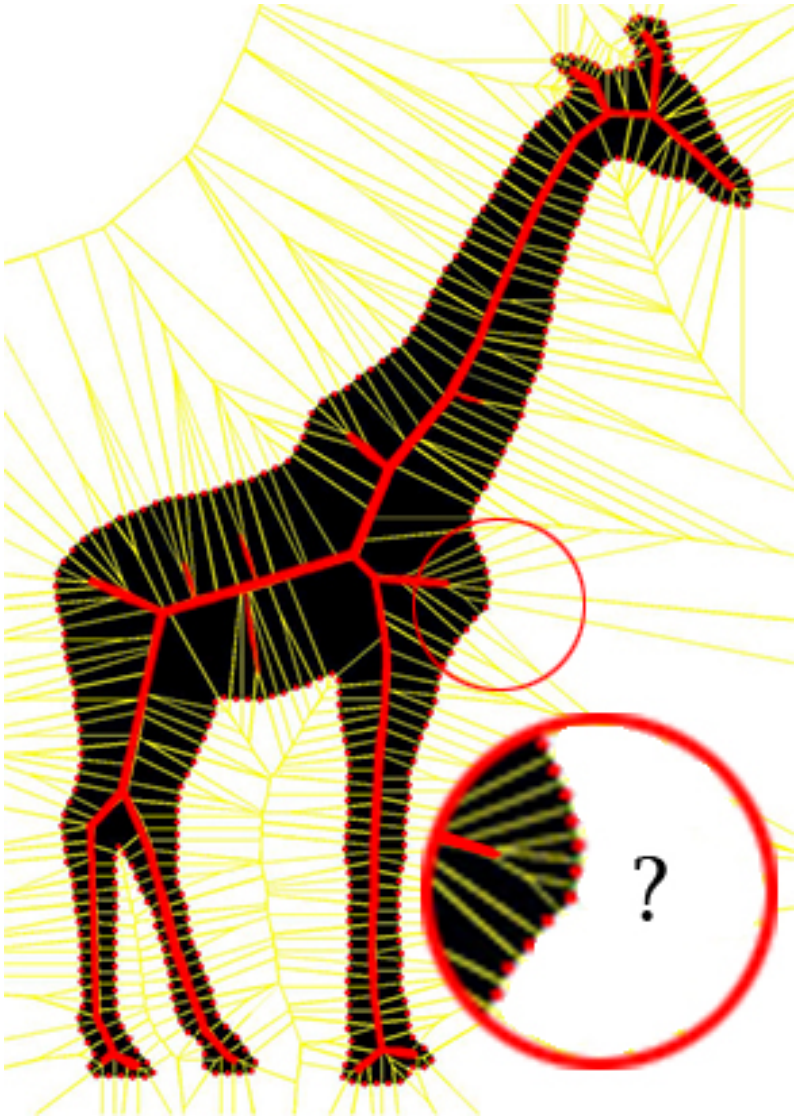
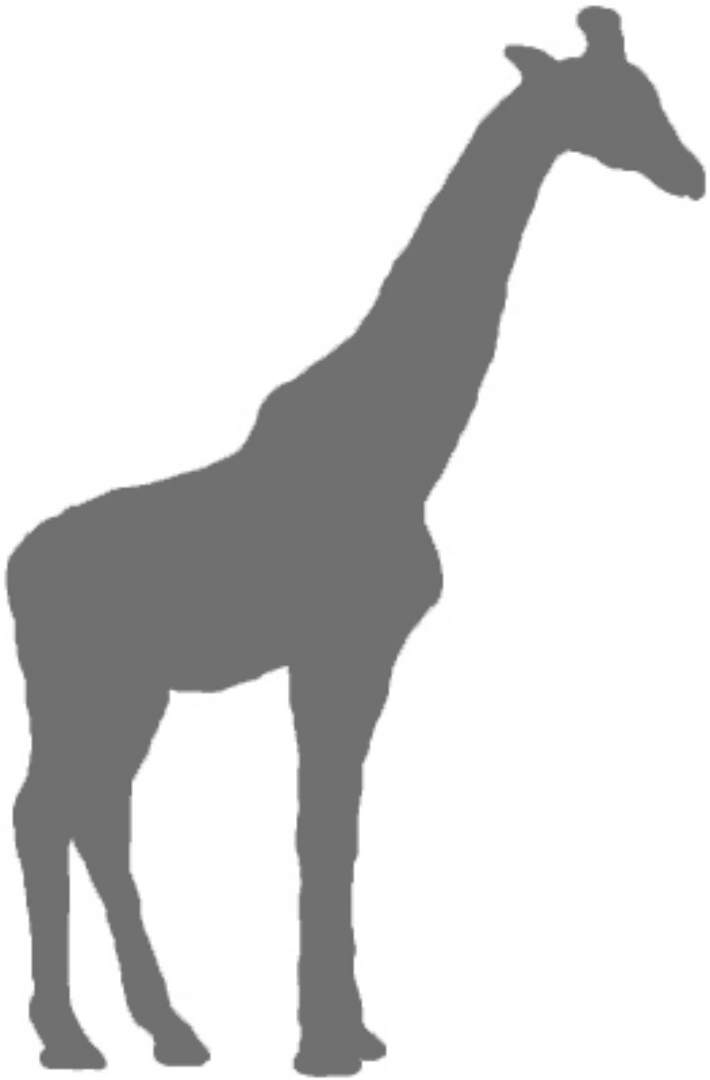
Voronoi's Limitations



- Selecting the correct samples of the boundary pixels.
- Sensitivity to noise.
- Many algorithms in this category are slow and more complicated.
- Needs extra prunning steps.

Thinning Solutions



- Peeling pixels from the boundary until no more pixels can be removed.
- Each boundary pixel is checked with their 8 neighbors using a set of rules.

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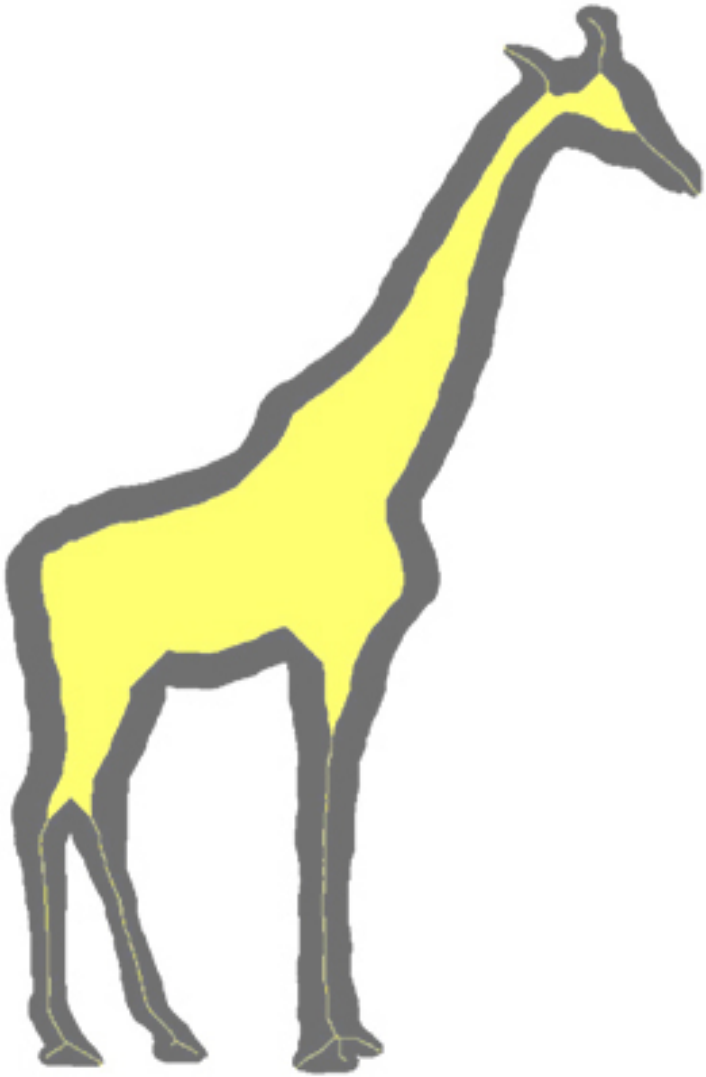

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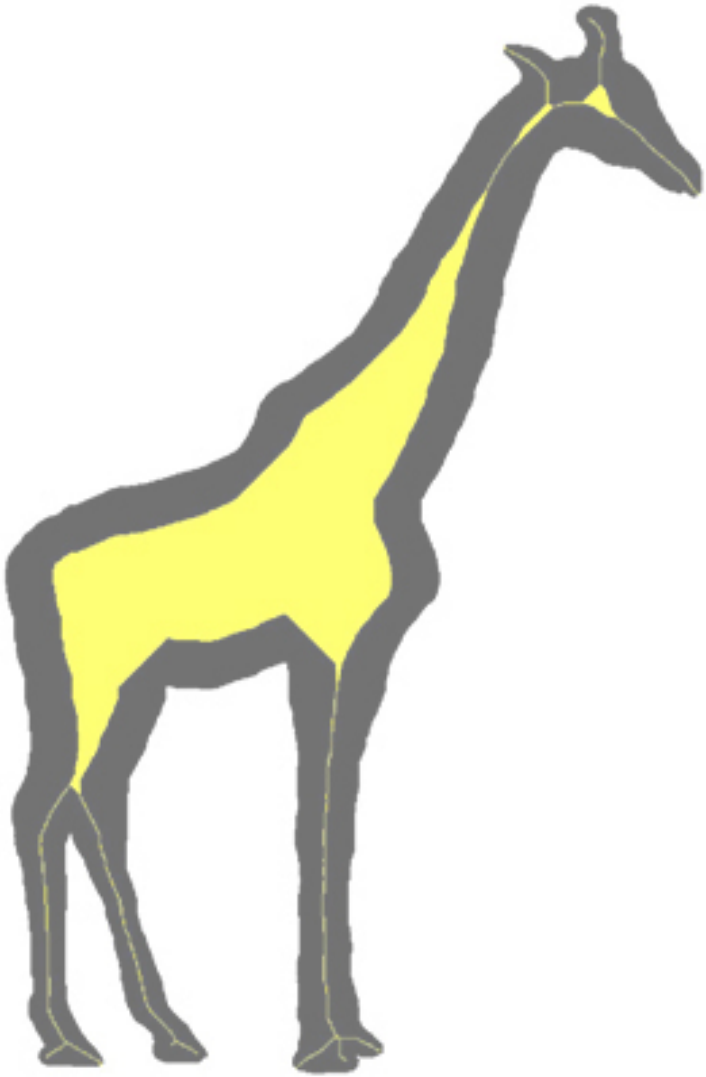

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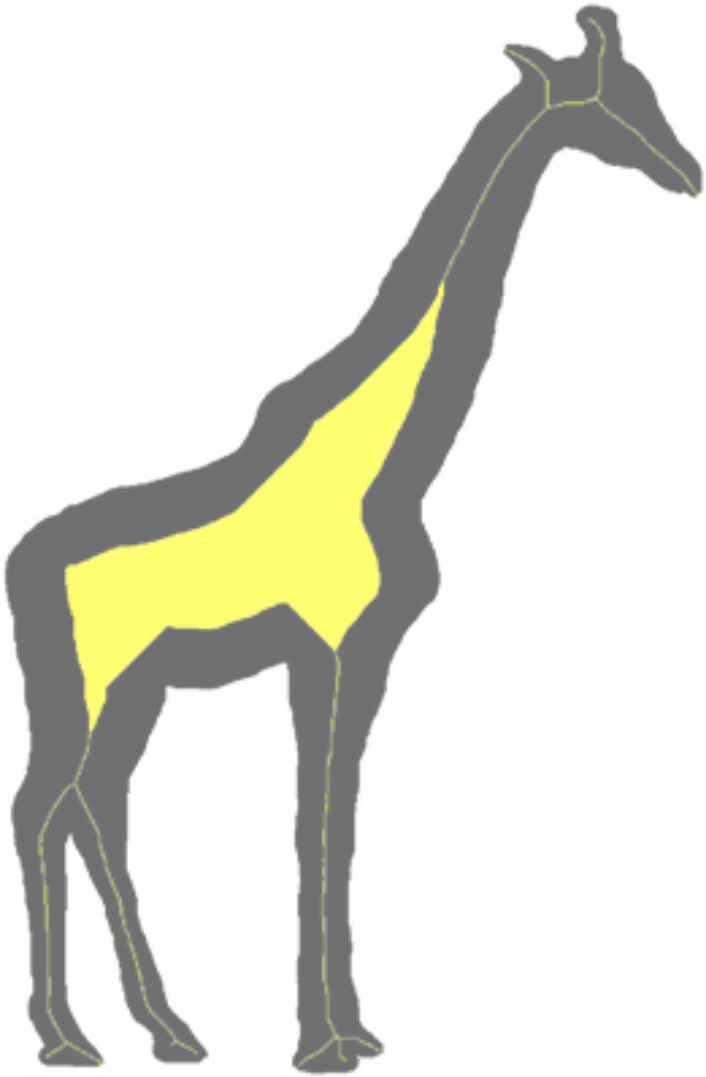

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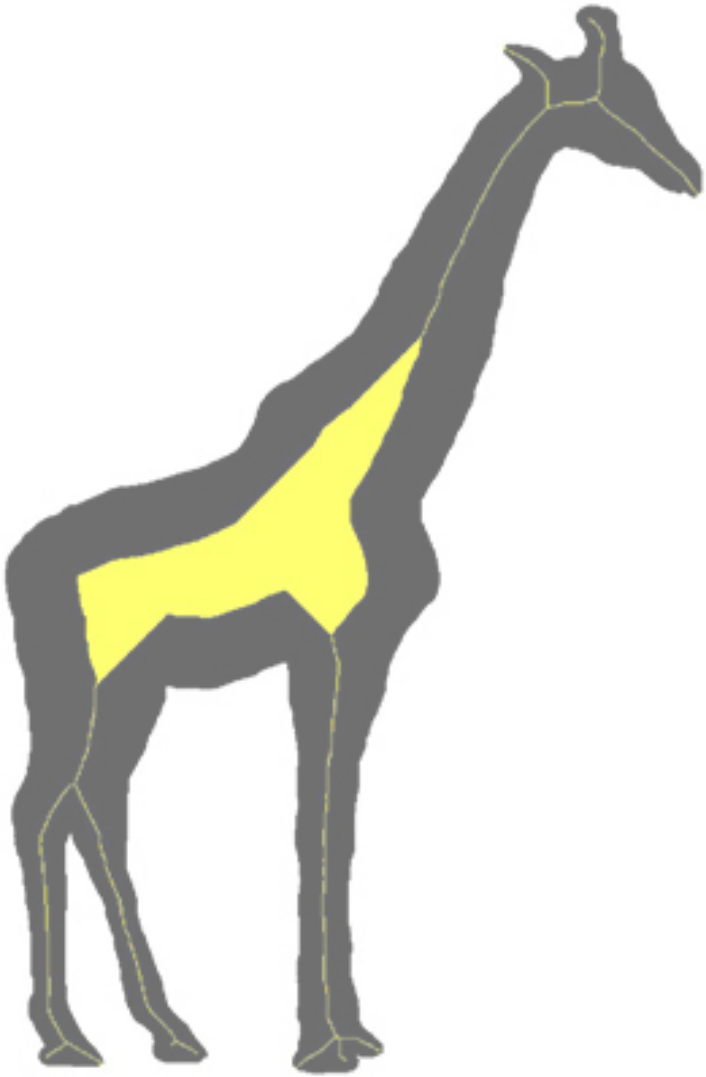

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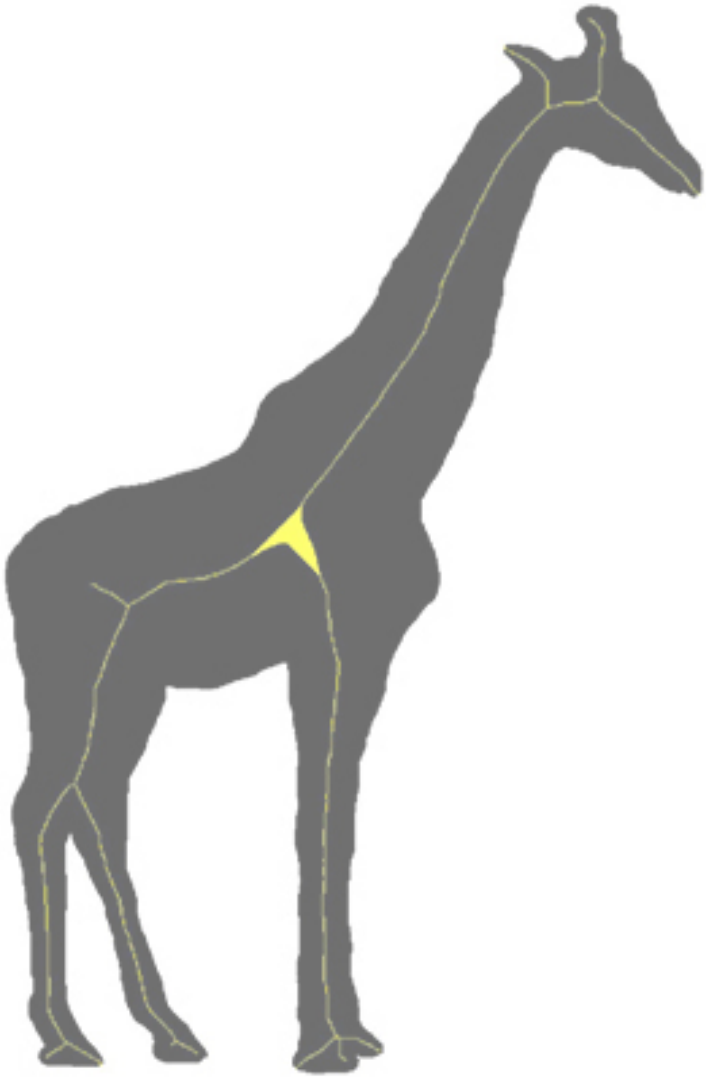

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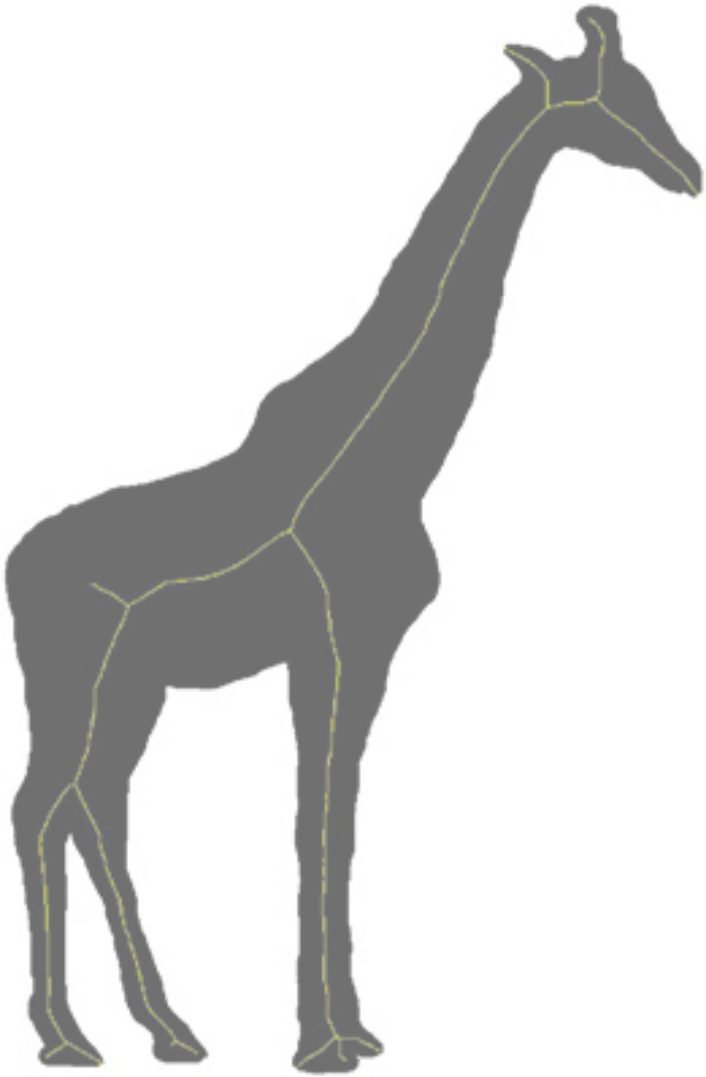

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- Noise sensitivity.
- Rotation sensitivity.
- No shape reconstruction.
- Fails to compute the medial axis.
- Time consuming.

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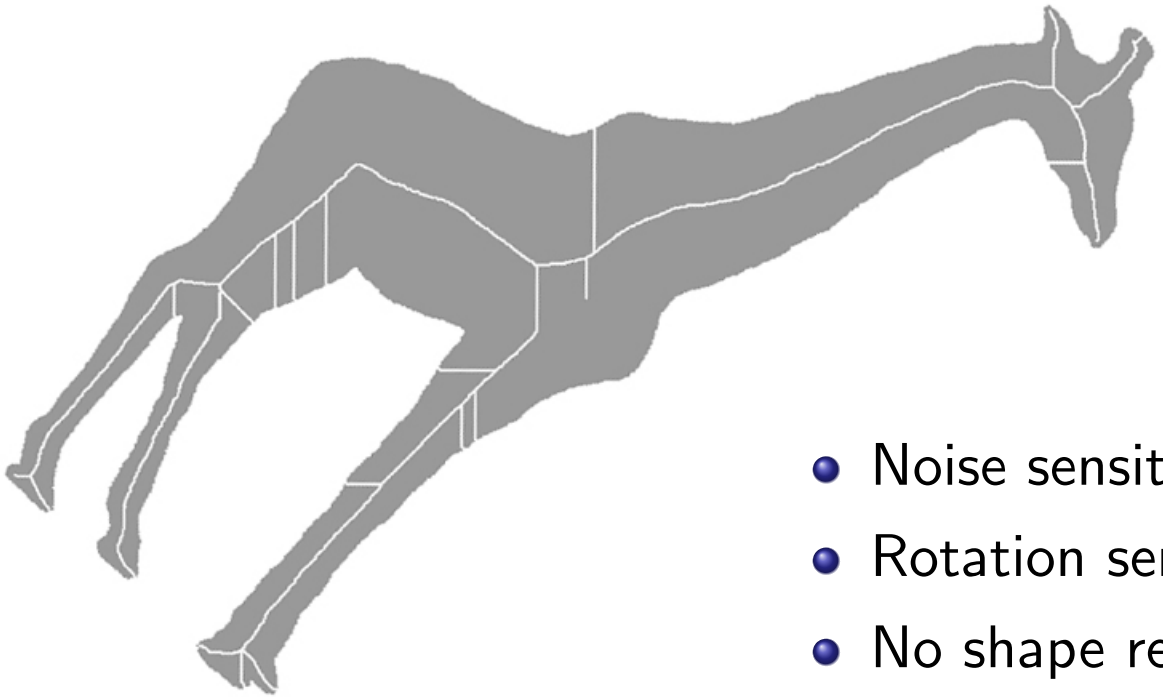

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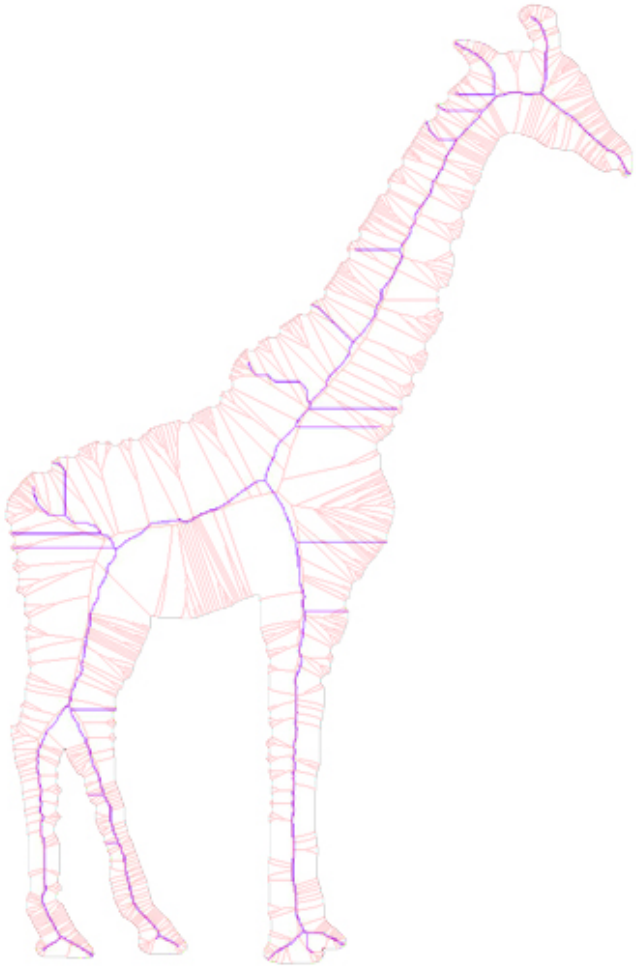

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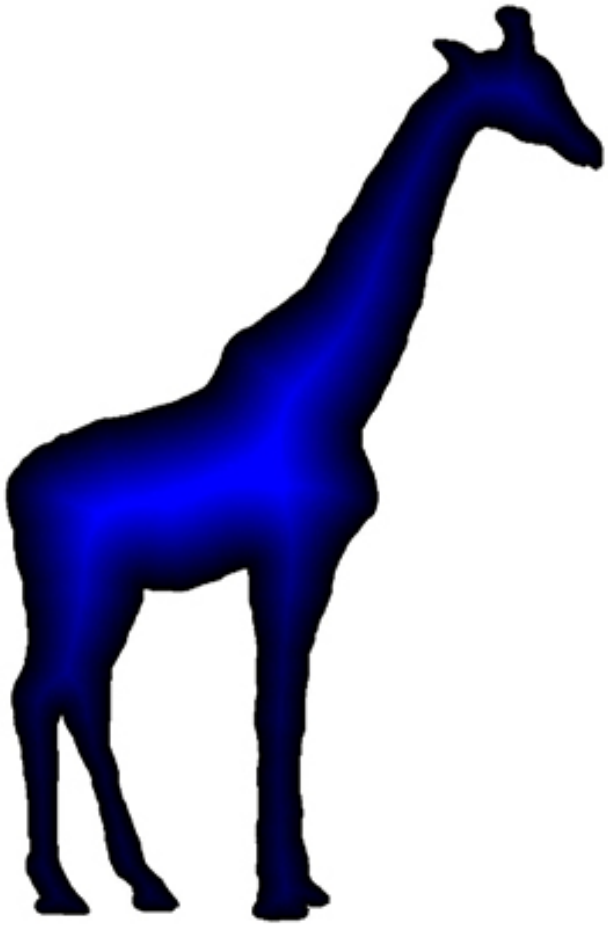
Feature Transform & Distance Transform



- The feature transform computes the closest boundary point for each pixel.
- The distance transform computes the distance to the nearest boundary pixel.
- Points with at least two closest points (same distance to boundary) are selected as medial axis points.

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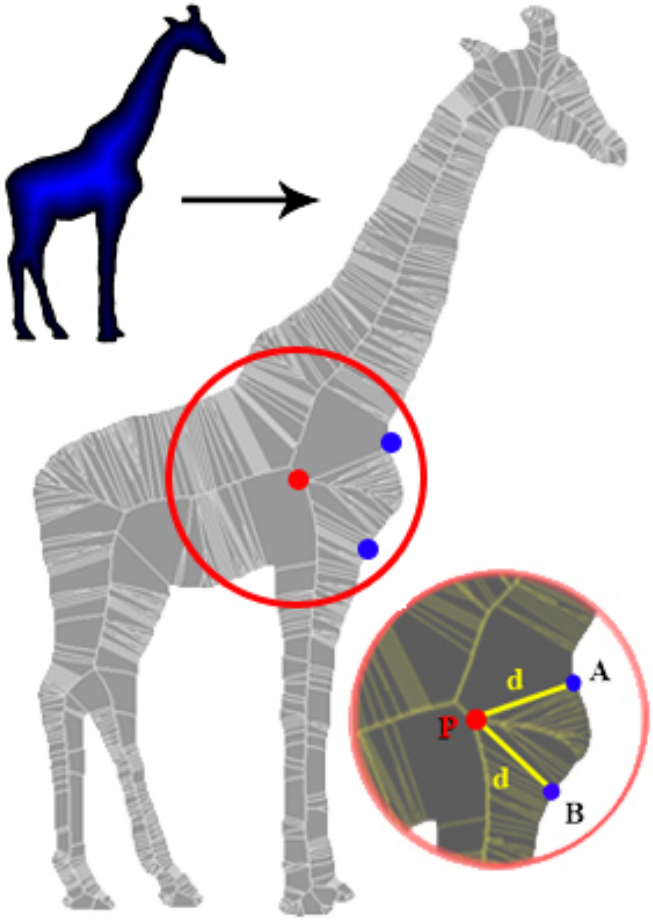

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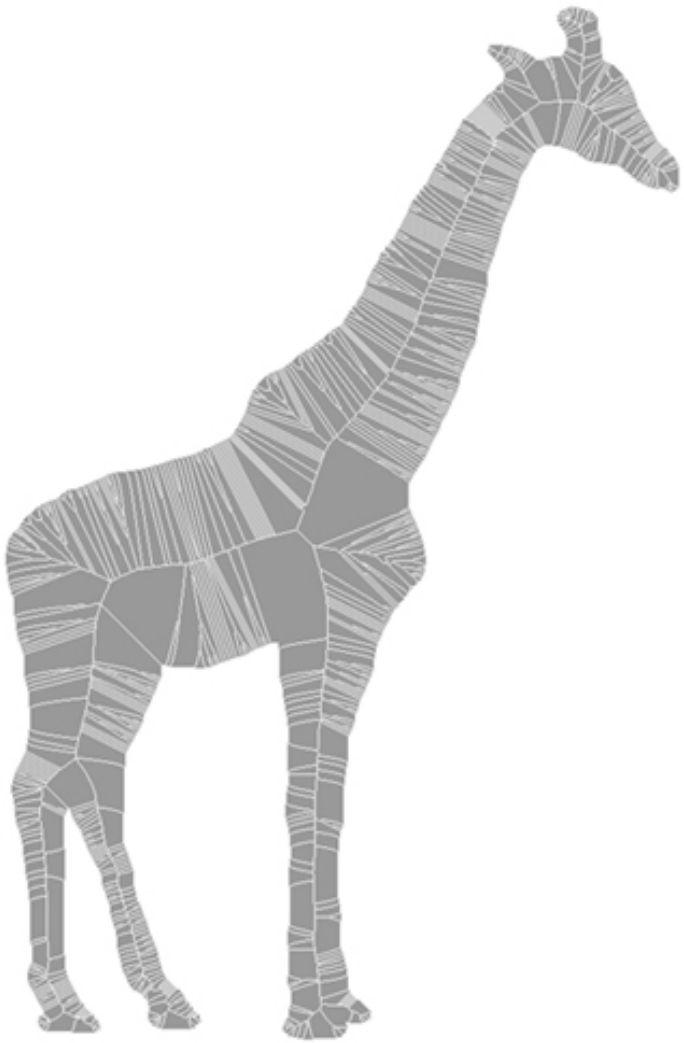
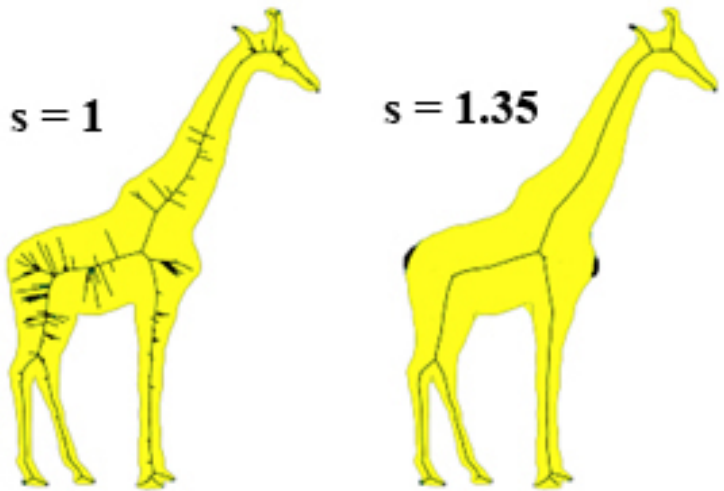
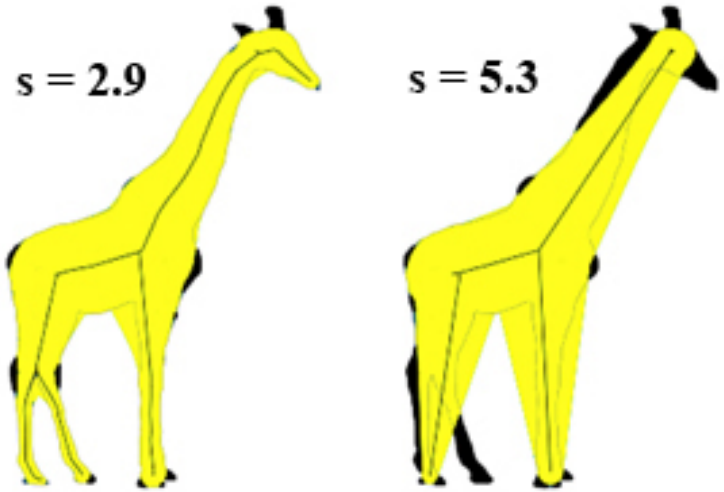


- Noise sensitivity.
- Needs extra pruning.
- Parameter selection associated to the pruning technique.

Pre-processing the shape's boundary



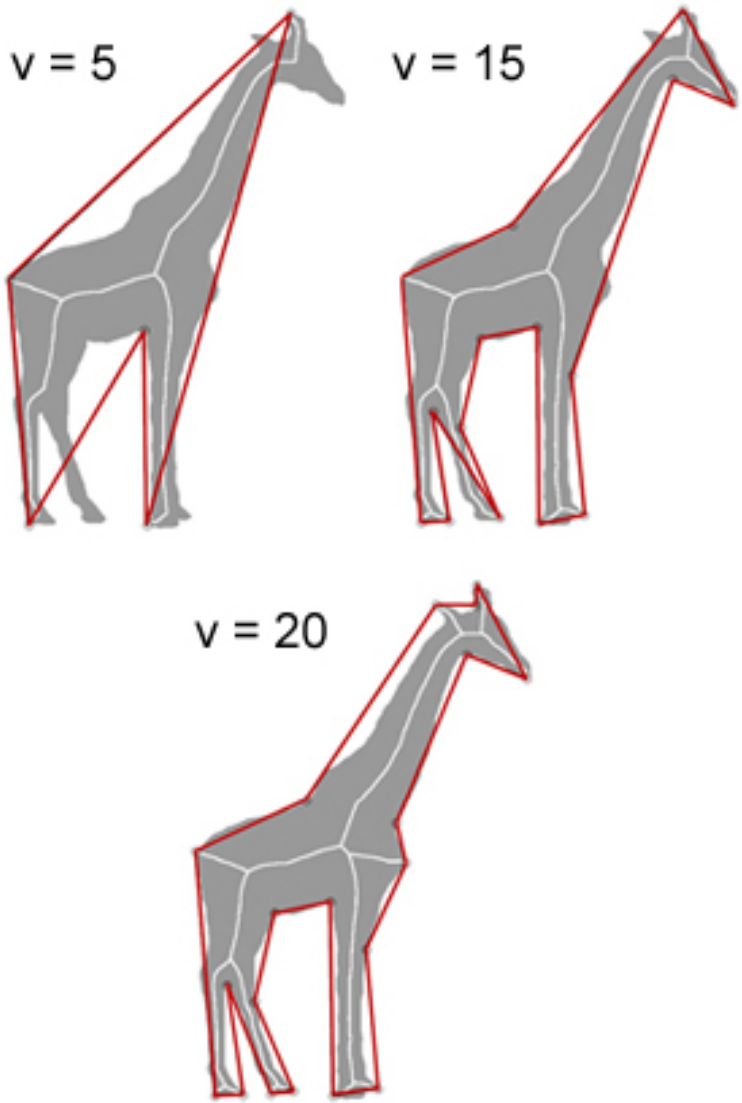


- Uses a noisy pre-computed medial axis.
- Grows the original shape by scaling the radii of the medial disks and then removing branches
- Creates simpler skeleton representation.

- Parameter selection?
- Shift skeleton from the medial axis.
- Shape holes are occluded when the shape is grown.

The scale axis transform. Giesen J. et al. 2008.

Pre-processing the shape's boundary

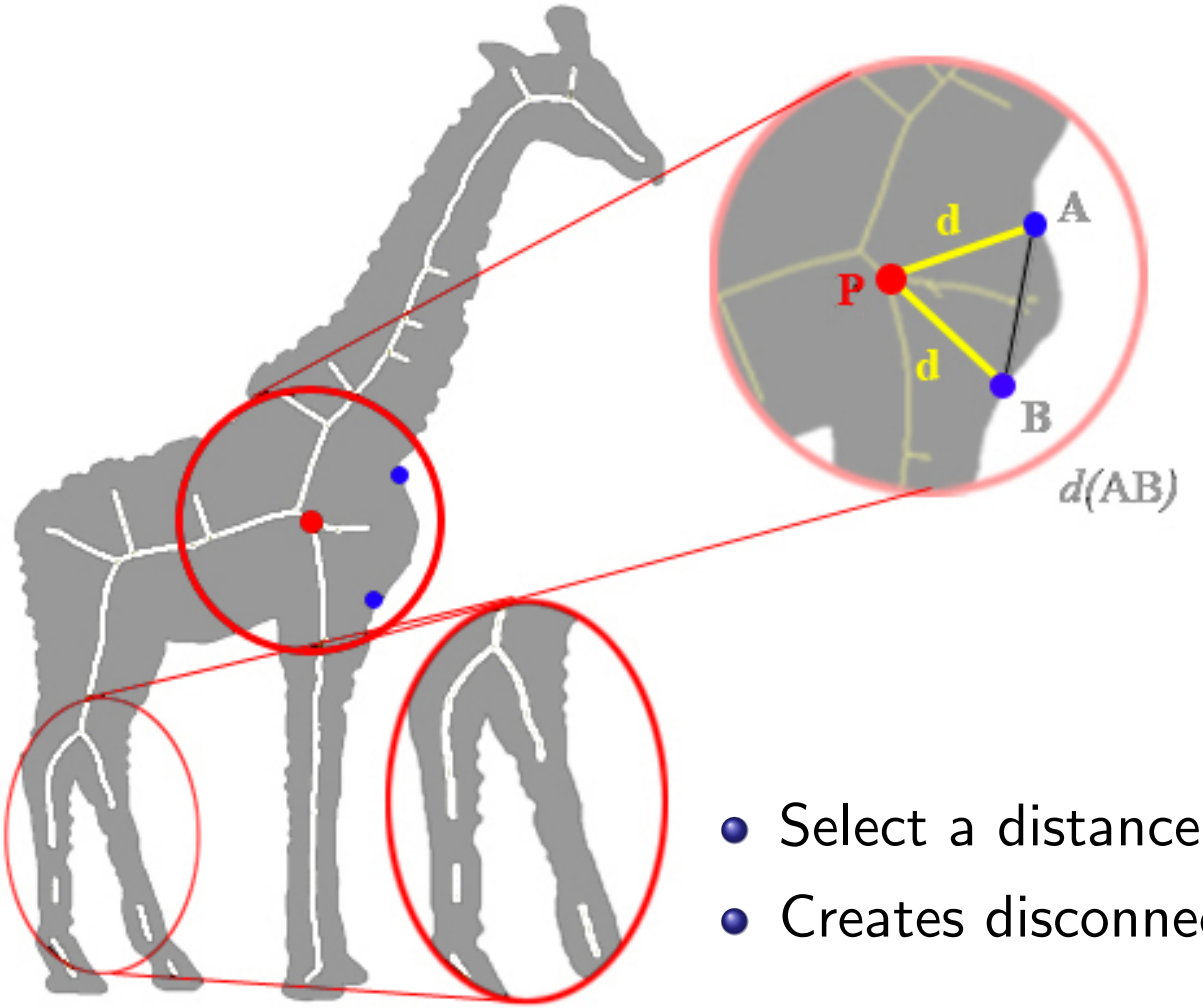


- Simplify the shape's boundary using a Discrete Evolution Approach.
- Uses the approximation to prune pre-computed medial axis.
- Uses the intuition of shape sides.

- Parameter selection?
- A priori knowledge of the shape to prune.
- It is slow.

Skeleton pruning with discrete curve evolution. X. Bai. et al. 2007.

Remove unwanted points based on classification criteria



- Select a distance threshold value T. ???
- Creates disconnectivity.

Distance Prunning.
W.H. Hesselink and J.B. Roerdink 2007.

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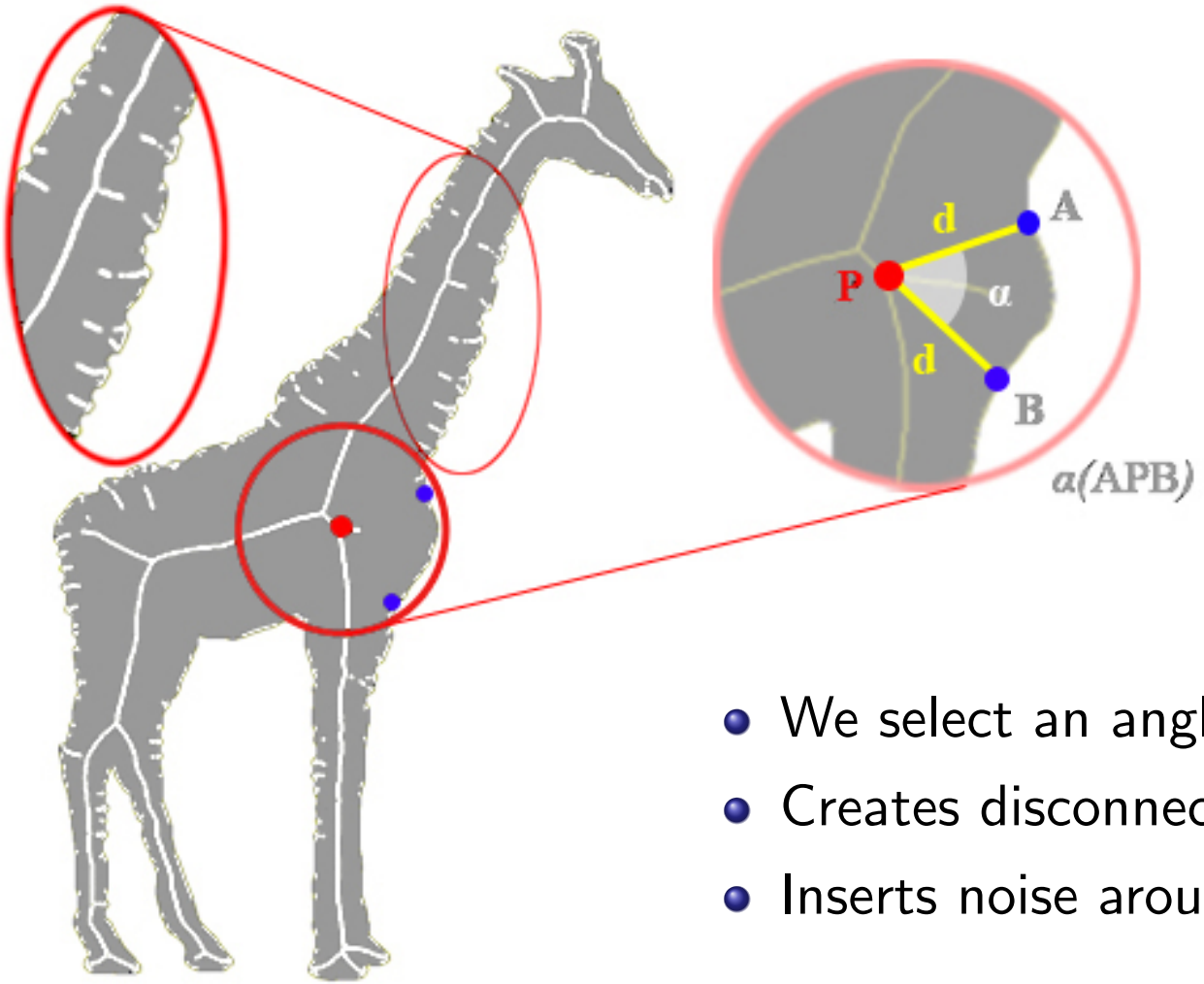


- We select an angle threshold value α. ???
- Creates disconnectivity.
- Inserts noise around the boundary.

Angular Pruning.
W.H. Hesselink and J.B. Roerdink 2007.

Algorithm Outline

Four Steps Algorithm

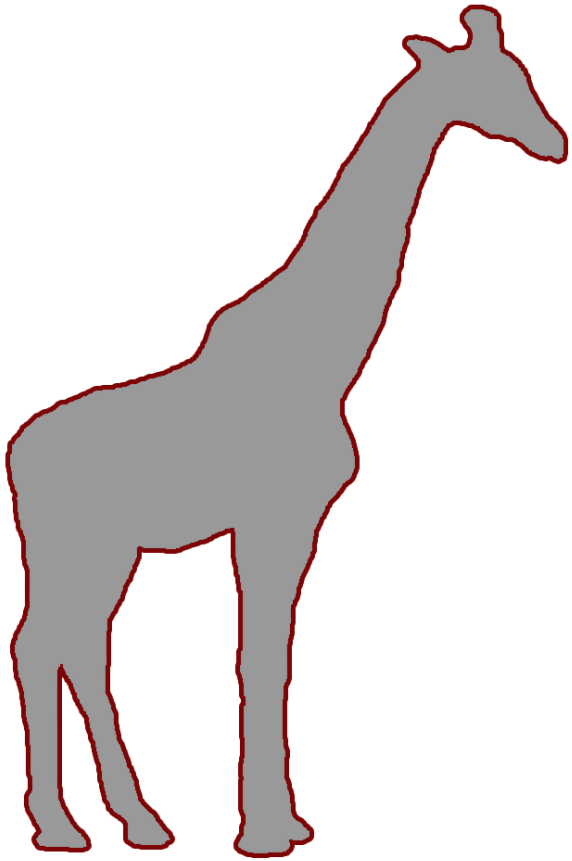
- Contour Approximation (e.g.: piecewise linear/cubic).
- Integer Medial Axis.
- Pruning.
- Skeleton vectorization.

Time Complexity

$$O(kn+N)$$

k: number of knots, n: contour length, N: image size

1. Contour Approximation of the boundary



- Select a threshold value T (distance from boundary to curve).
- Contour approximation using simple curves (e.g.: cubic or line segments).
- Assigns each boundary pixel to its curve.

An iterative procedure for the polygonal approximation of plane curves.
U. Ramer 1972
Time complexity: O(kn)
k: number of knots
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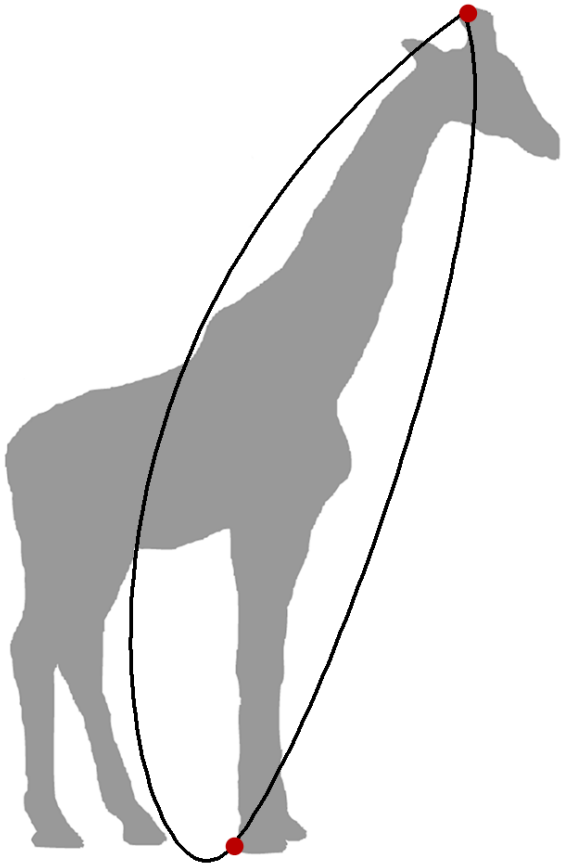

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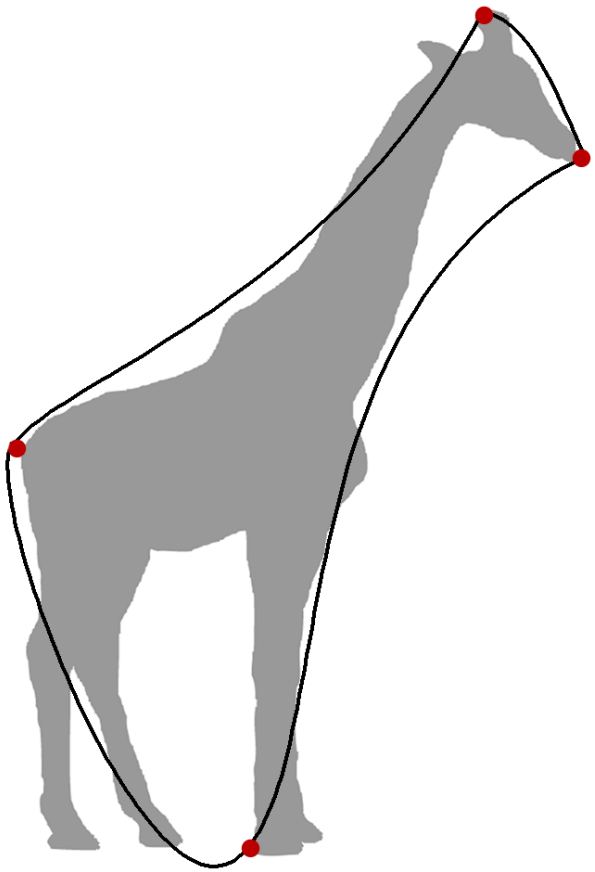

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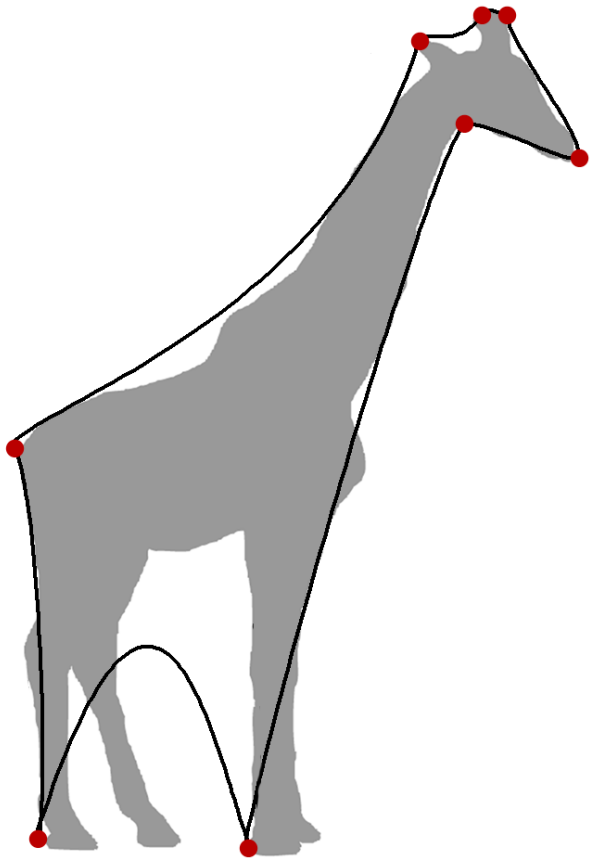

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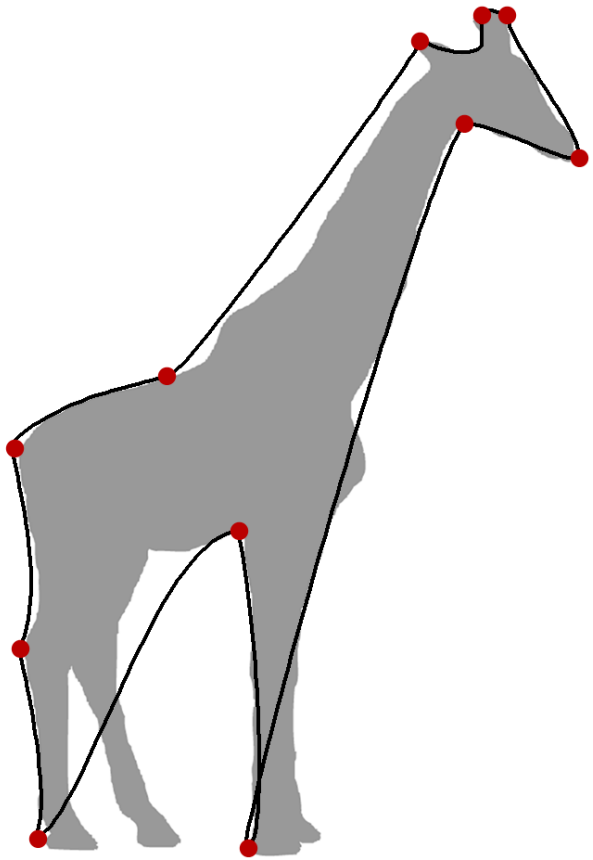

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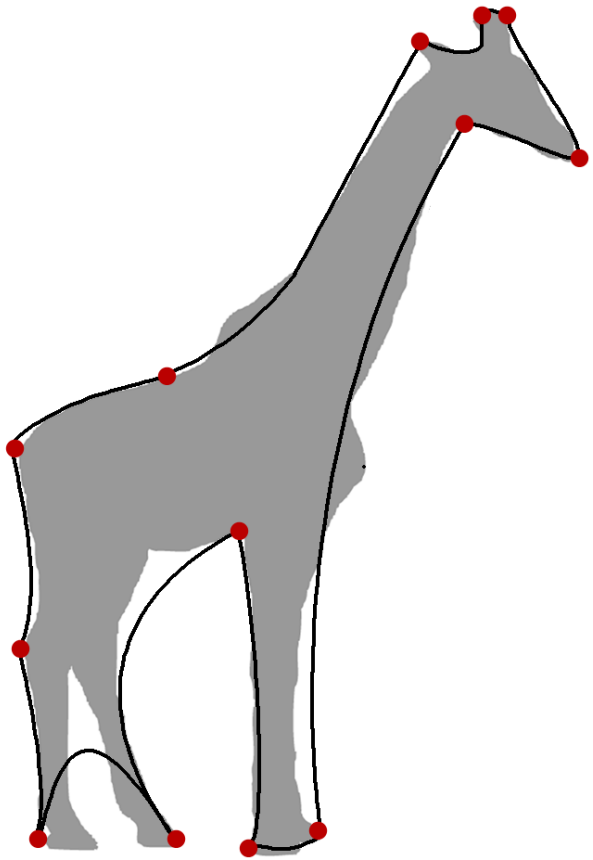

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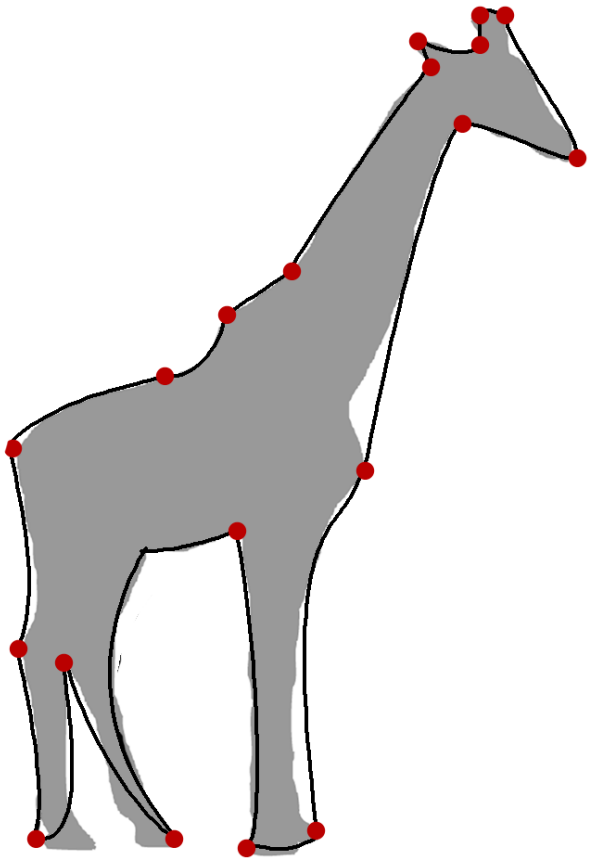

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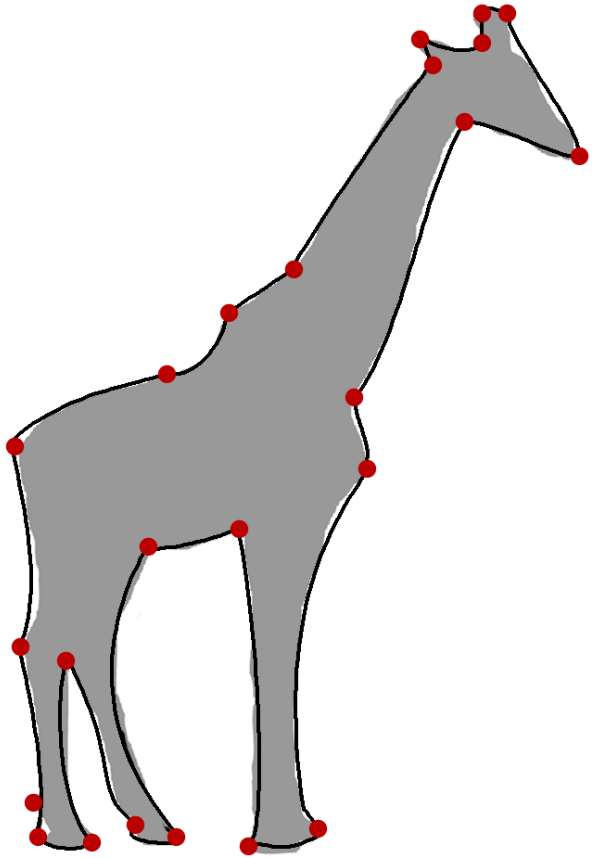

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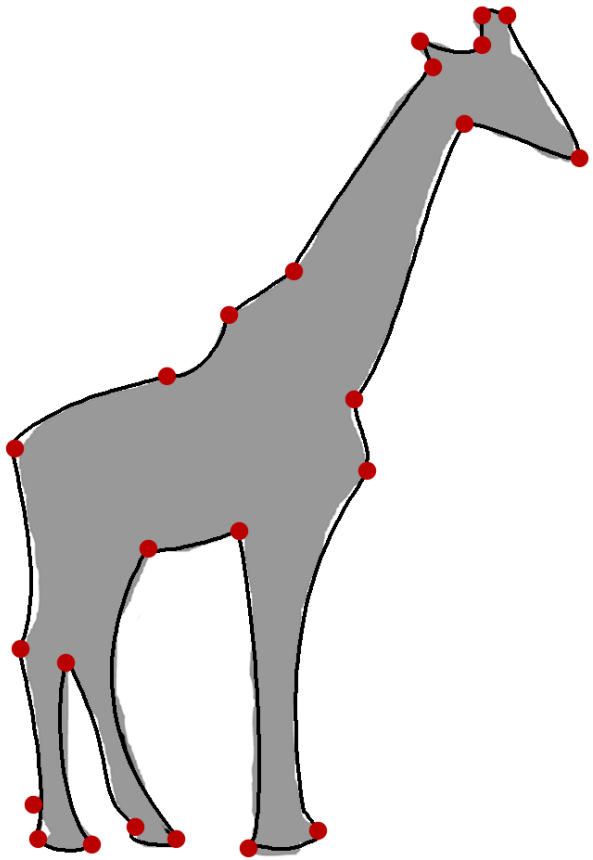

- Select a threshold value T (distance from boundary to curve).
- Contour approximation using simple curves (e.g.: cubic or line segments).
- Assigns each boundary pixel to its curve.

An iterative procedure for the polygonal approximation of plane curves.
U. Ramer 1972
Time complexity: O(kn)
k: number of knots
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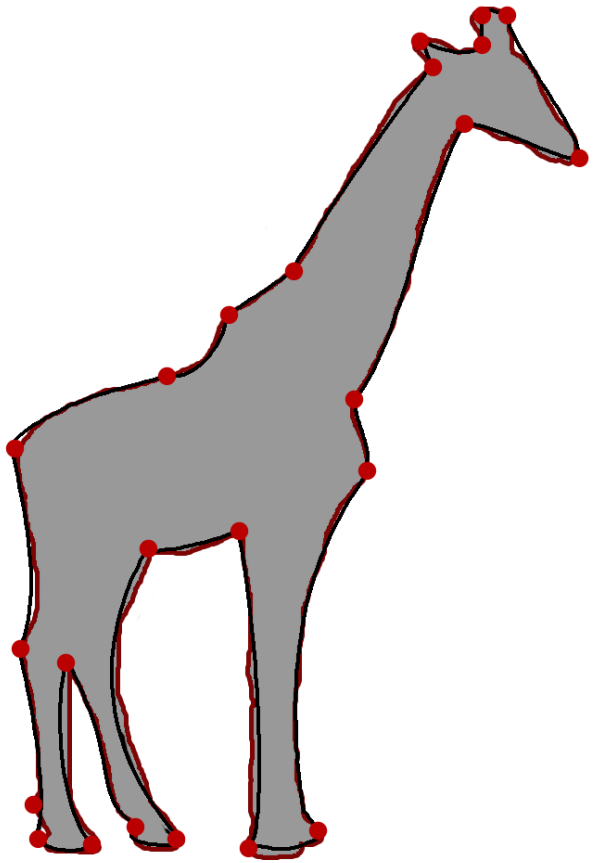

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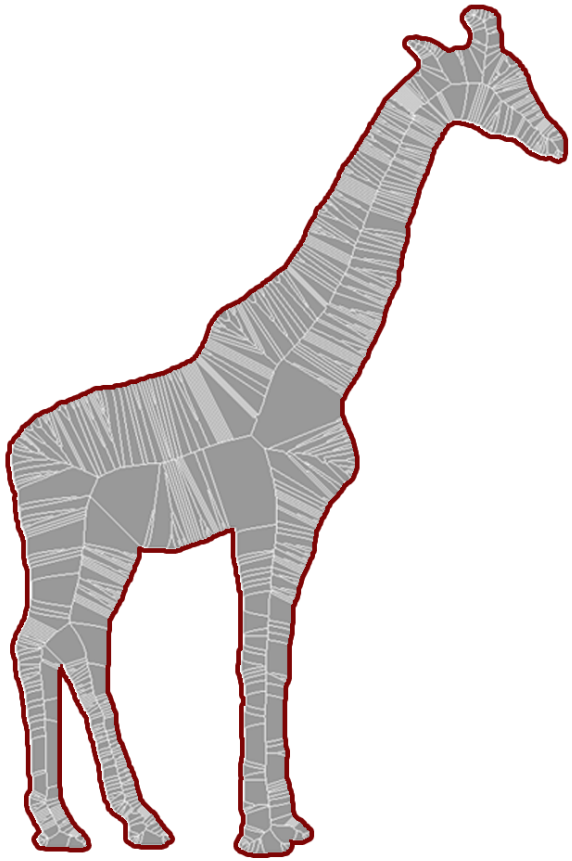

Euclidean skeletons of digital image and volume data in linear time by the integer medial axis transform
W.H. Hesselink and J.B. Roerdink 2007
Time complexity: O(N)
N: image size

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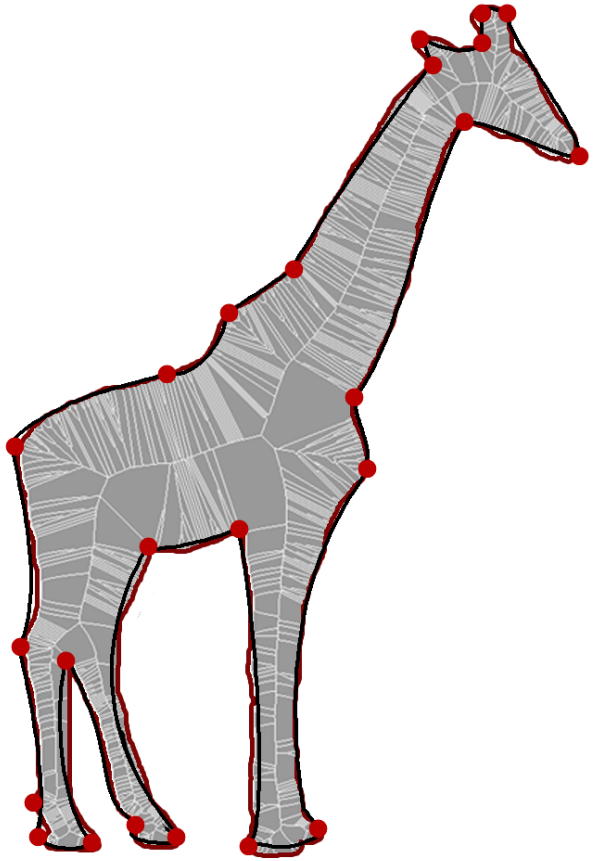

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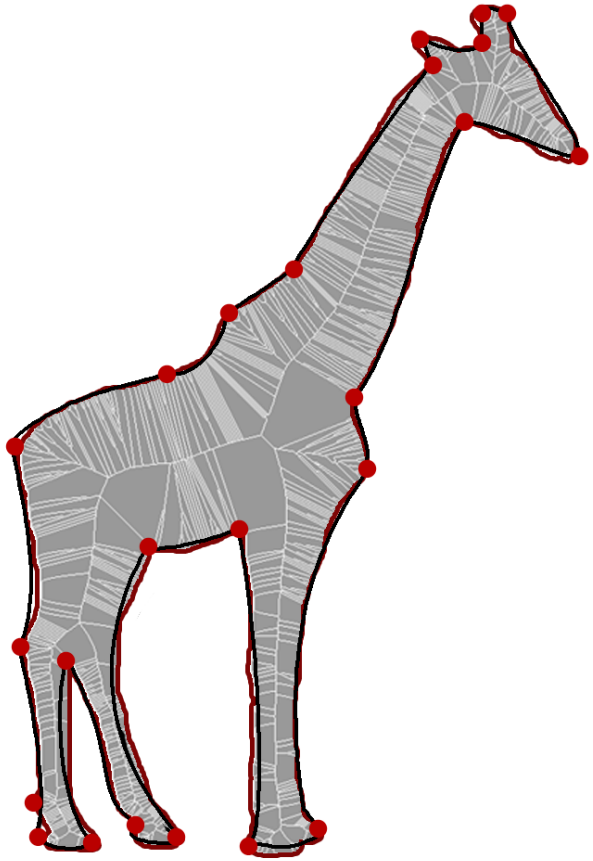

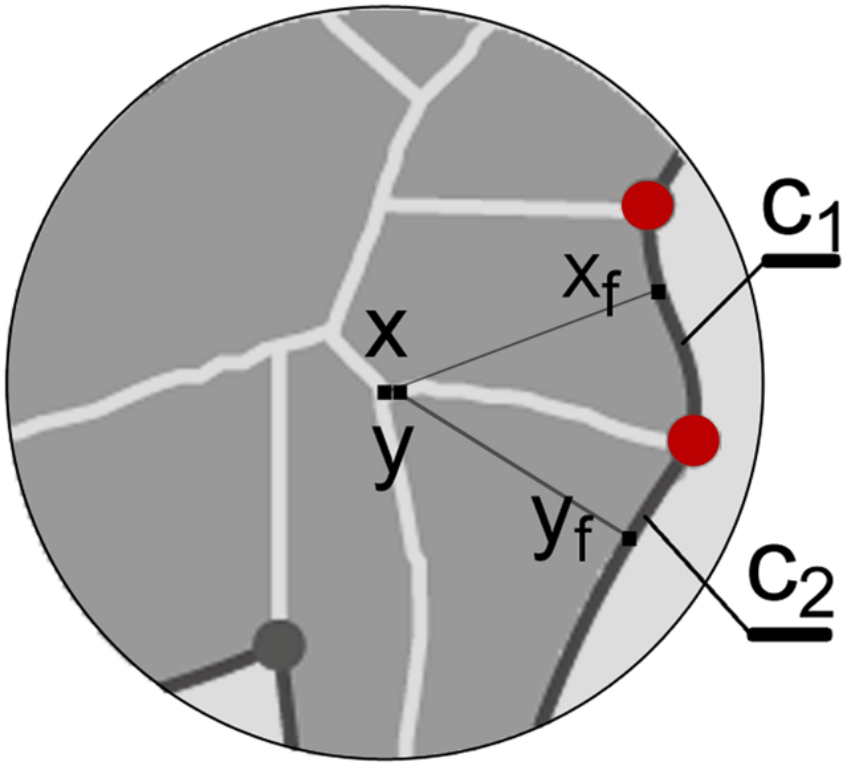

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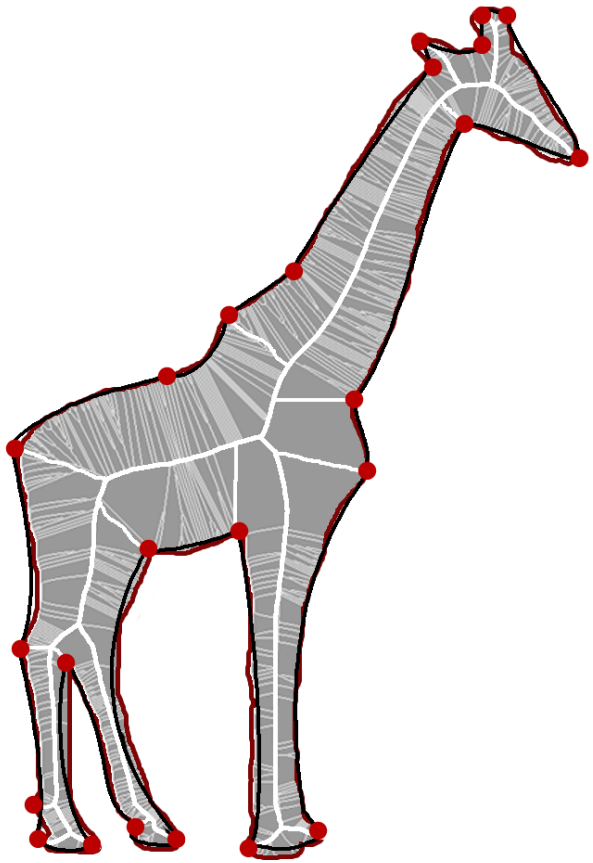

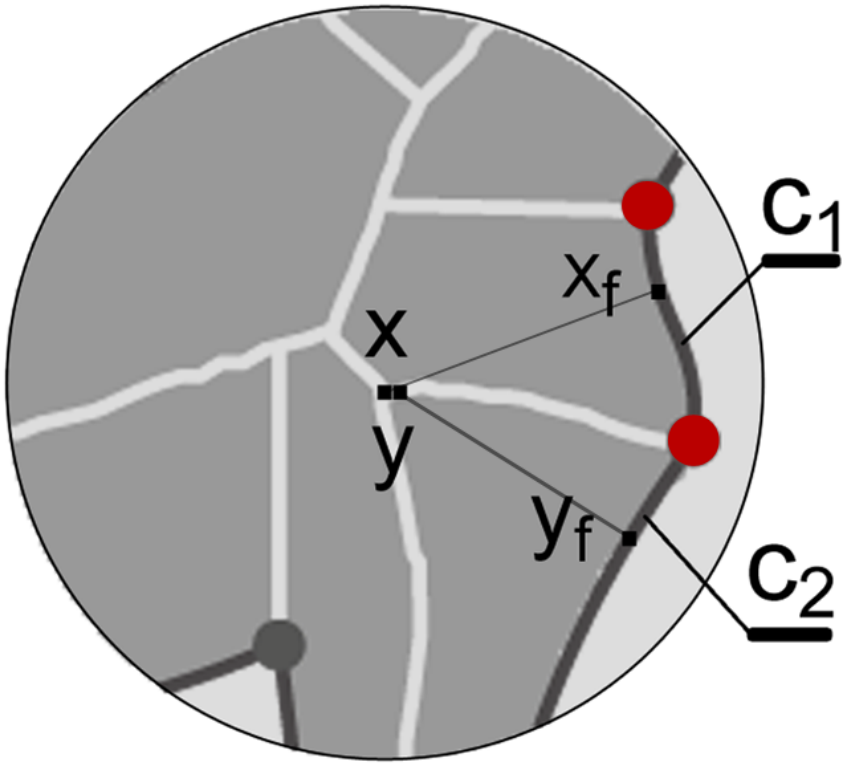

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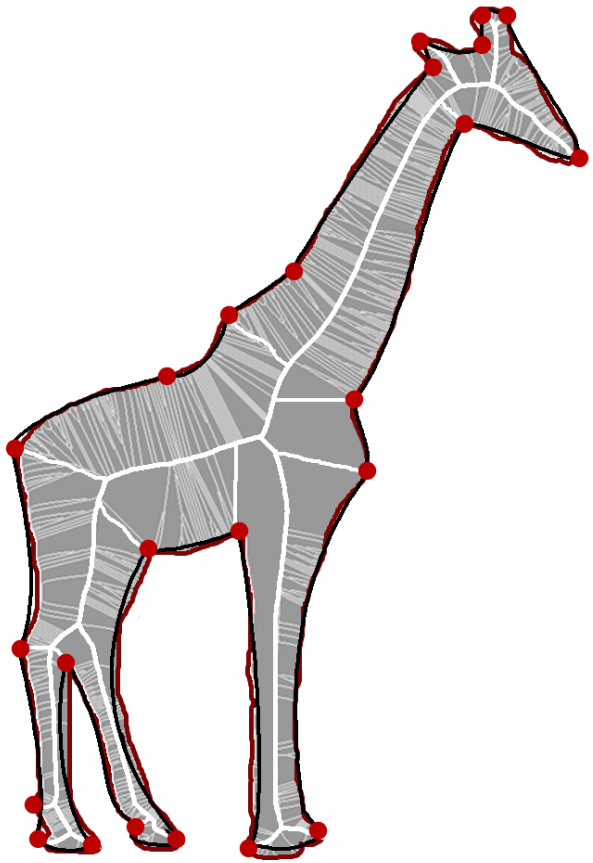

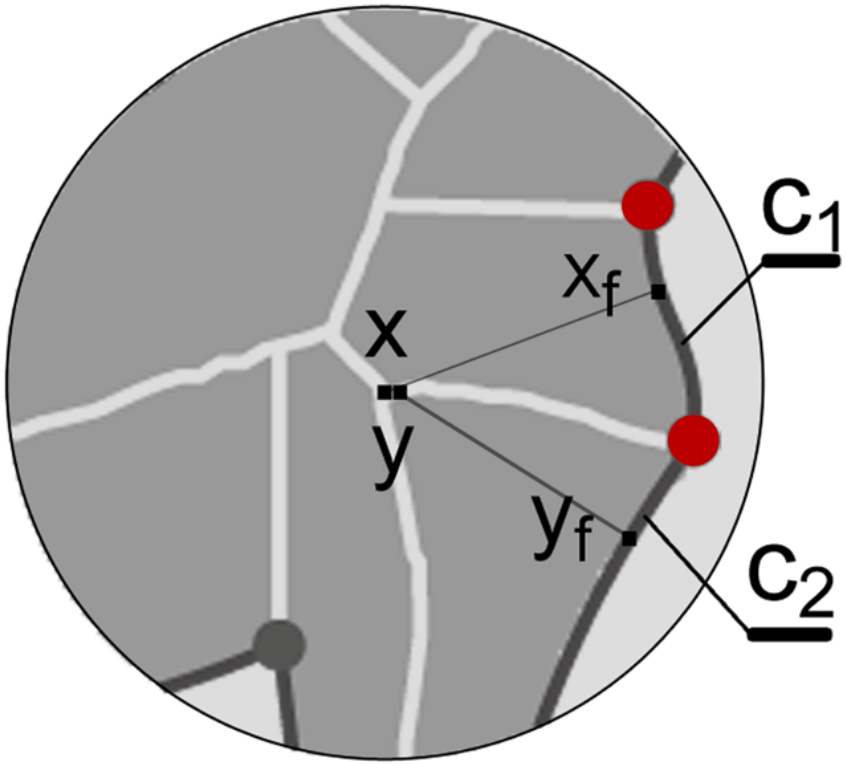

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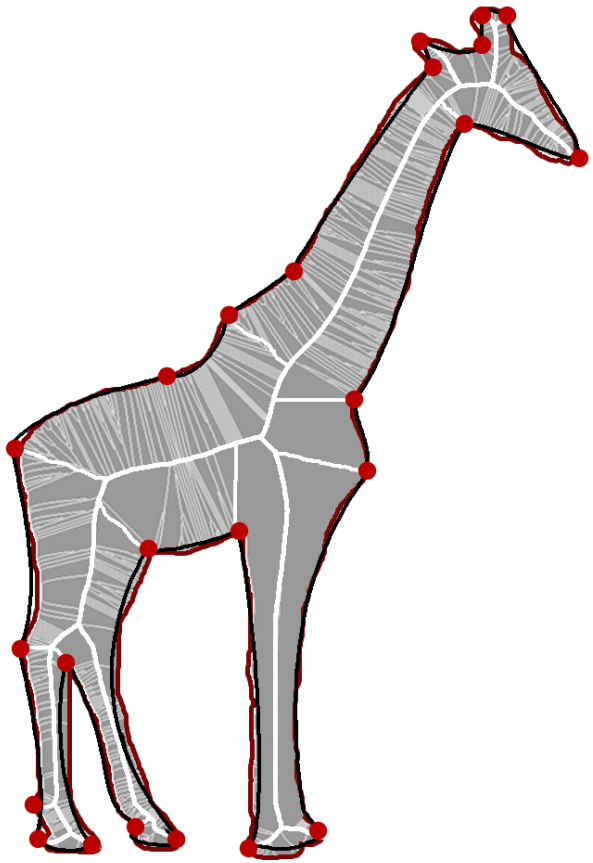

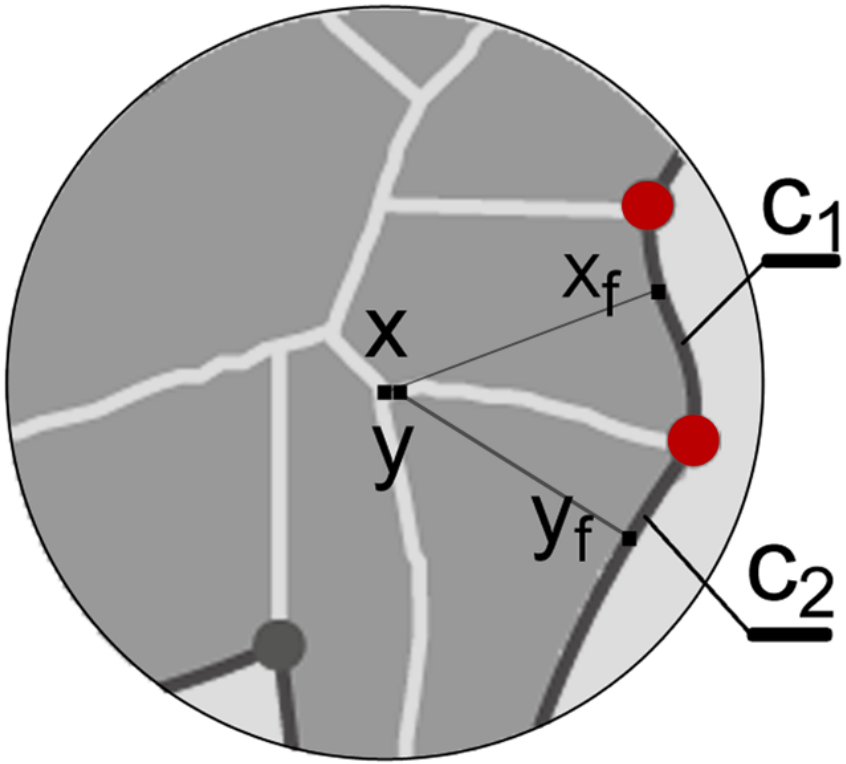

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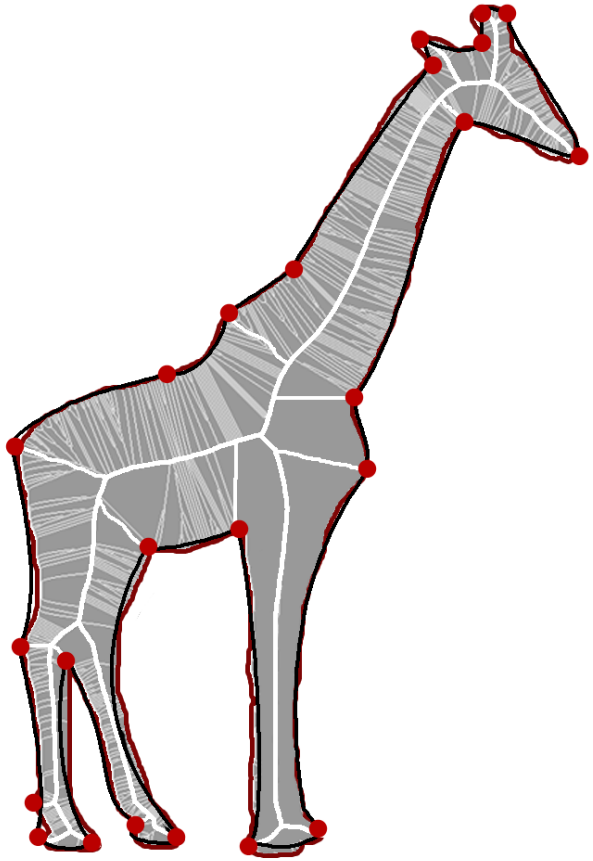

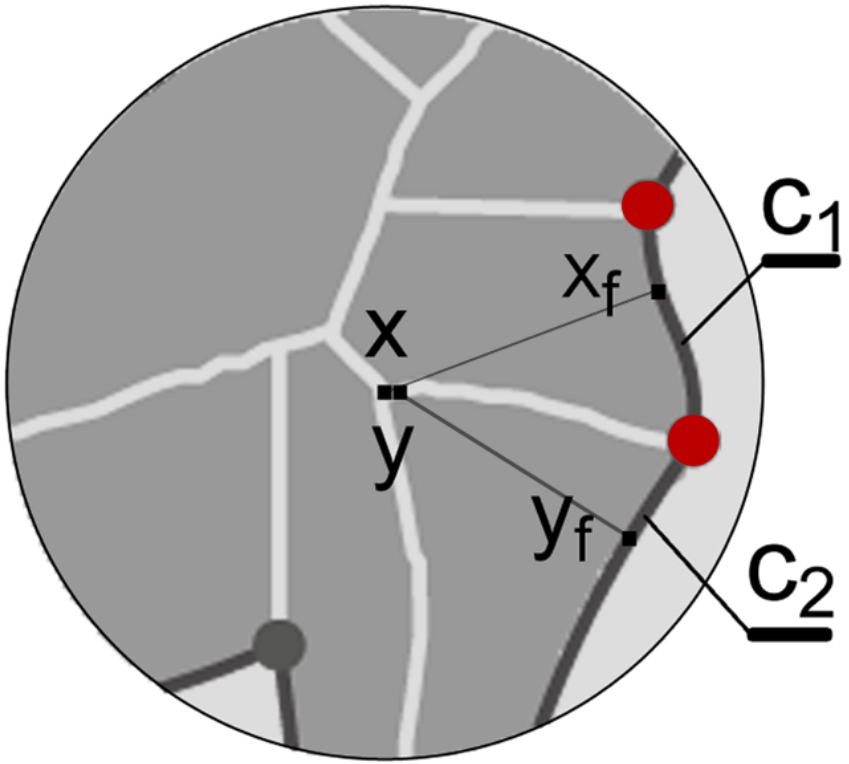

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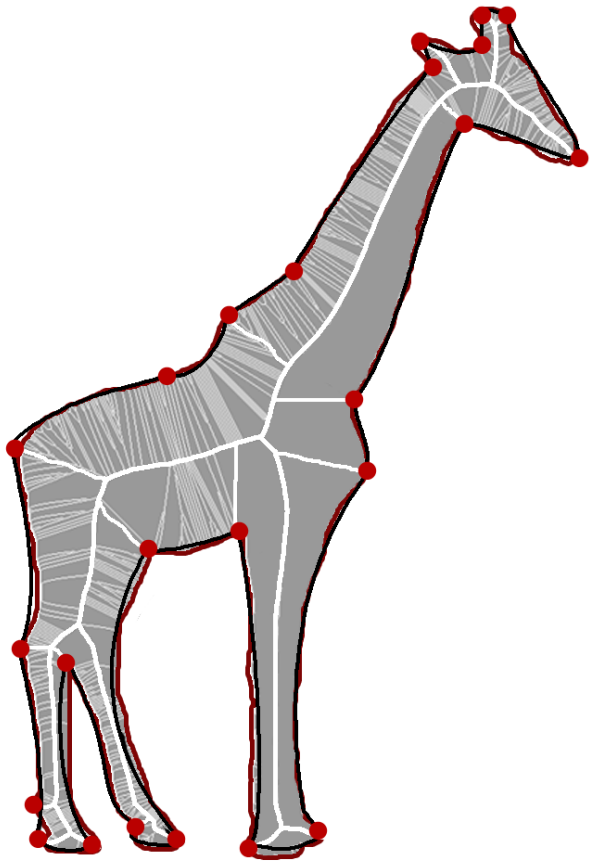

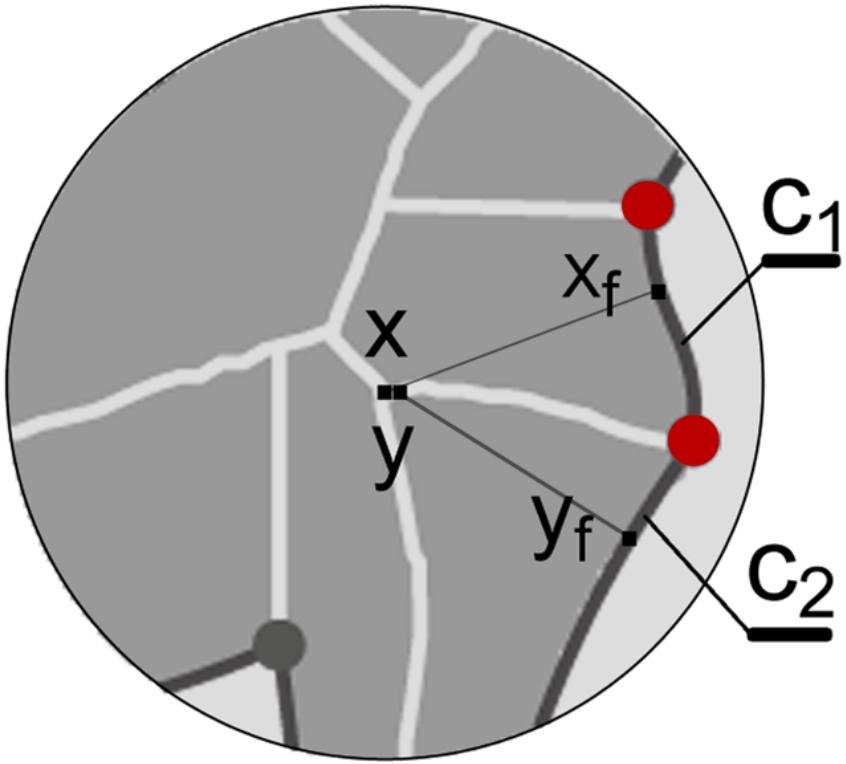

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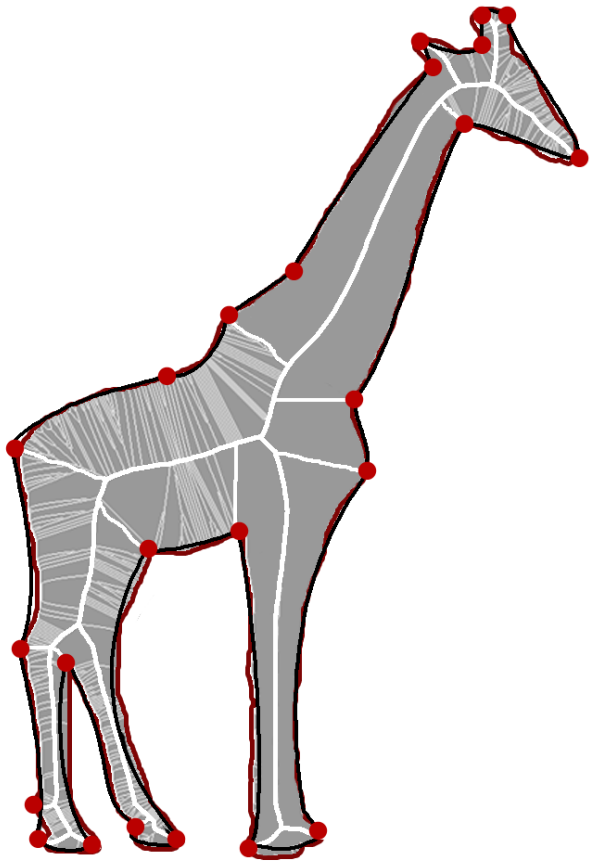

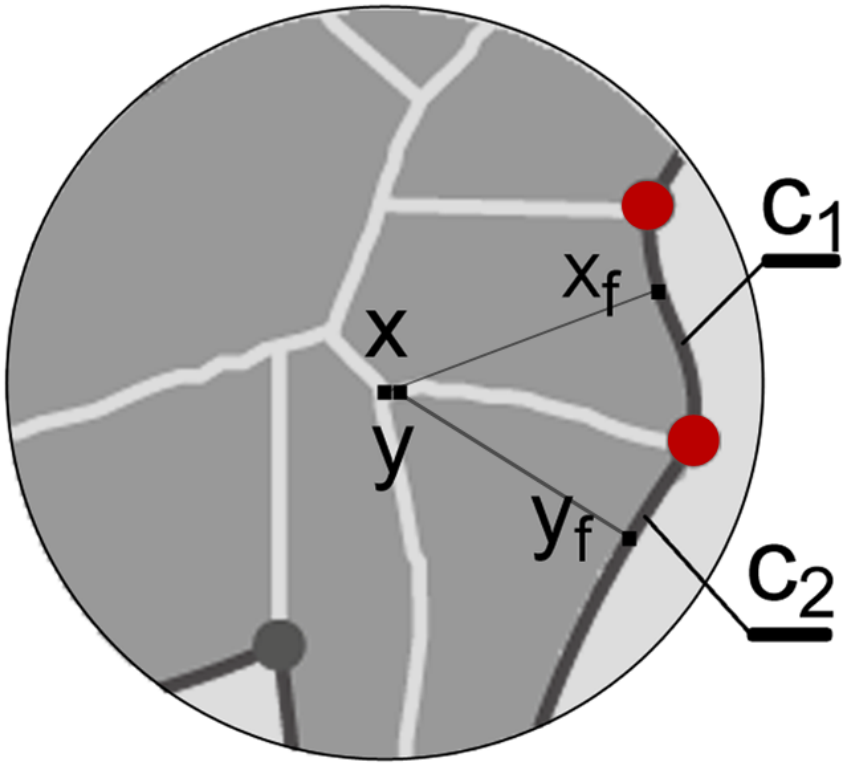

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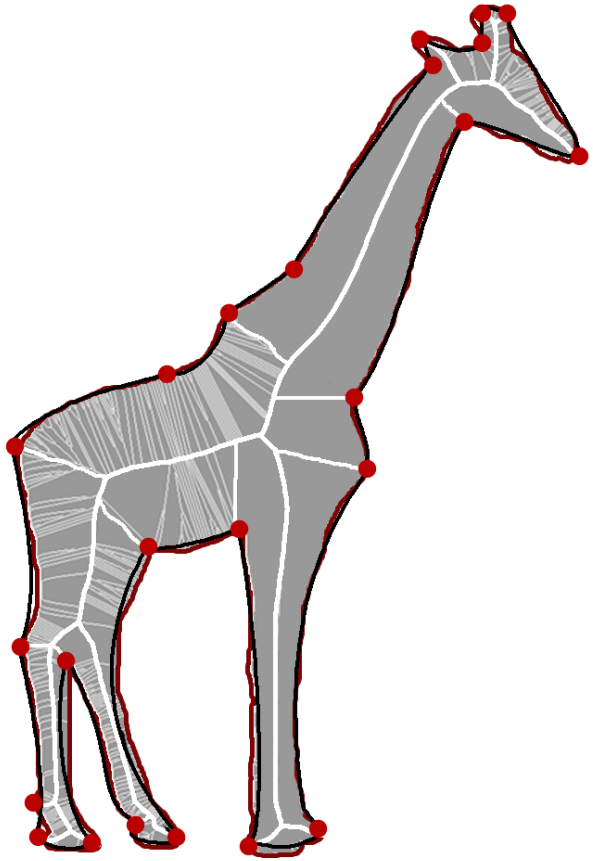

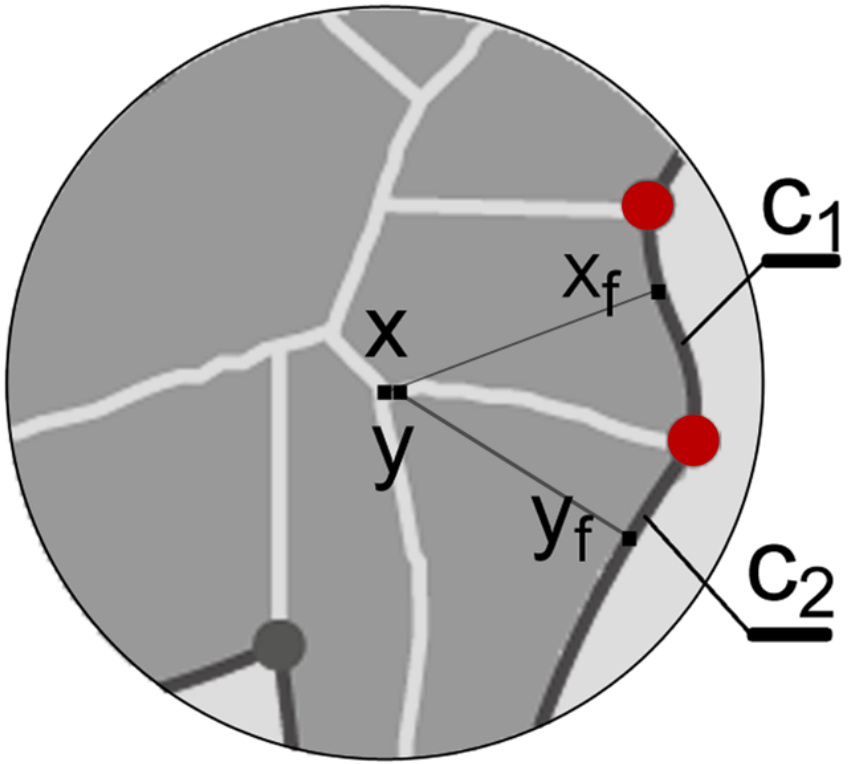

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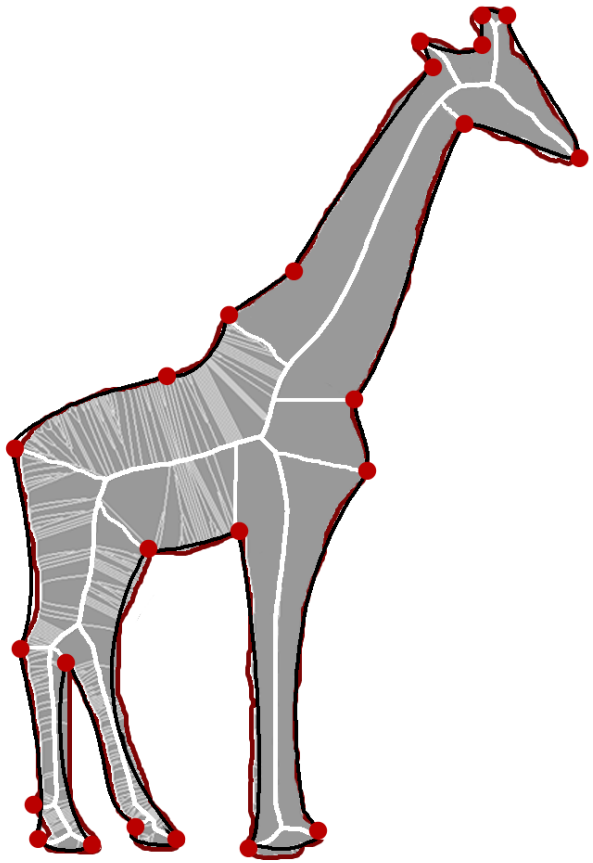

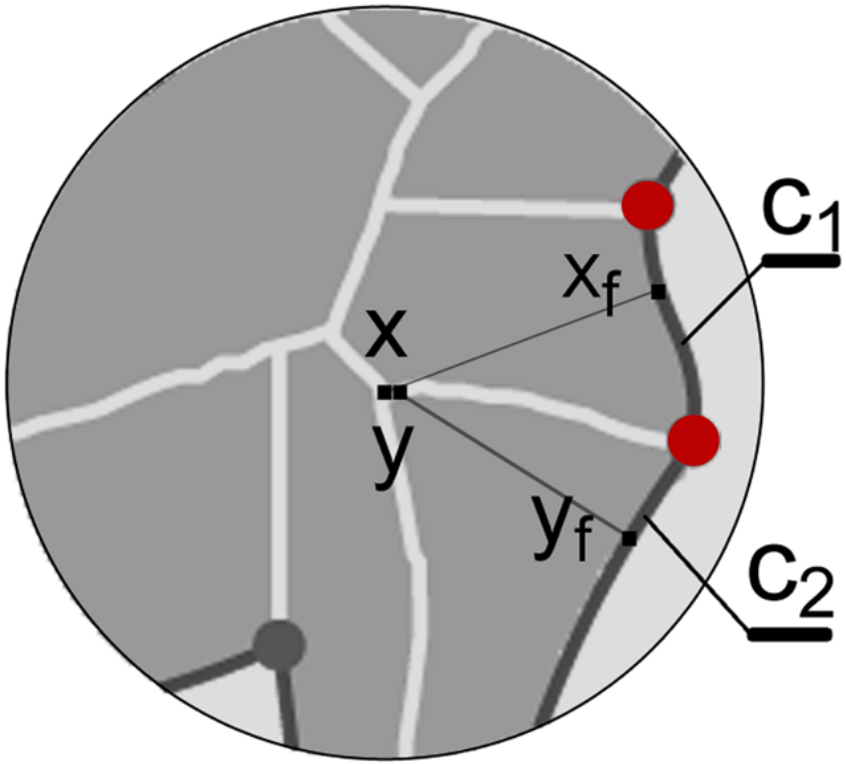

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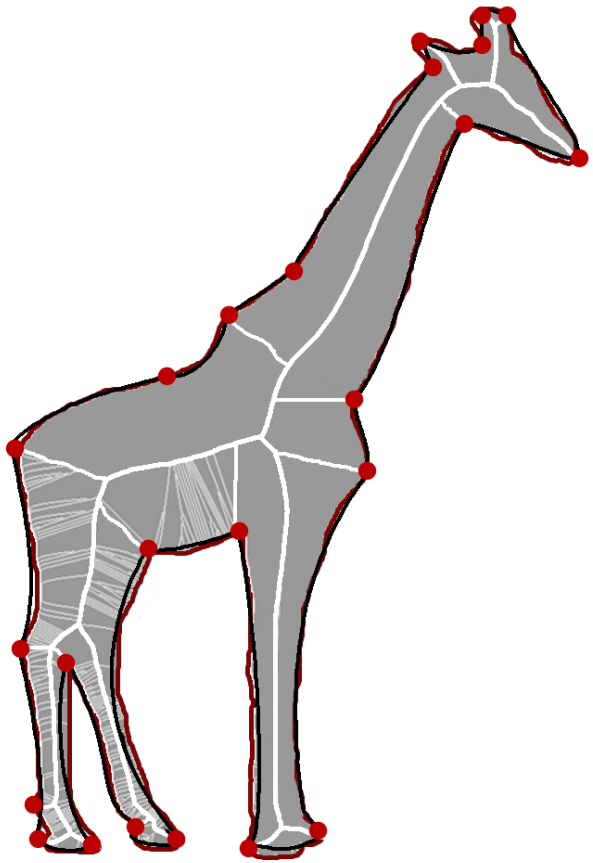

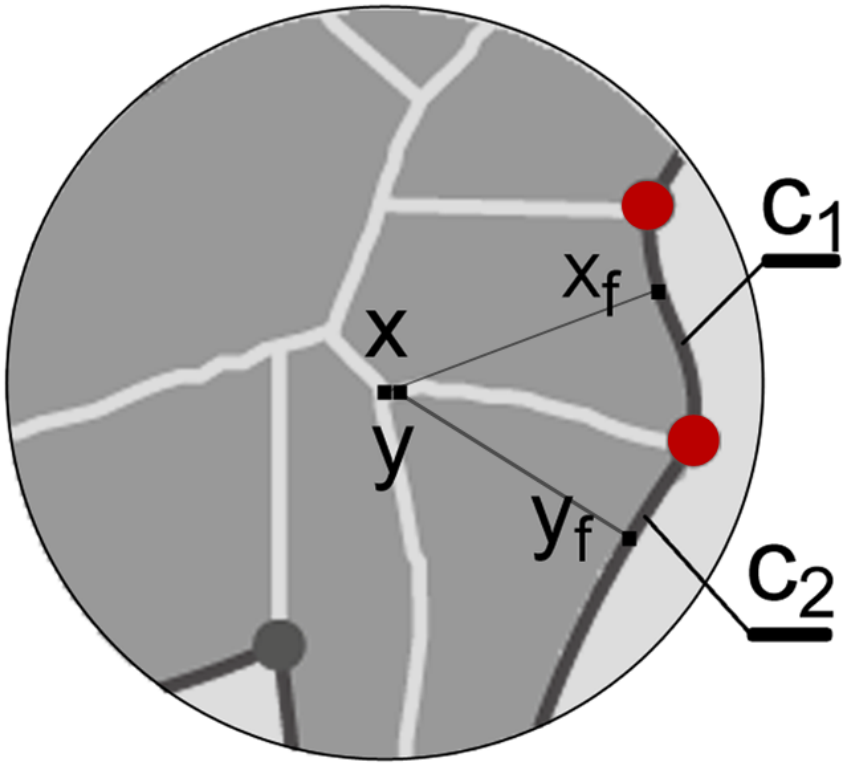

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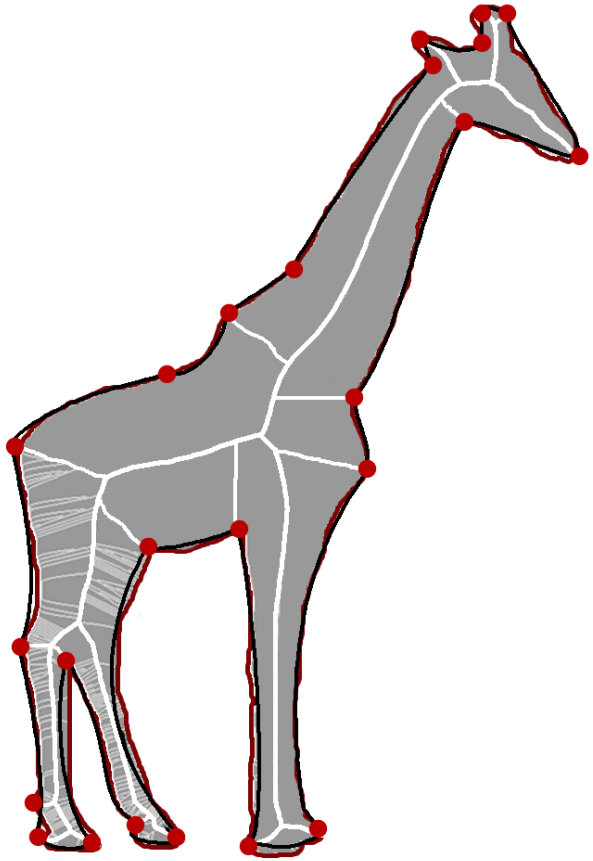

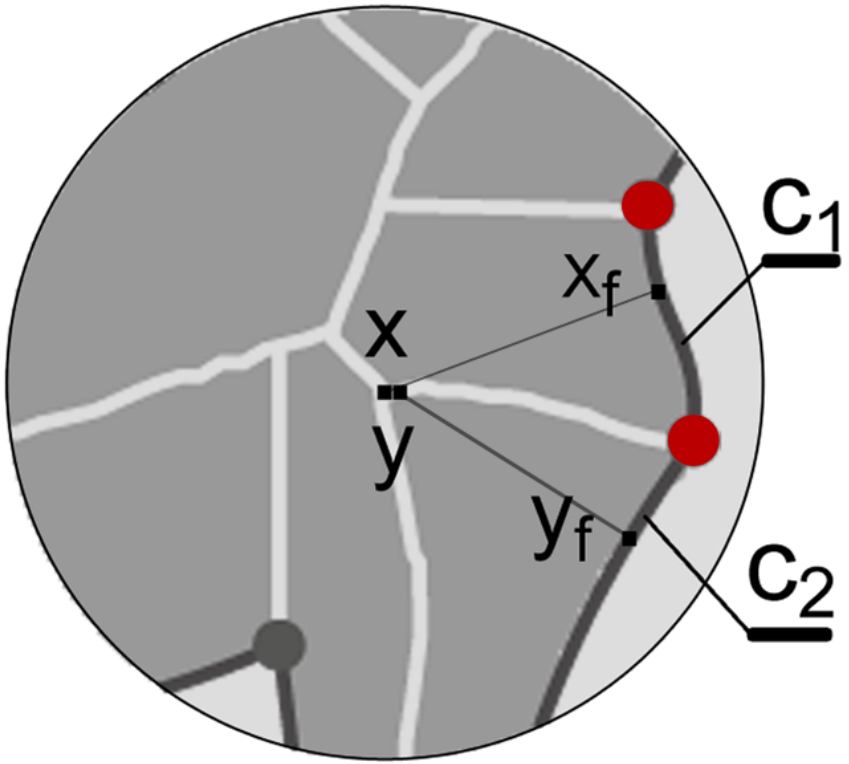

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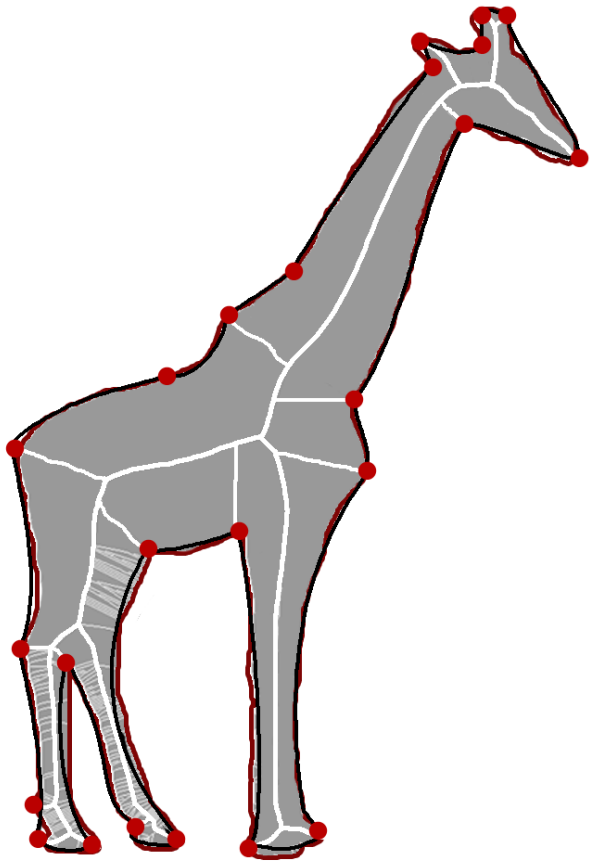

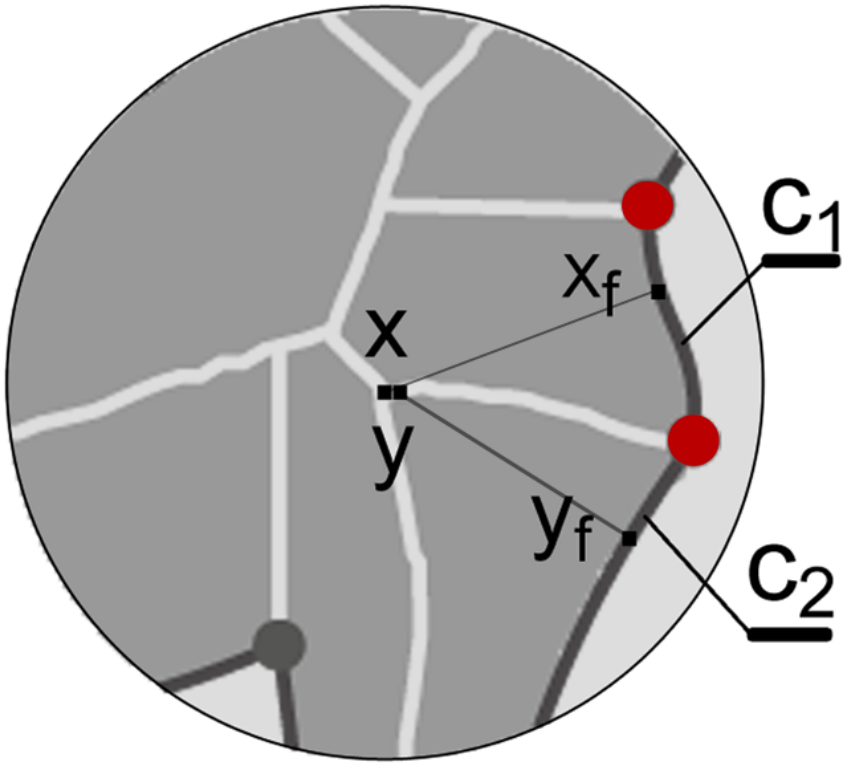

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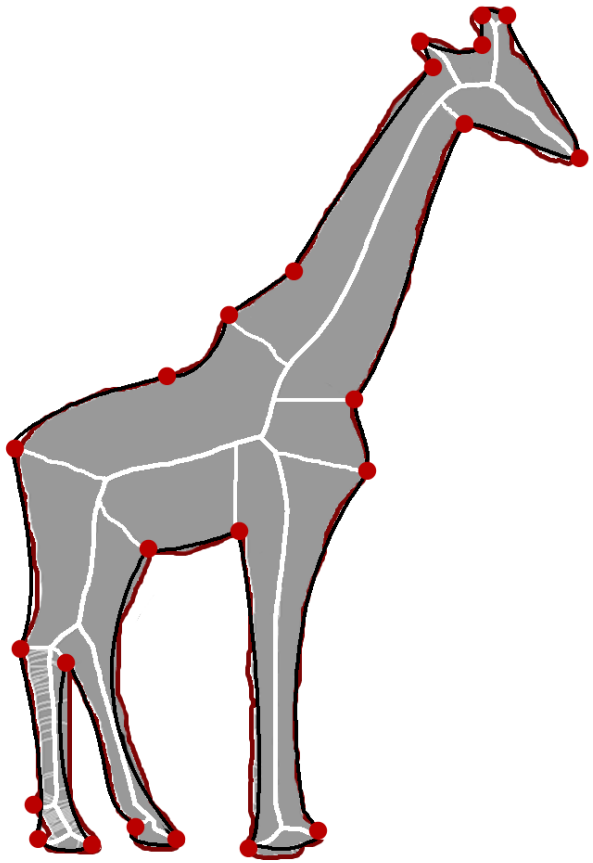

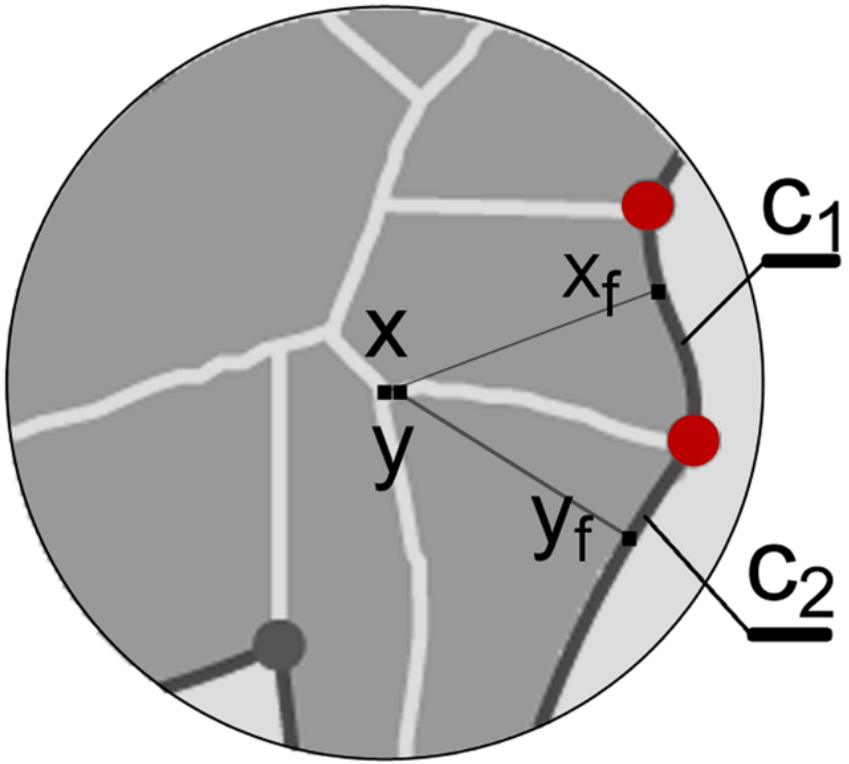

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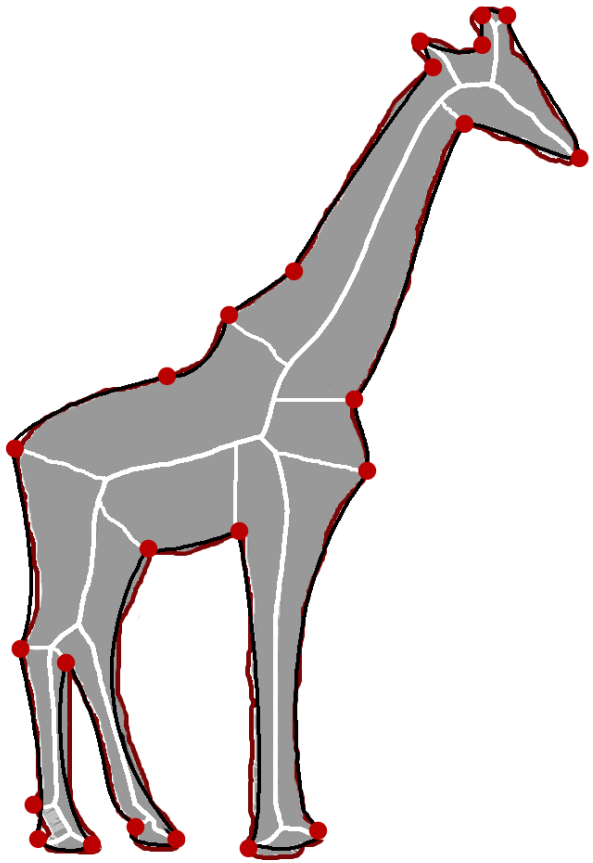

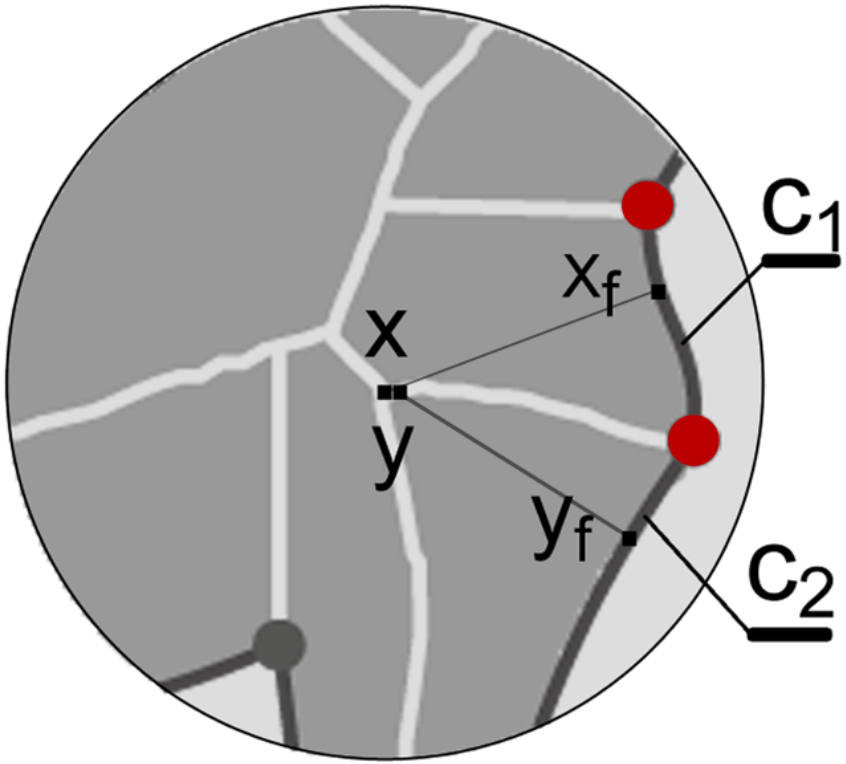

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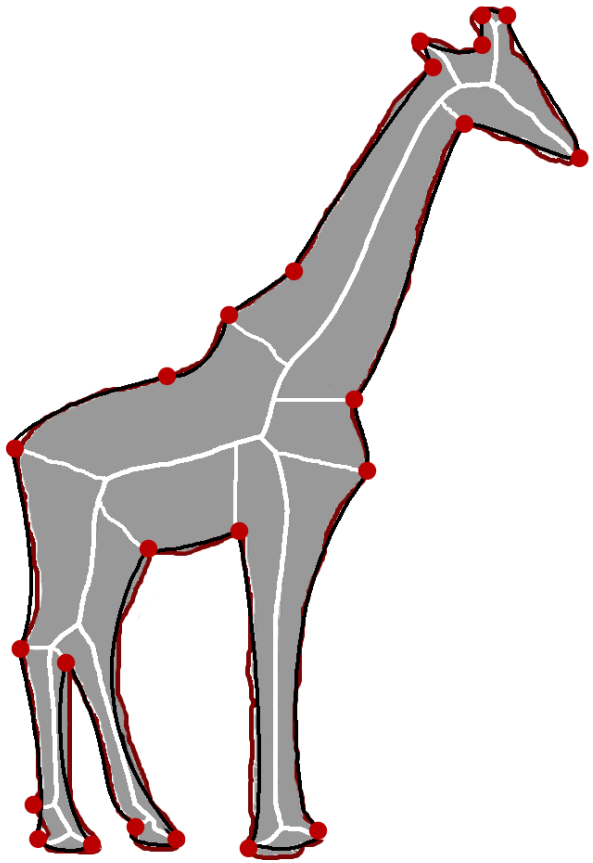

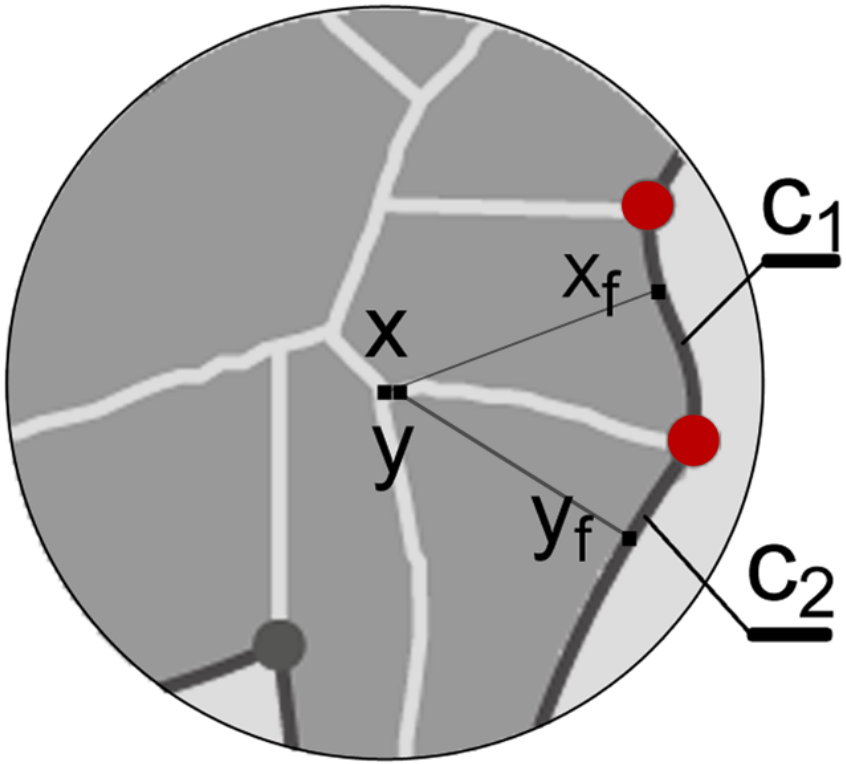

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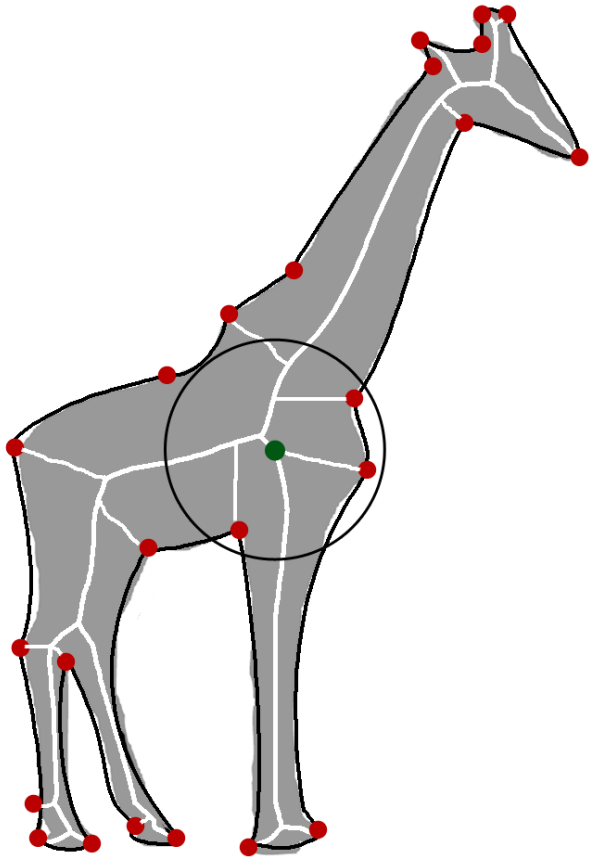
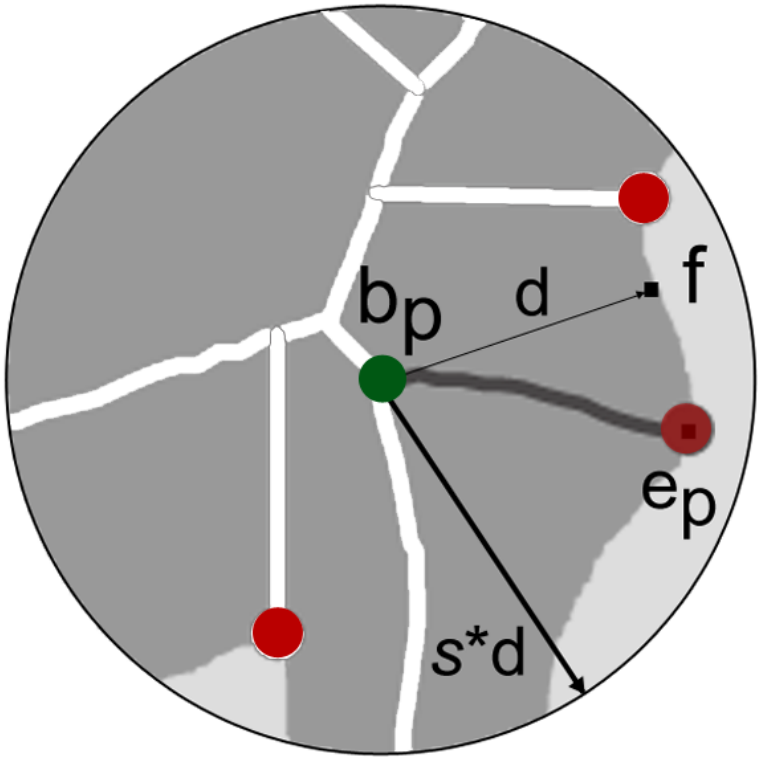
3. Check every branch chain for removal





Time complexity: O(n)
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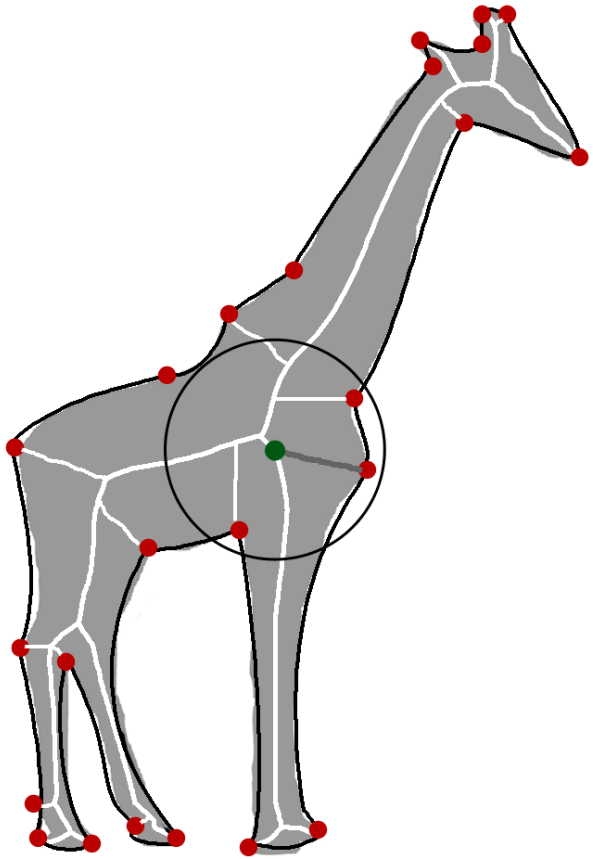

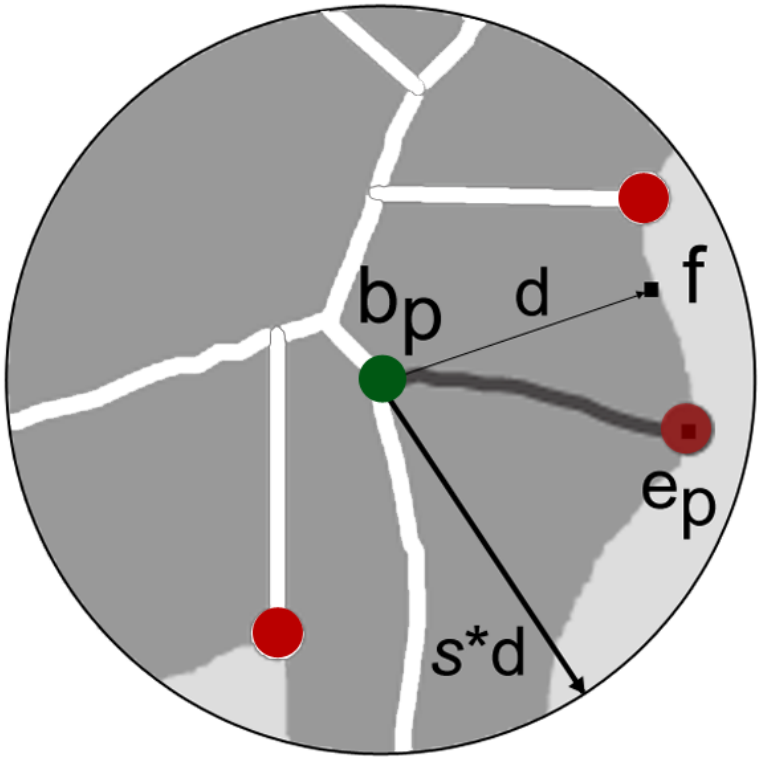

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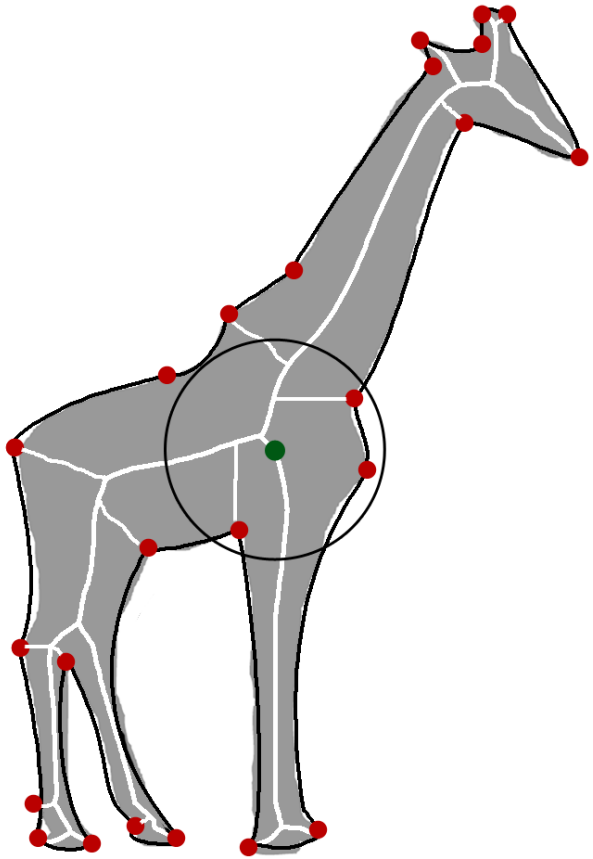

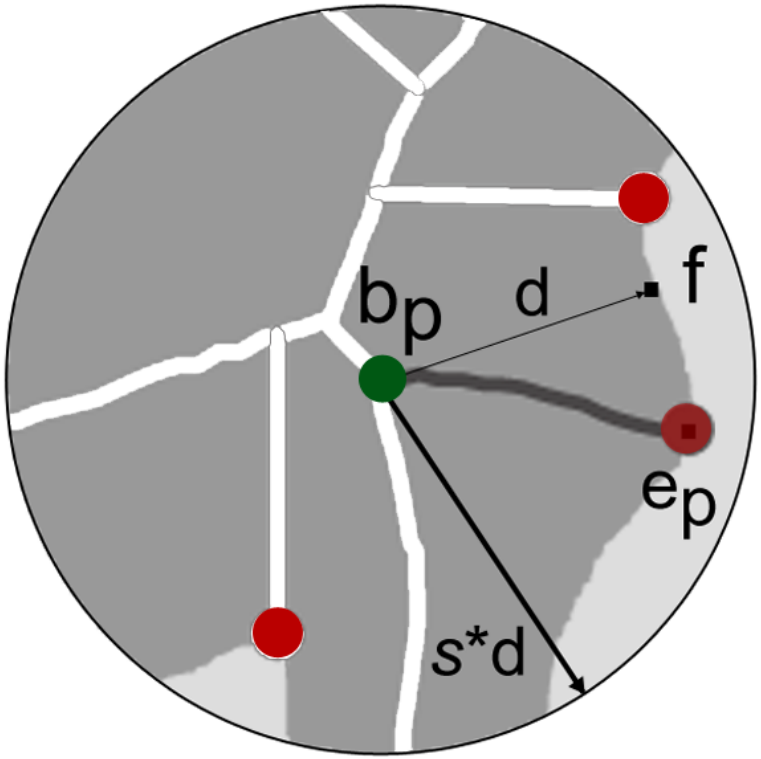

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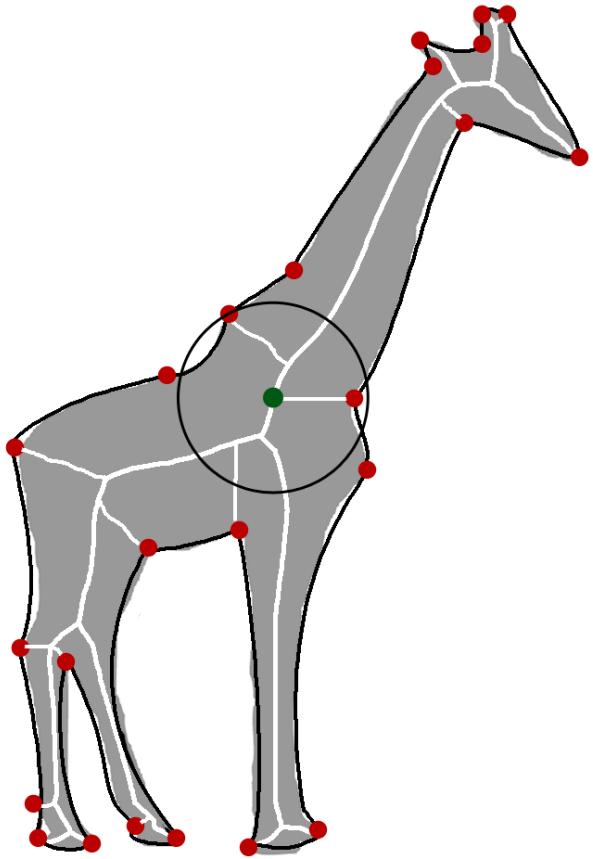

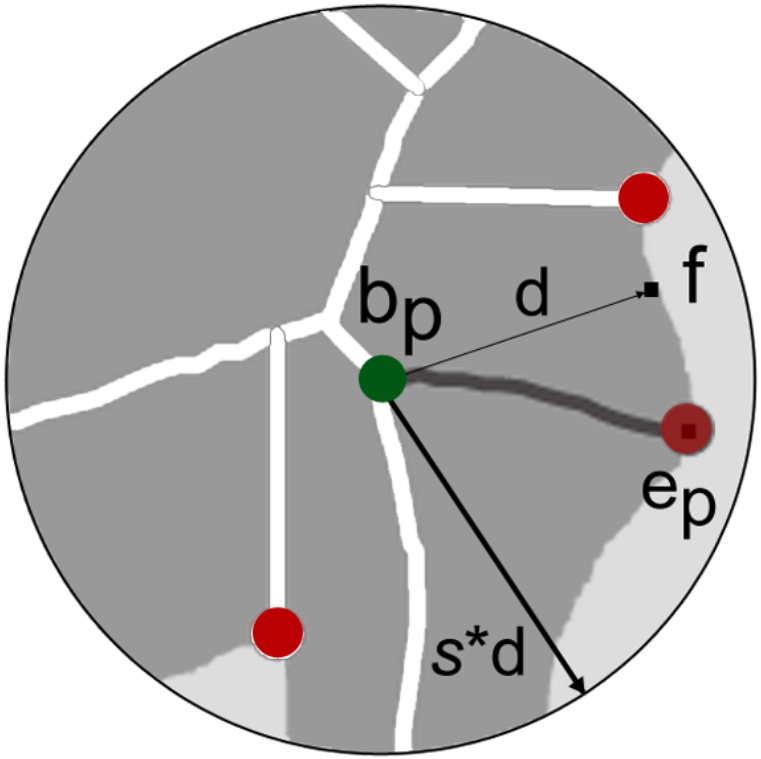

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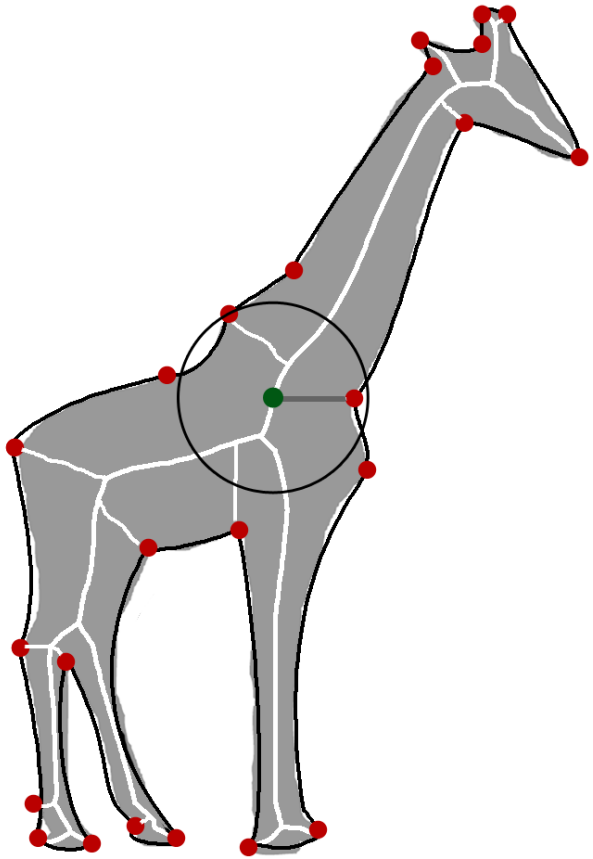

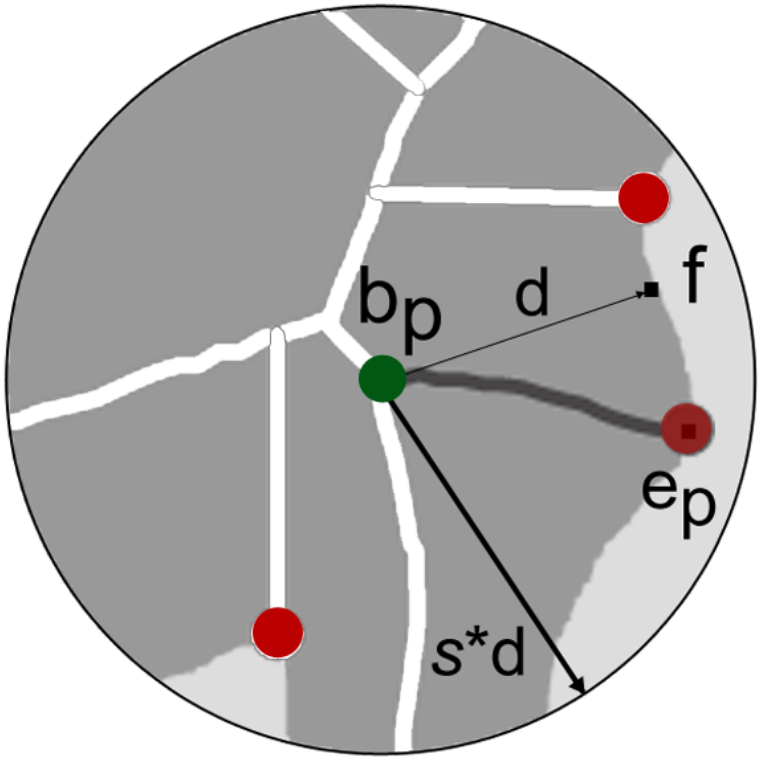

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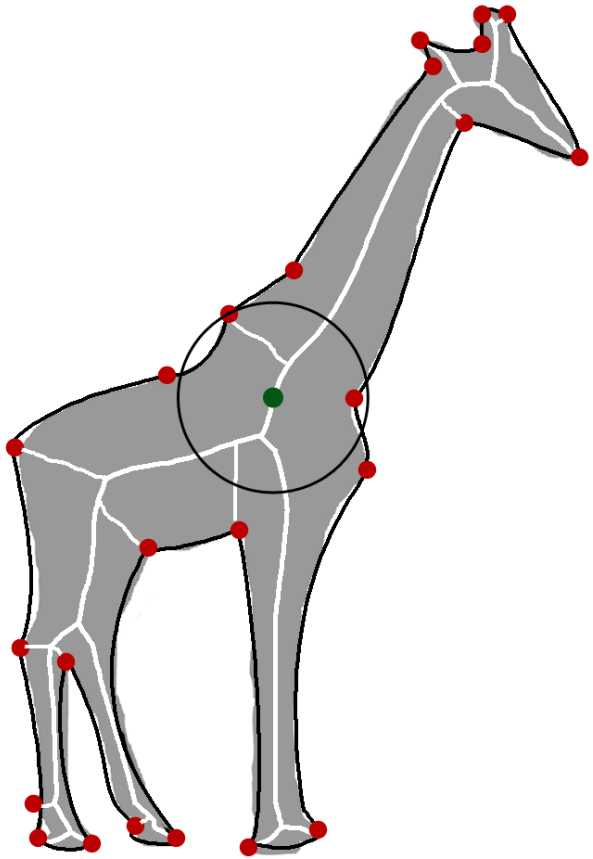

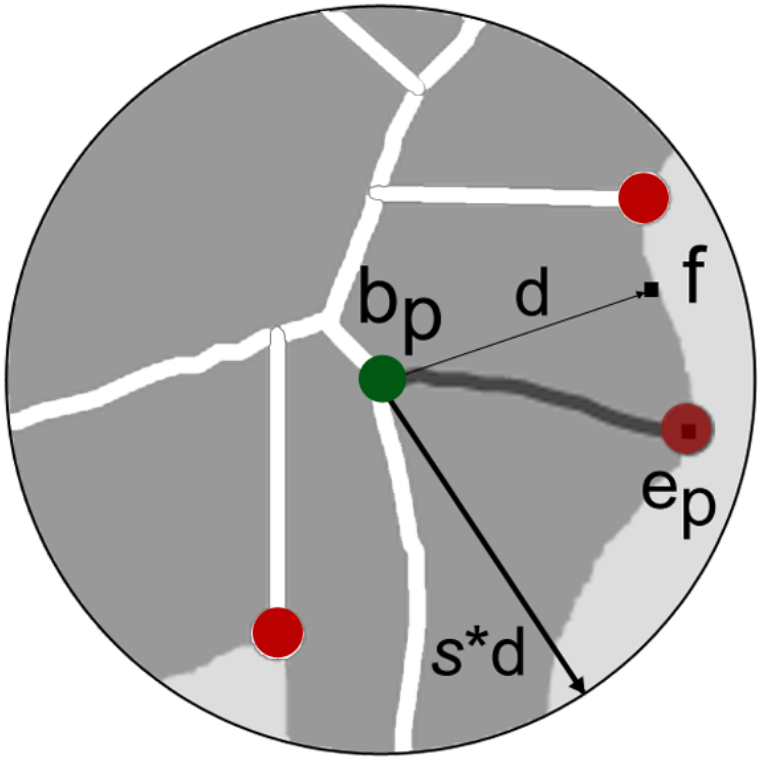

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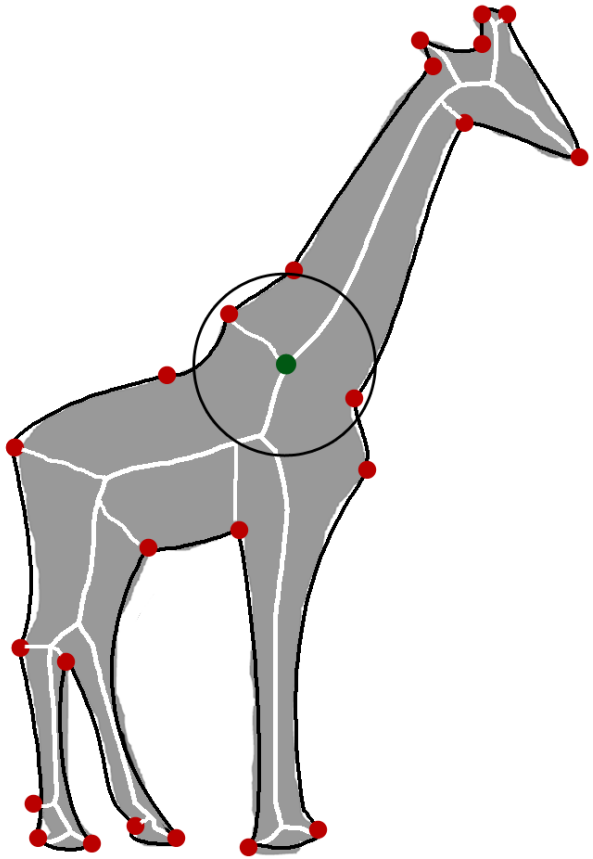

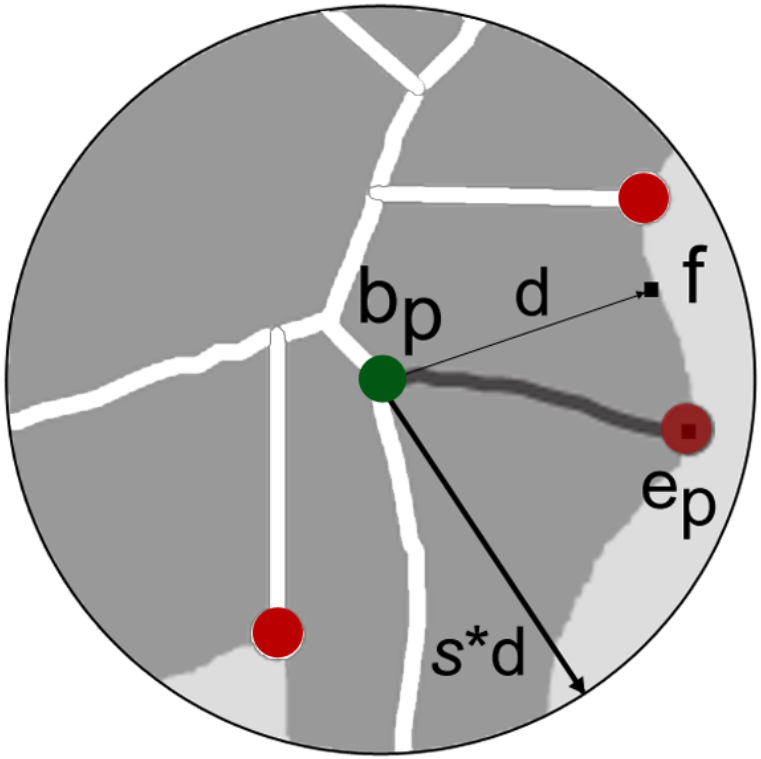

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n: skeleton pixels

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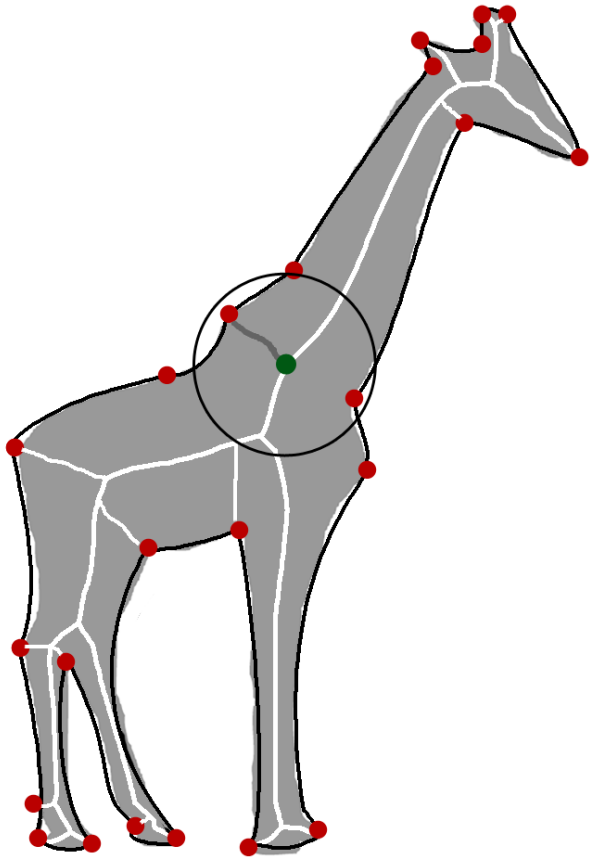
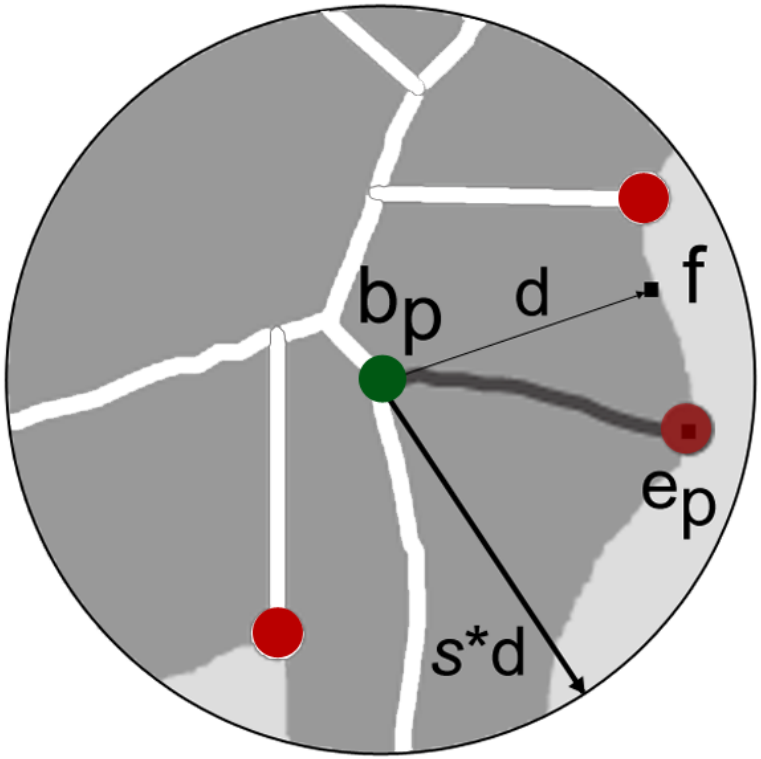
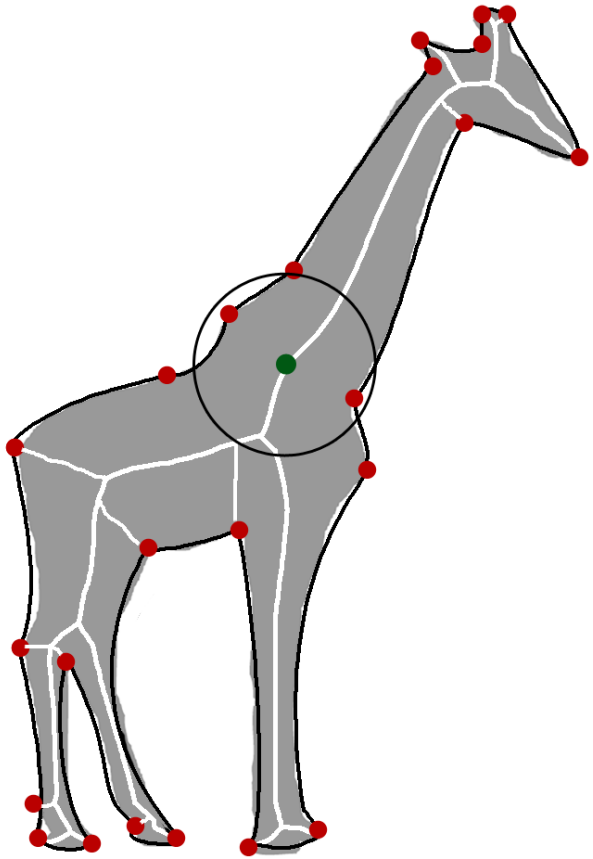
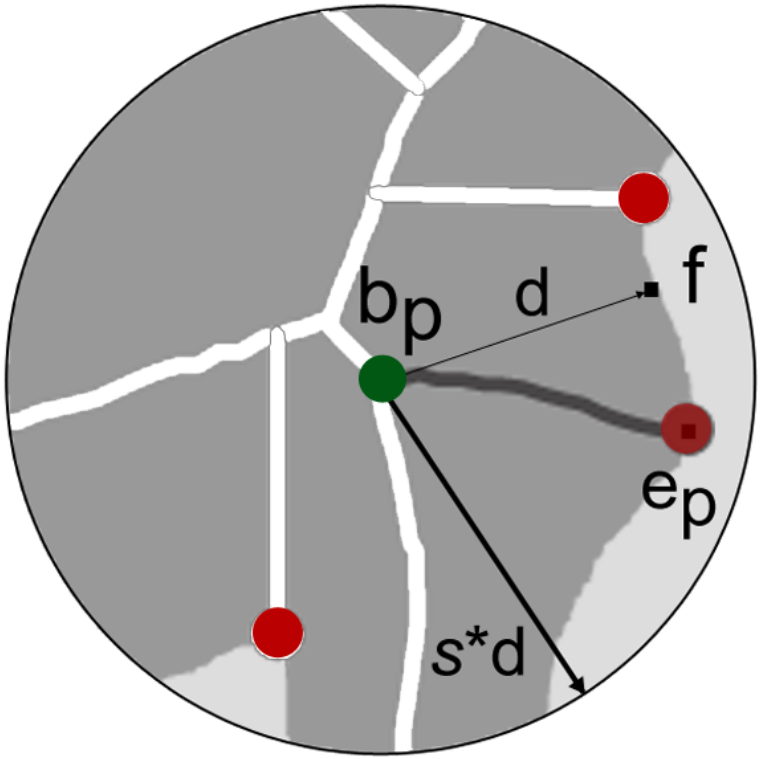




Time complexity: O(n)
n: skeleton pixels

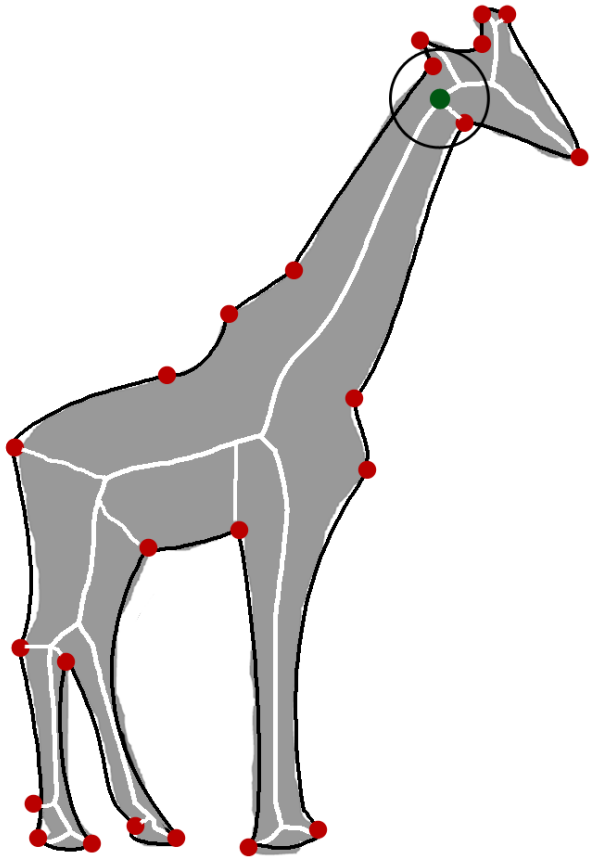
3. Check every branch chain for removal

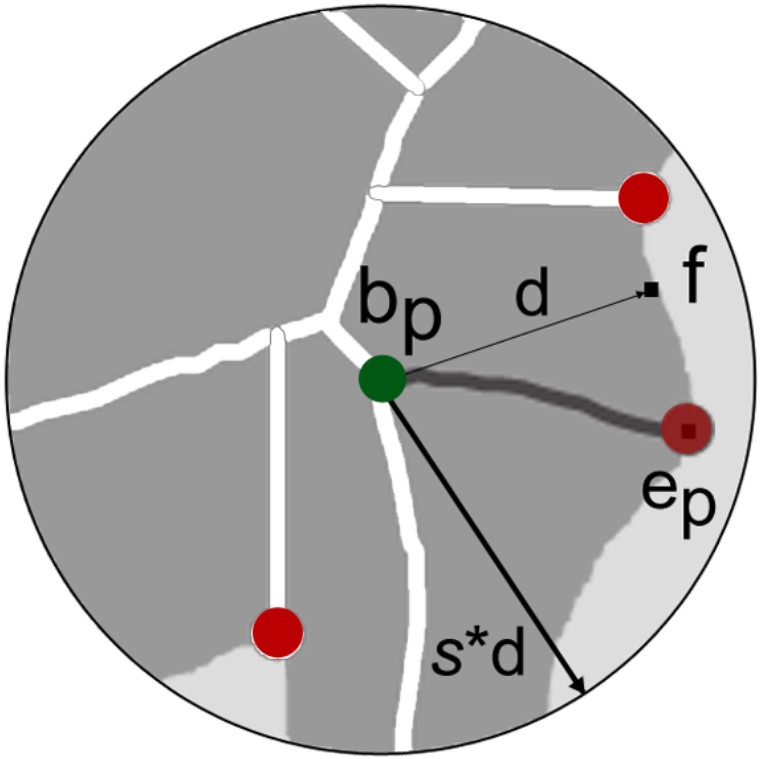




Time complexity: O(n)
n: skeleton pixels

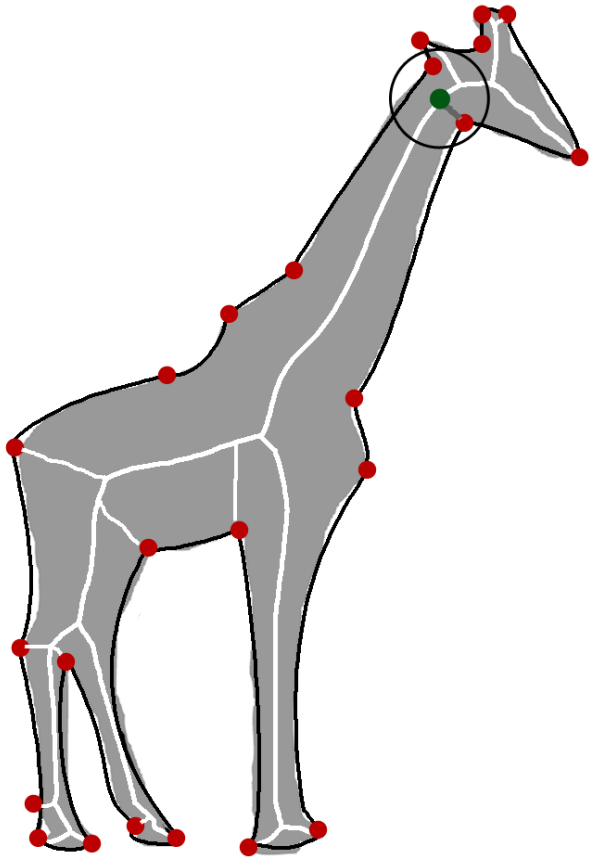
3. Check every branch chain for removal

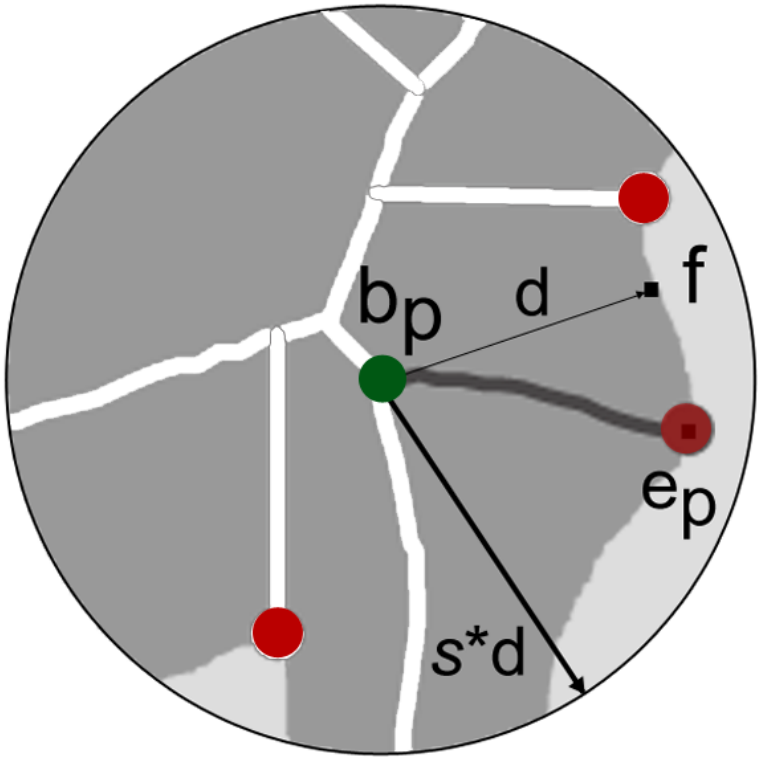




Time complexity: O(n)
n: skeleton pixels

3. Check every branch chain for removal





Time complexity: O(n)
n: skeleton pixels

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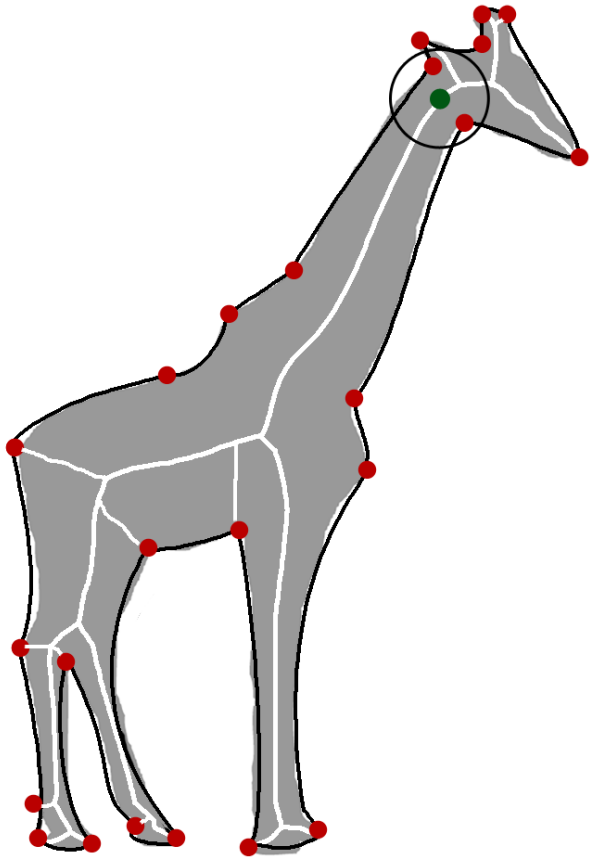

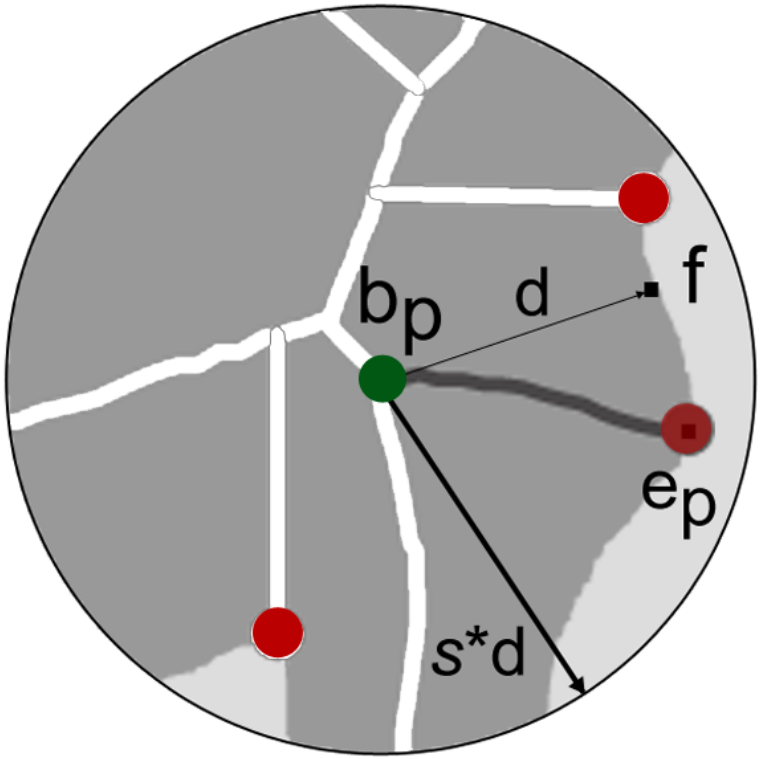

Time complexity: O(n)
n: skeleton pixels

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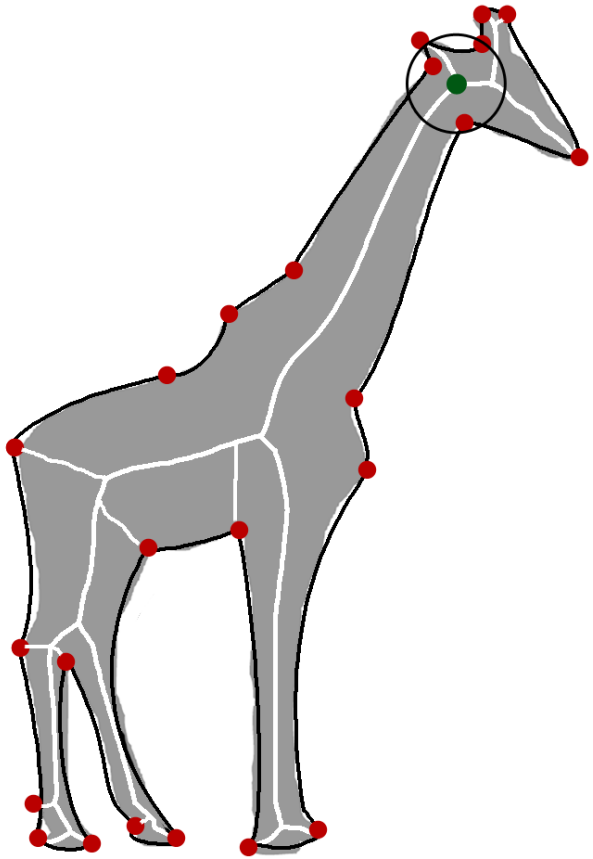

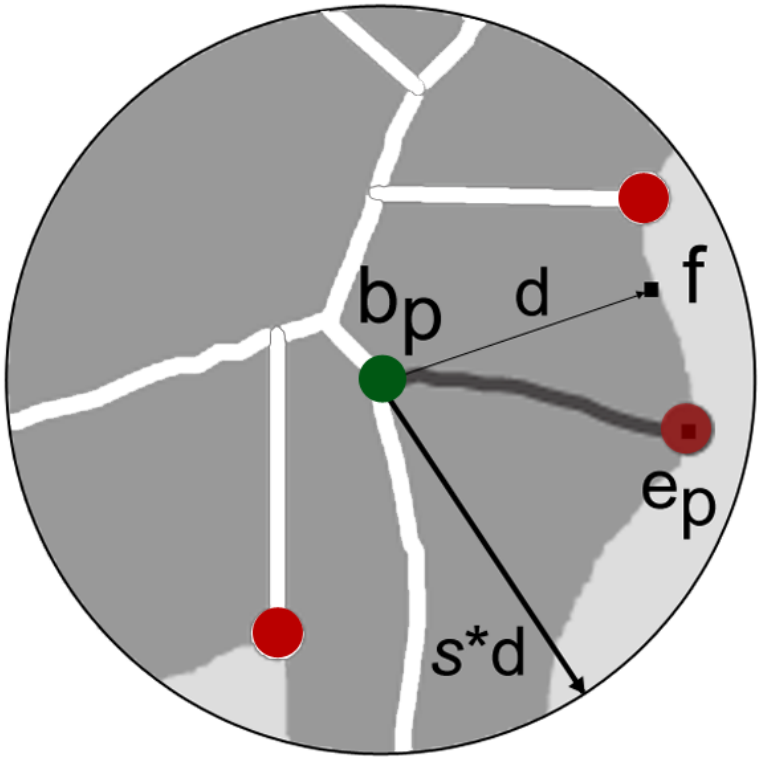

Time complexity: O(n)
n: skeleton pixels

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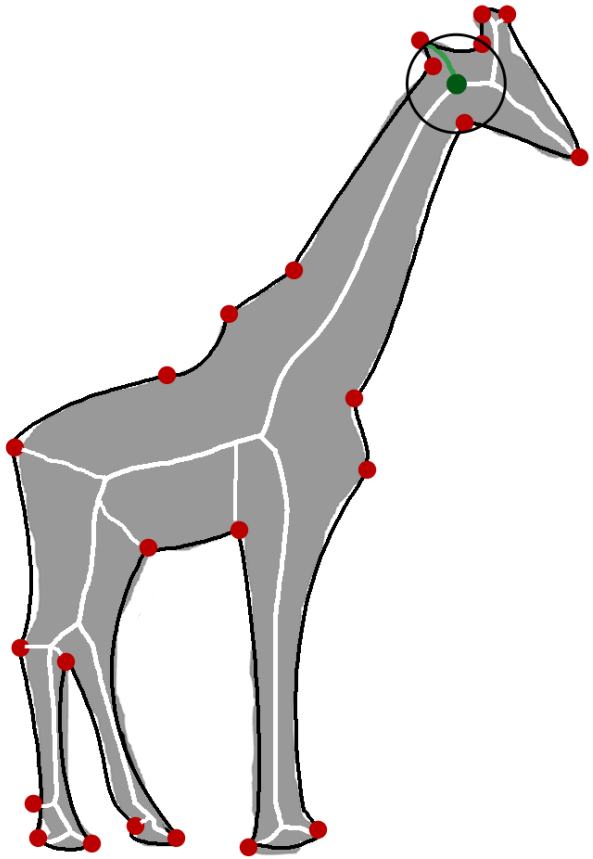

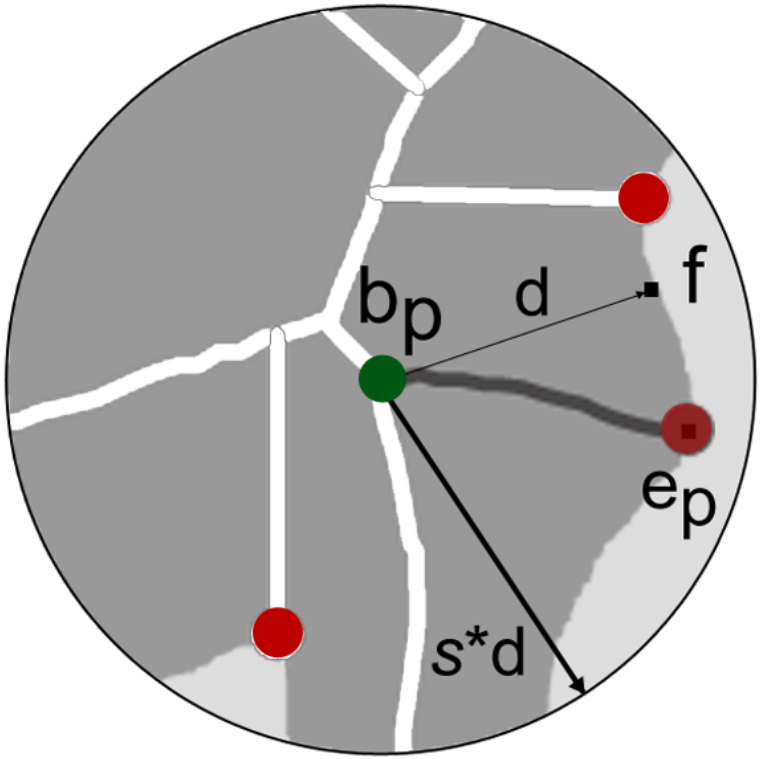

Time complexity: O(n)
n: skeleton pixels

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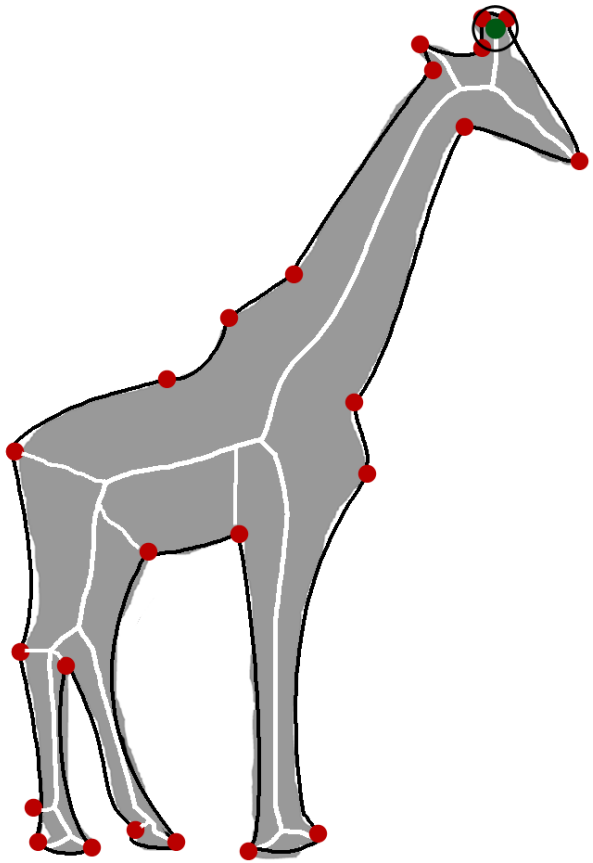

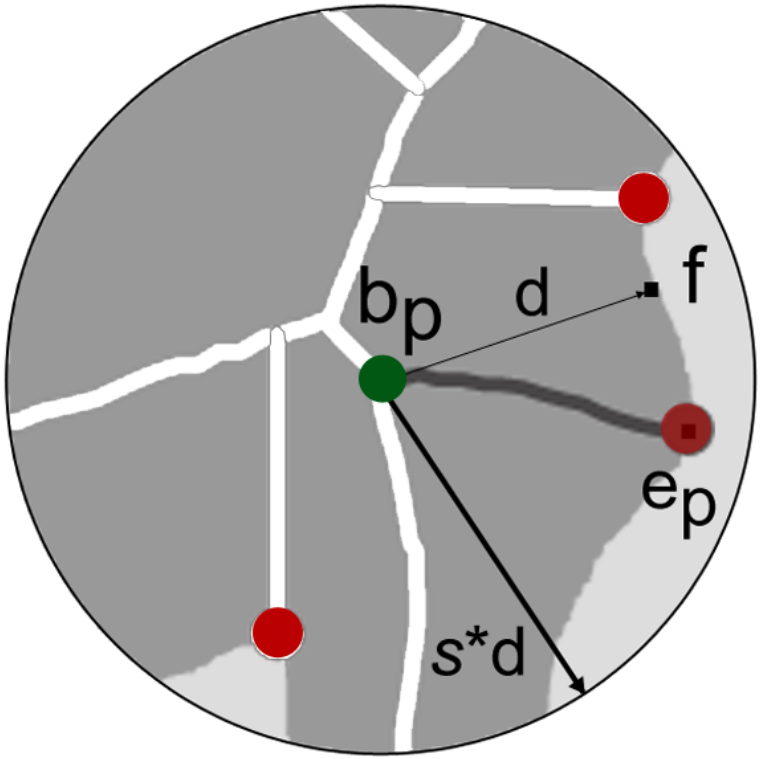

Time complexity: O(n)
n: skeleton pixels

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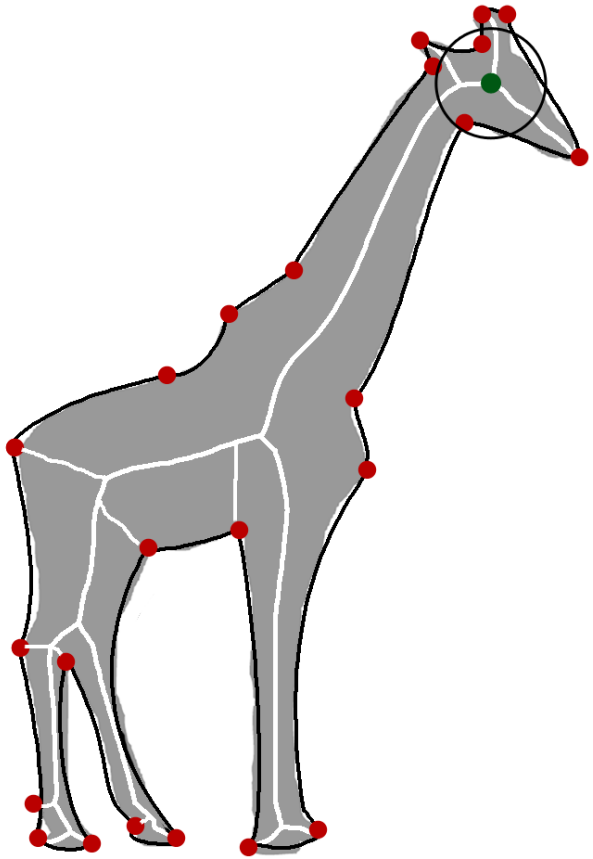

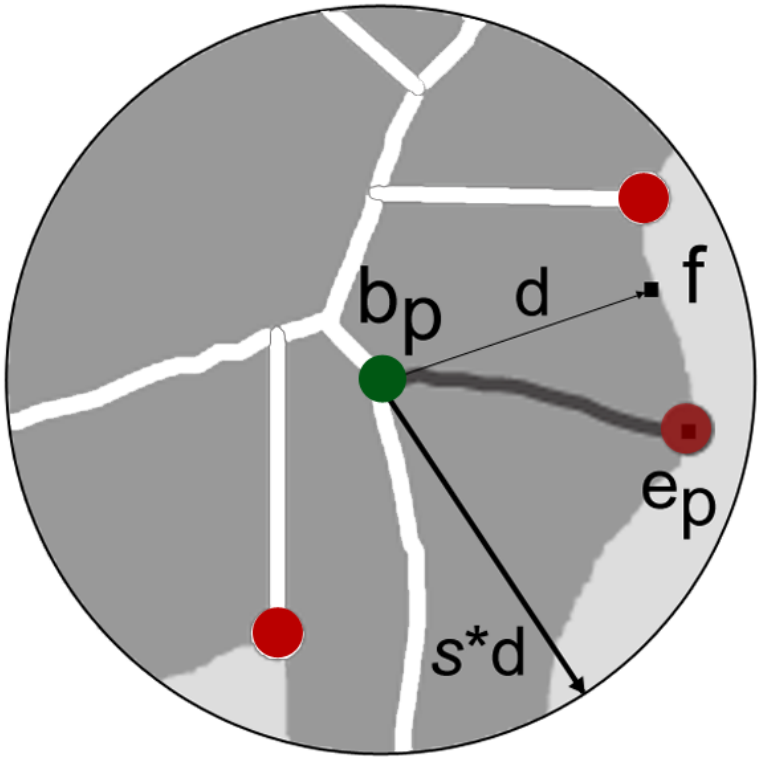

Time complexity: O(n)
n: skeleton pixels

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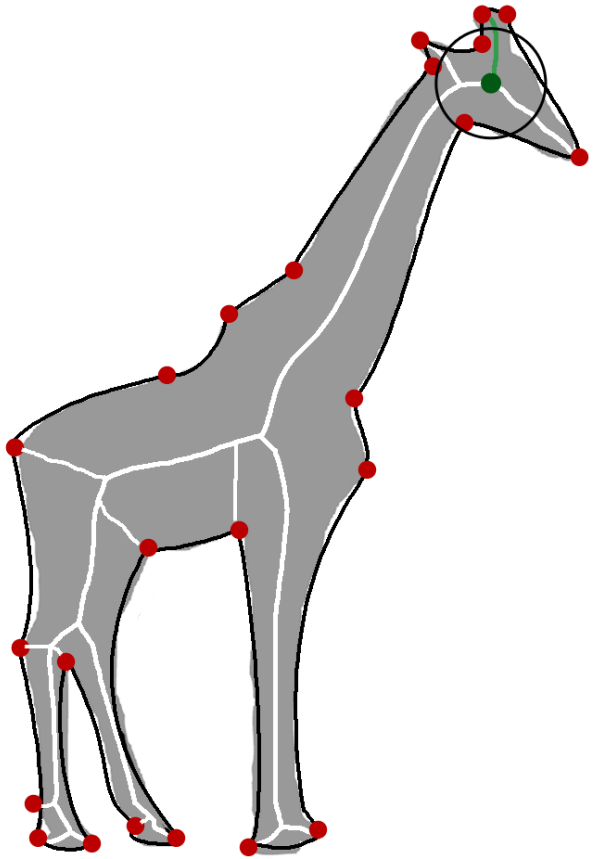

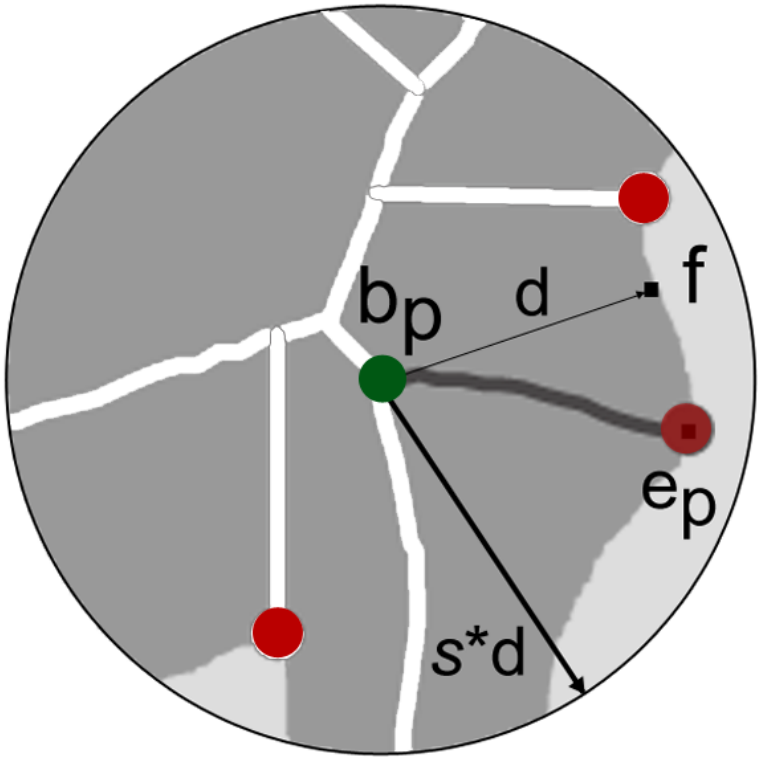

Time complexity: O(n)
n: skeleton pixels

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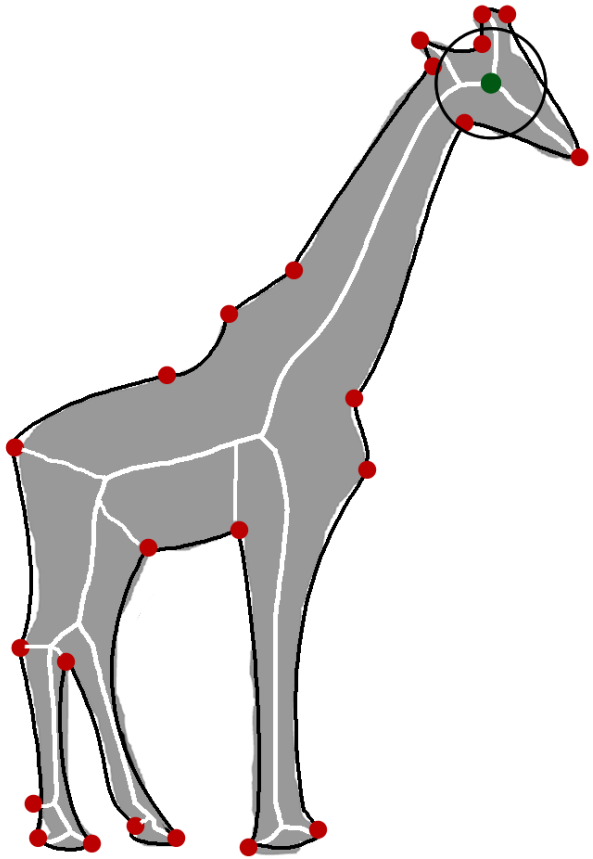

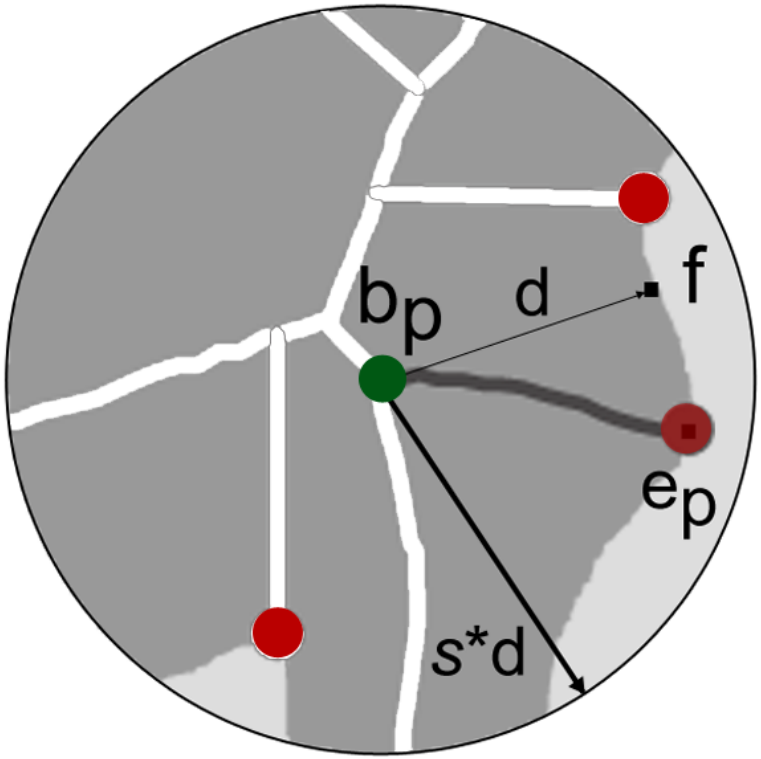

Time complexity: O(n)
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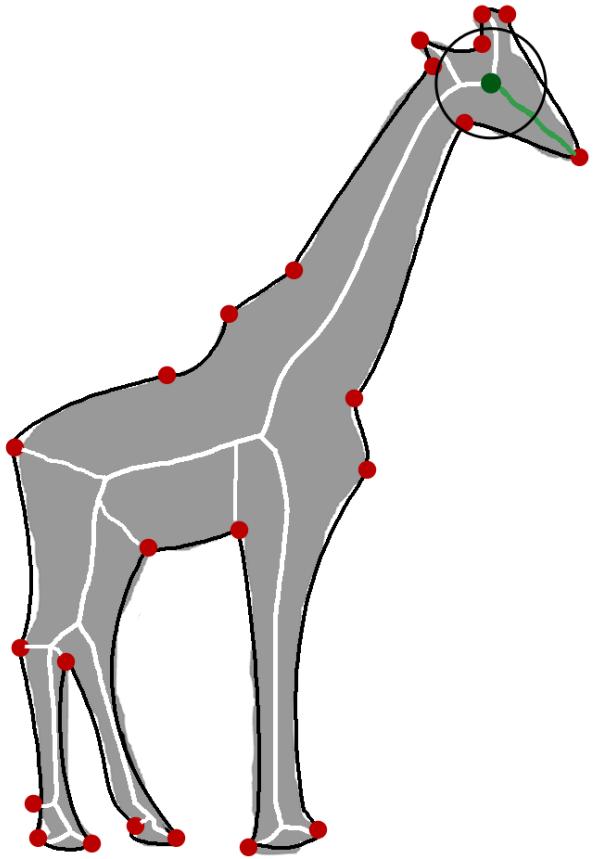

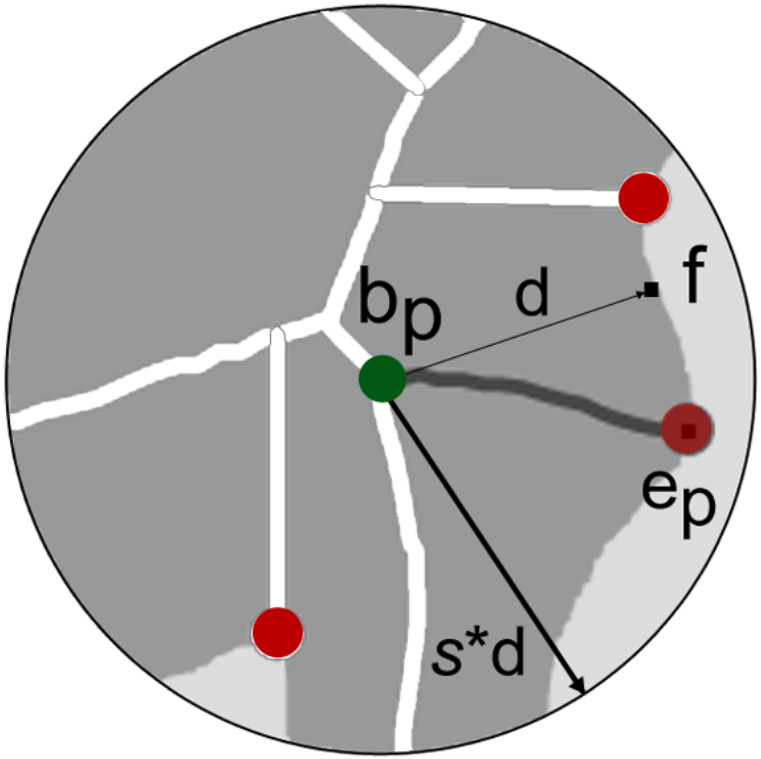

Time complexity: O(n)
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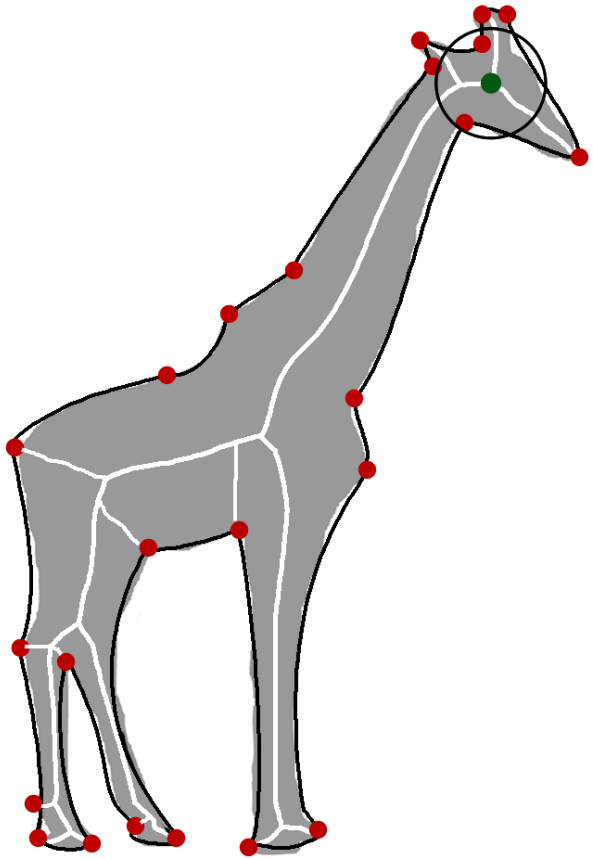

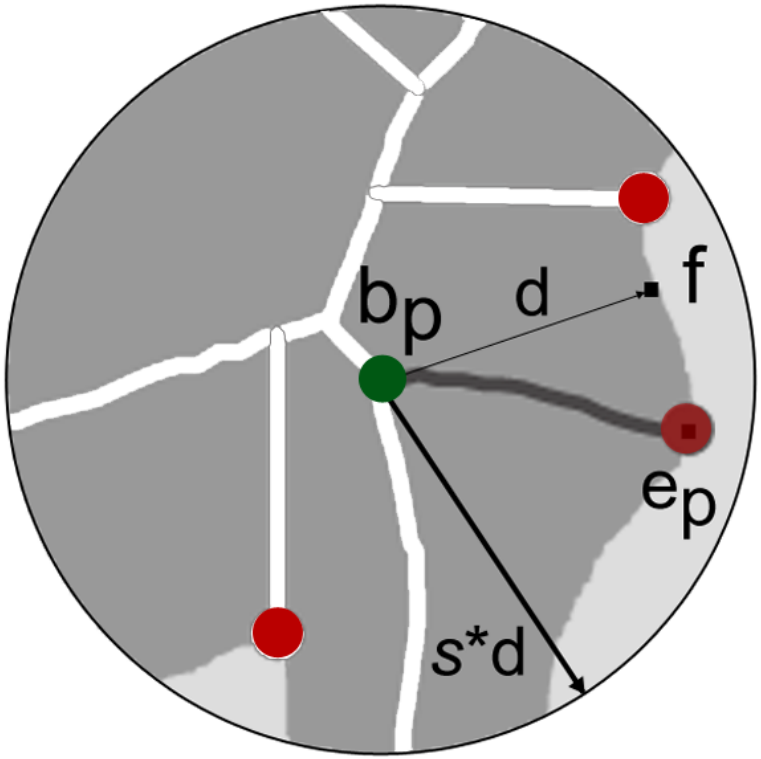

Time complexity: O(n)
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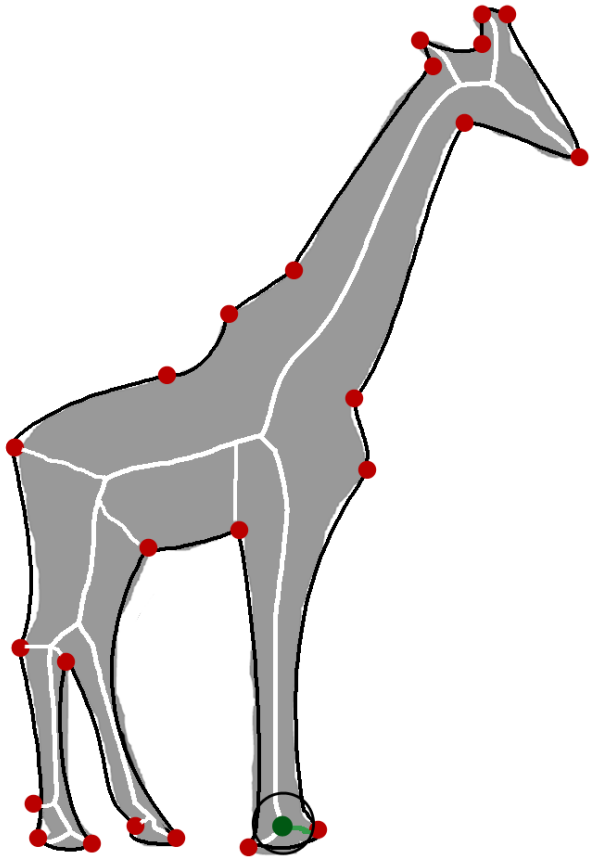

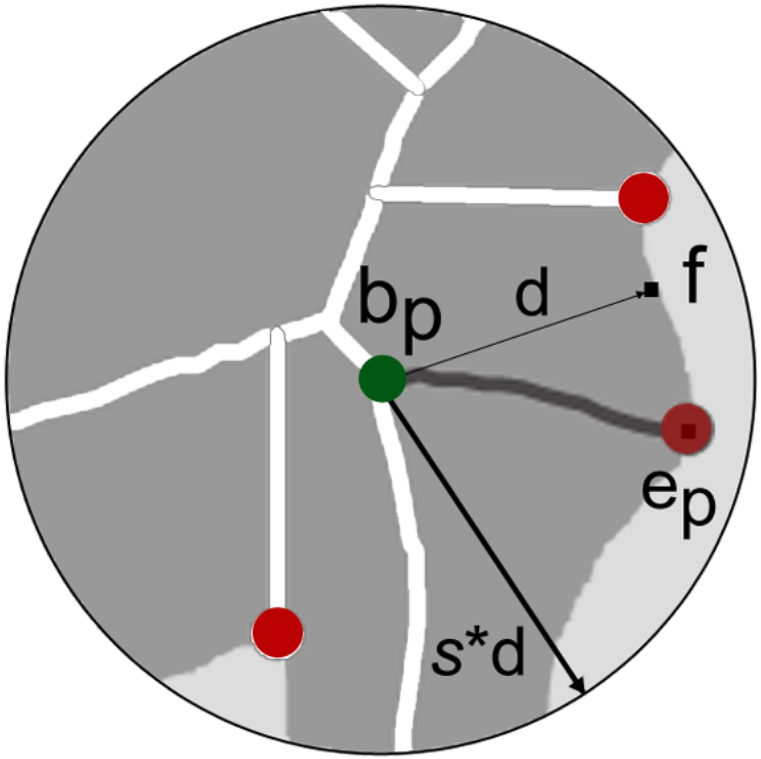

Time complexity: O(n)
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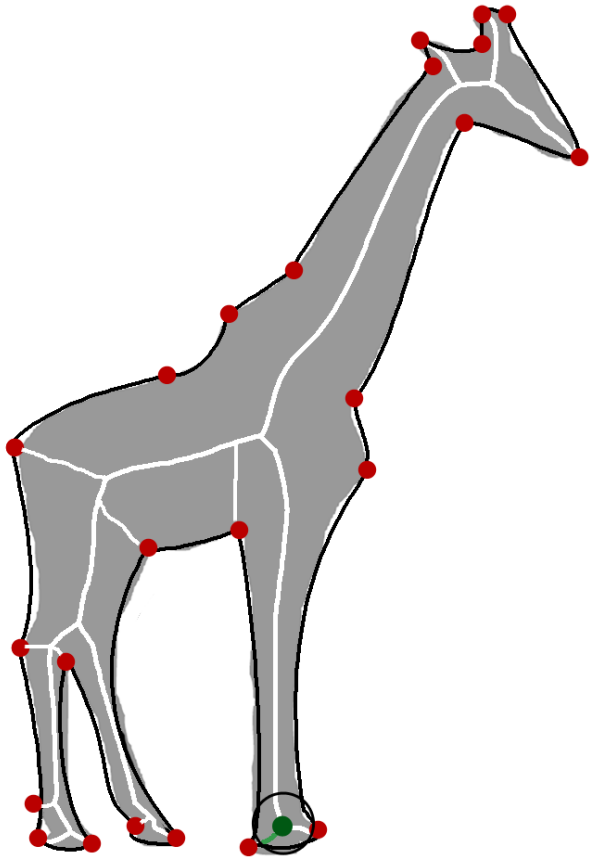

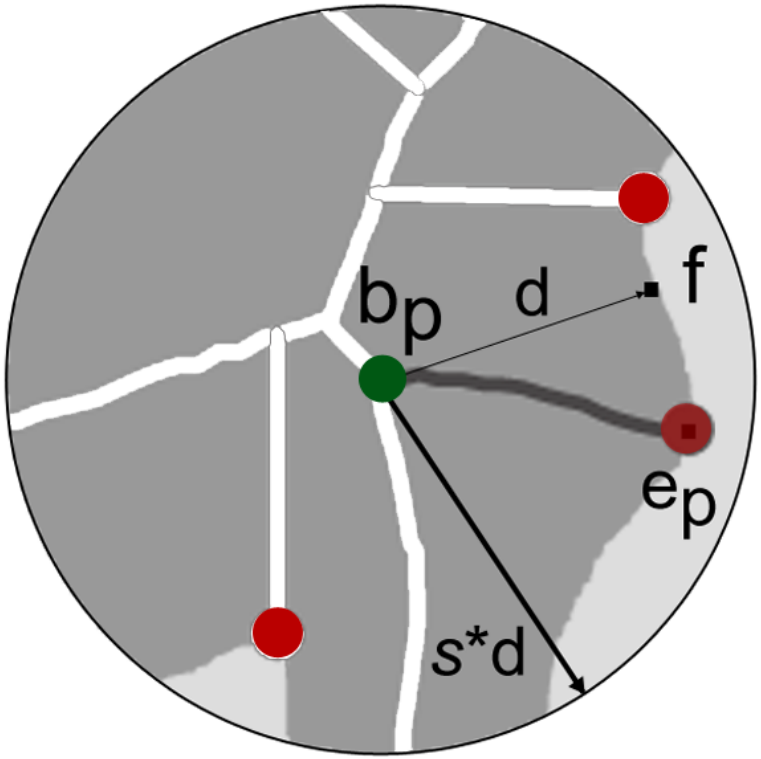

Time complexity: O(n)
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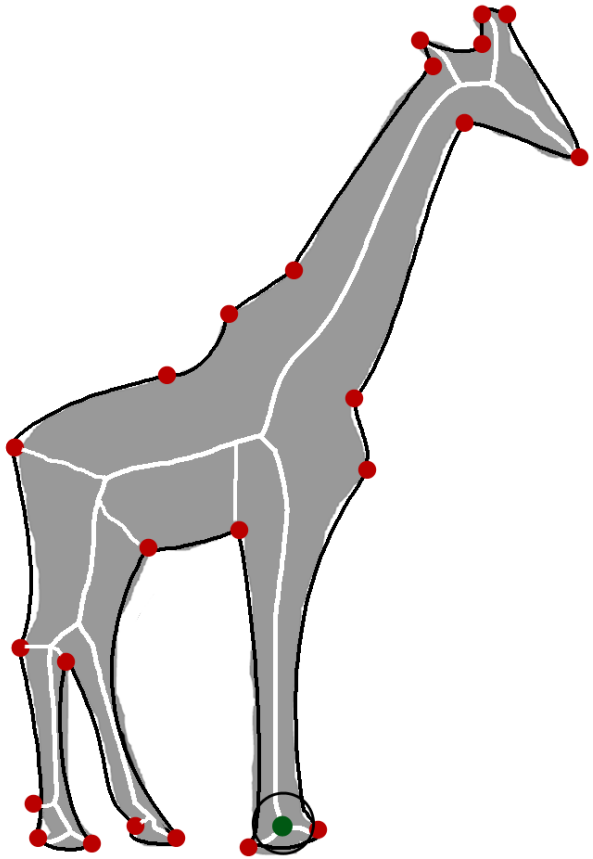

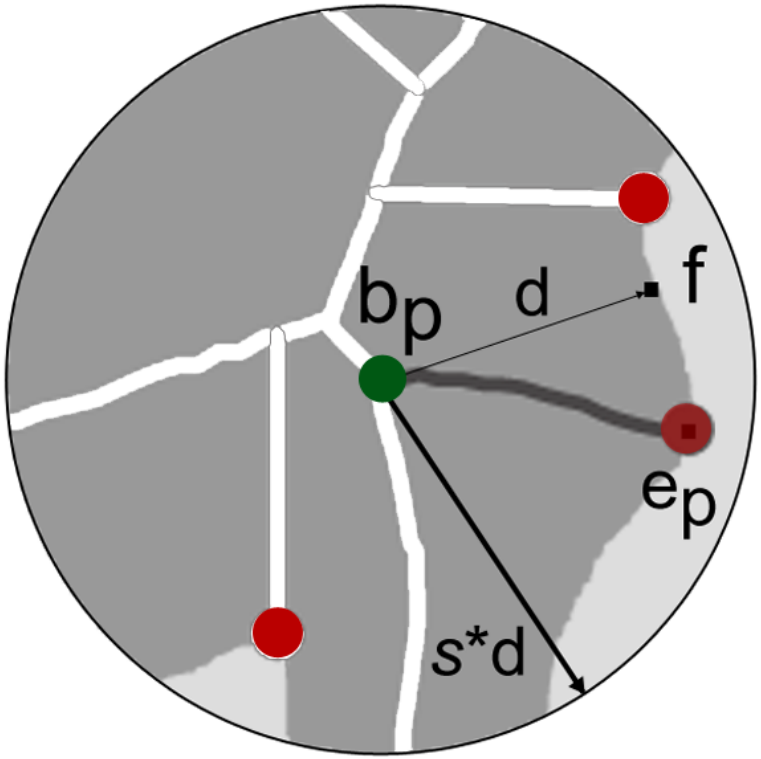

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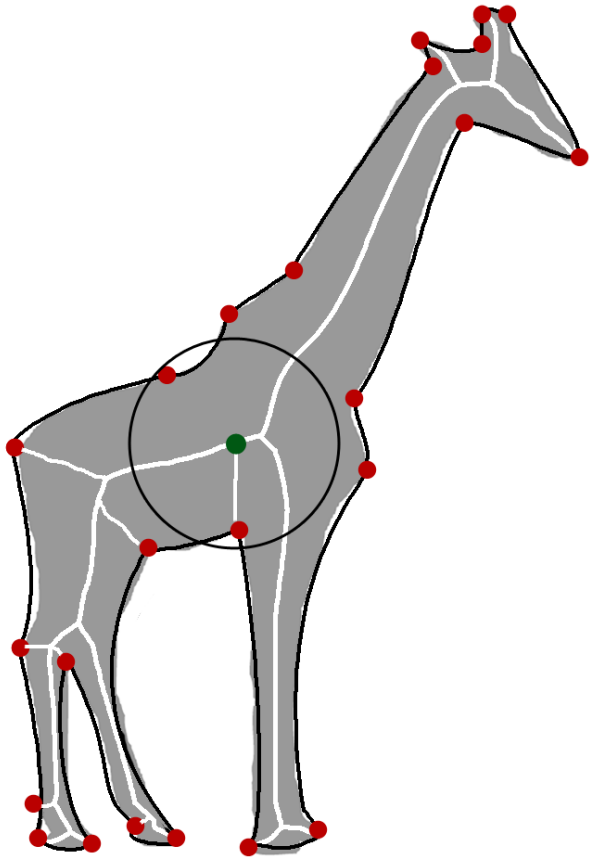

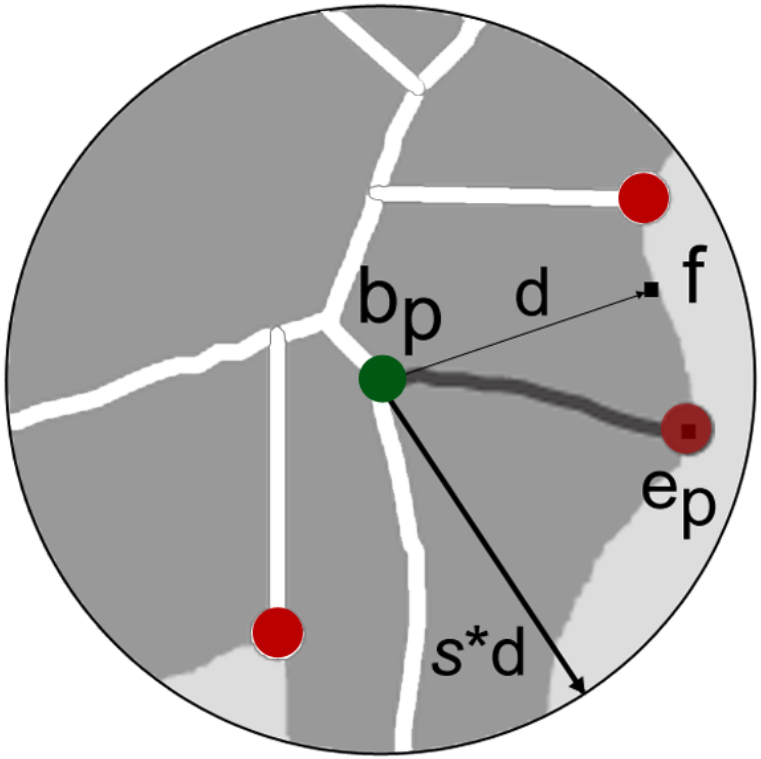

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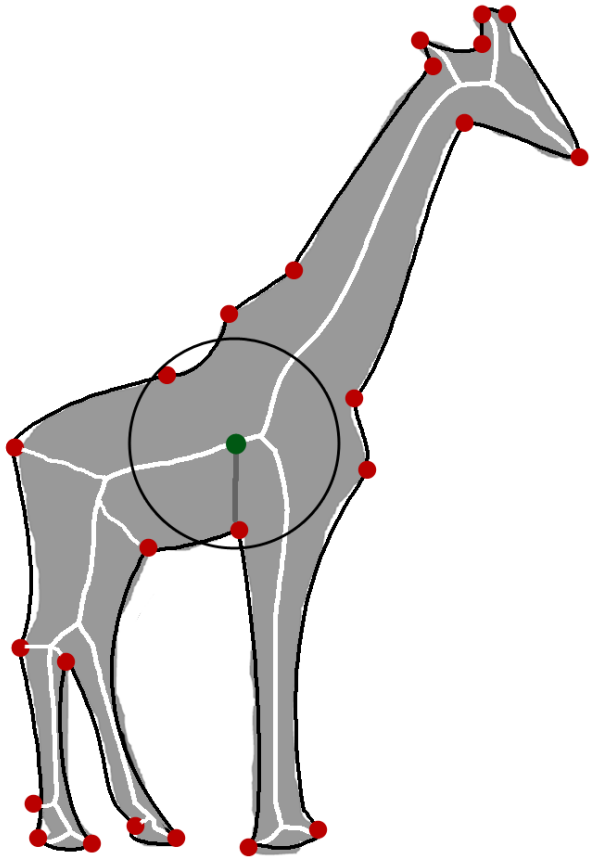

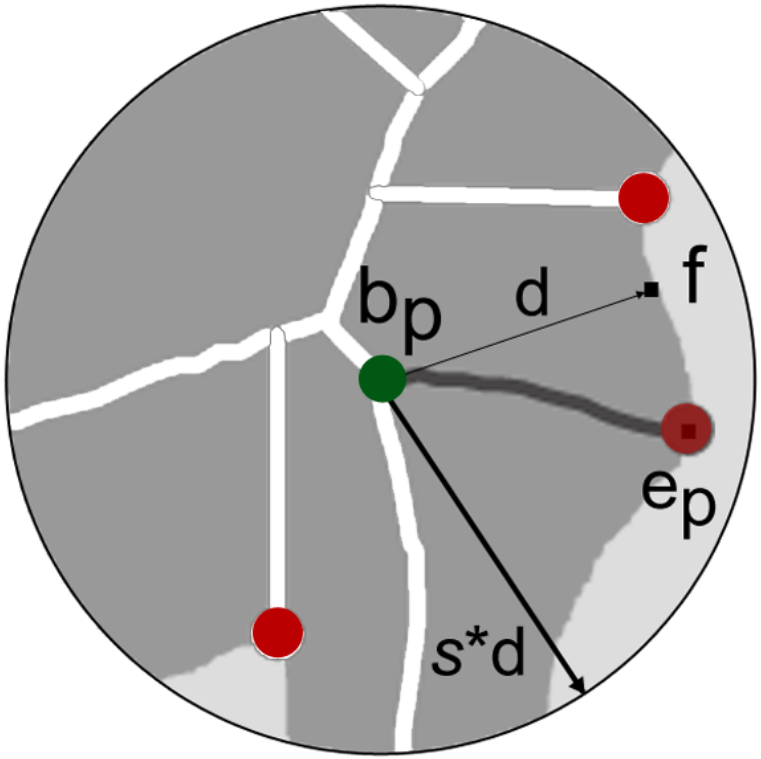

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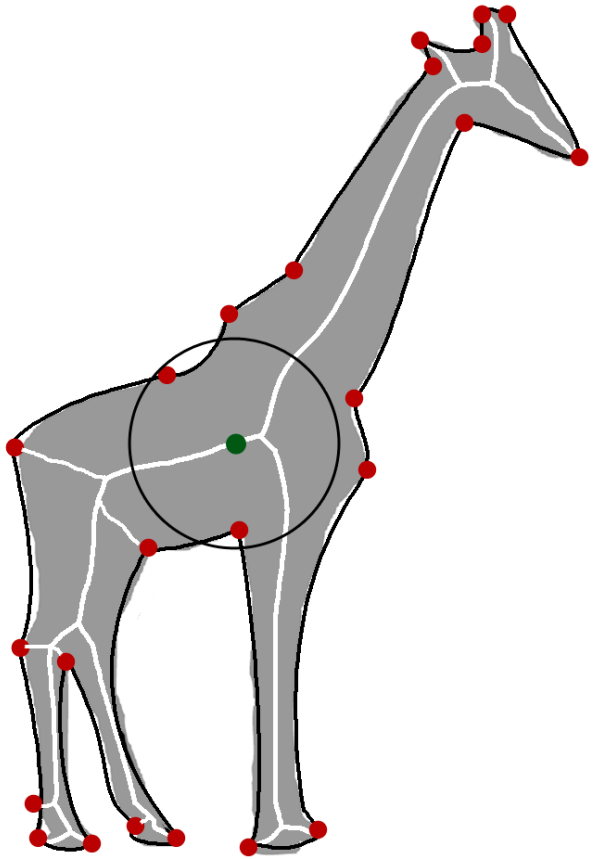

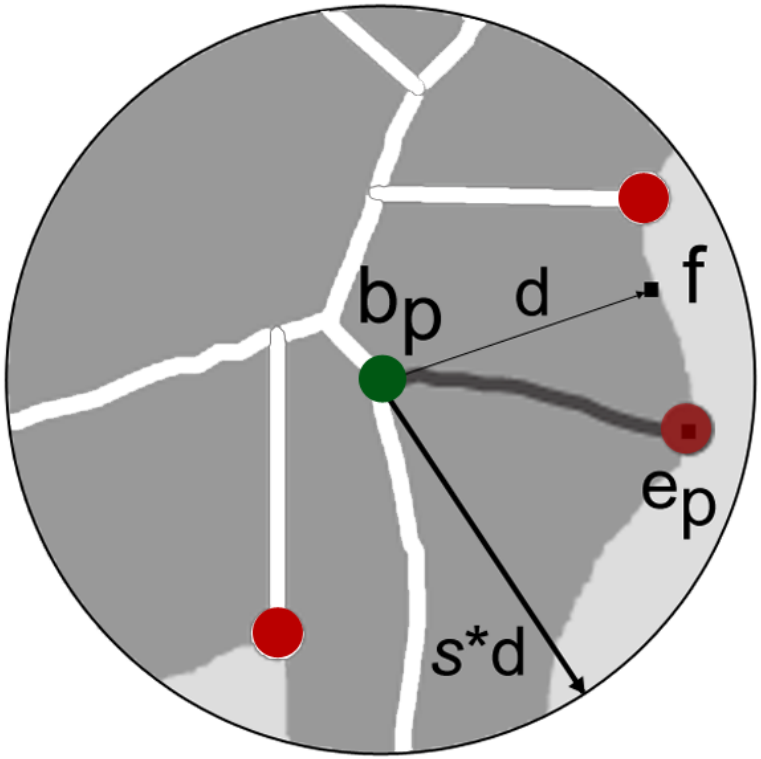

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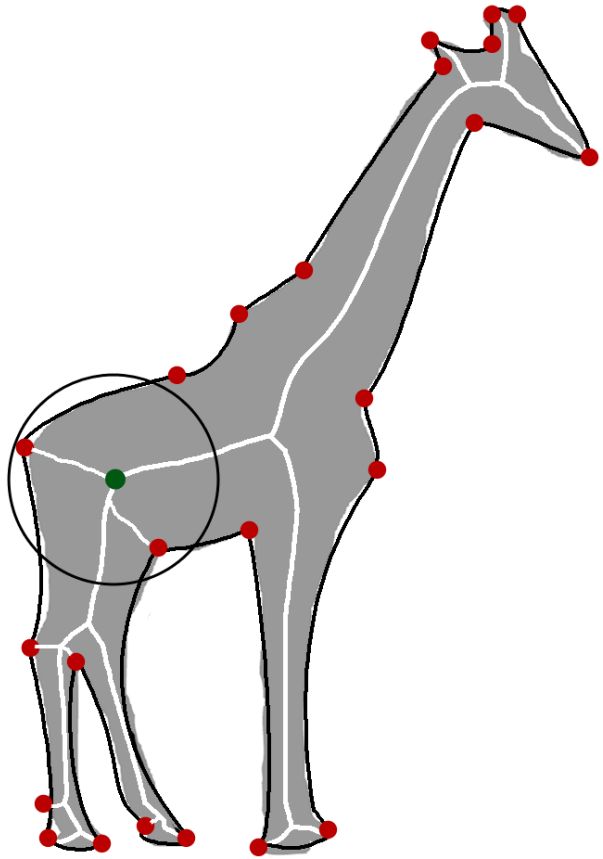

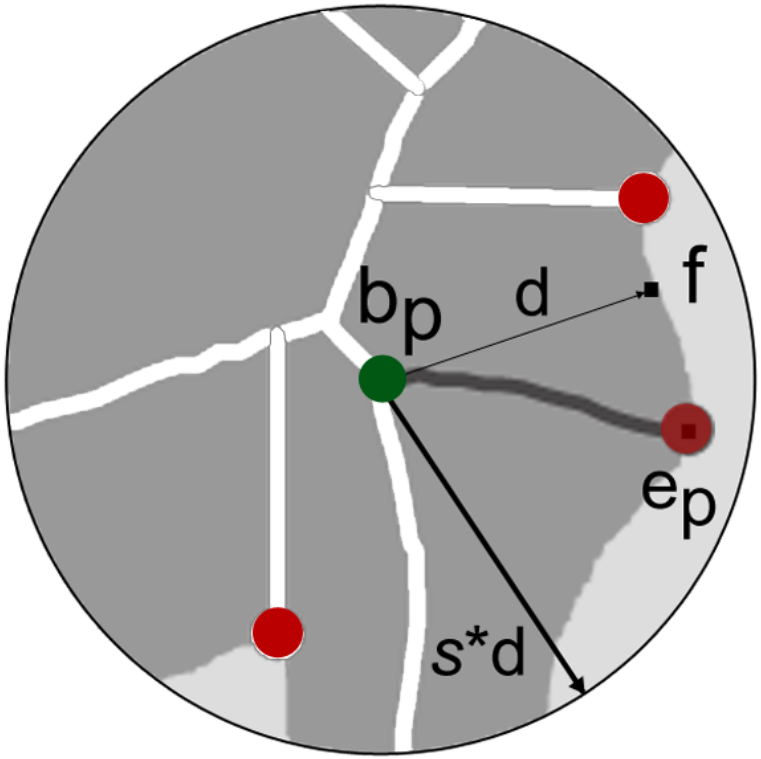

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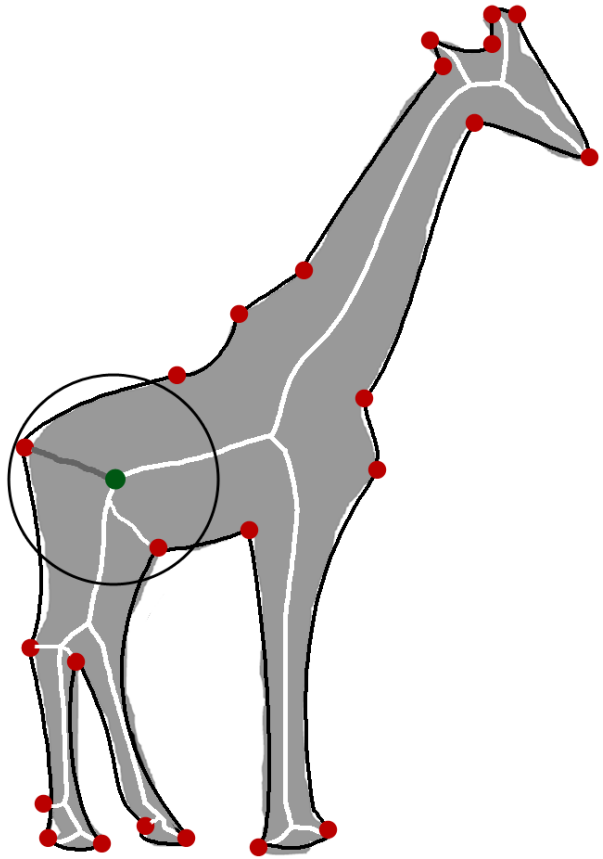

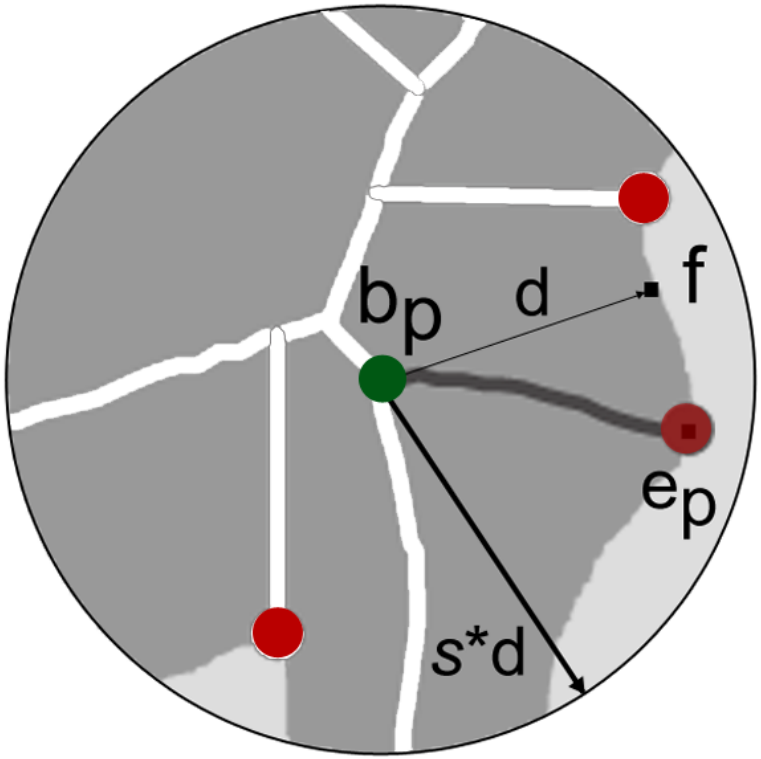

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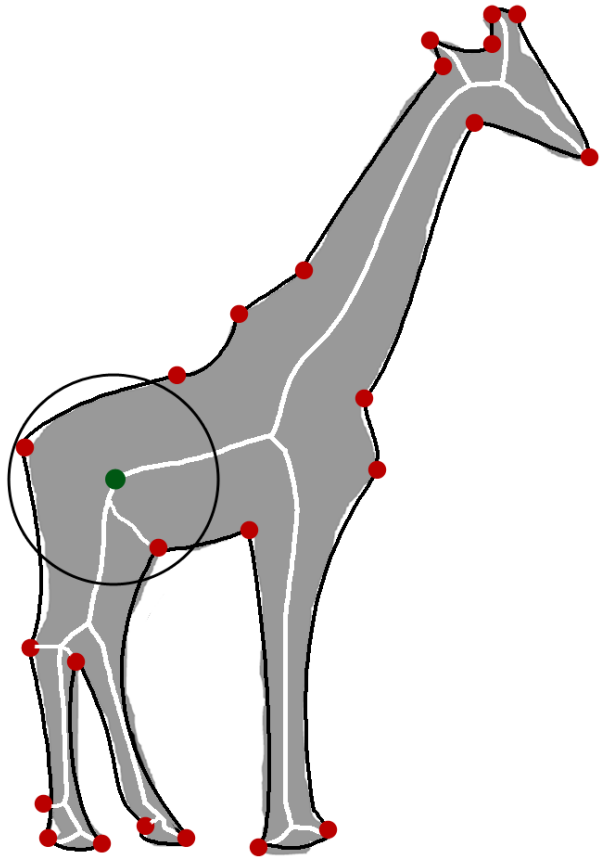

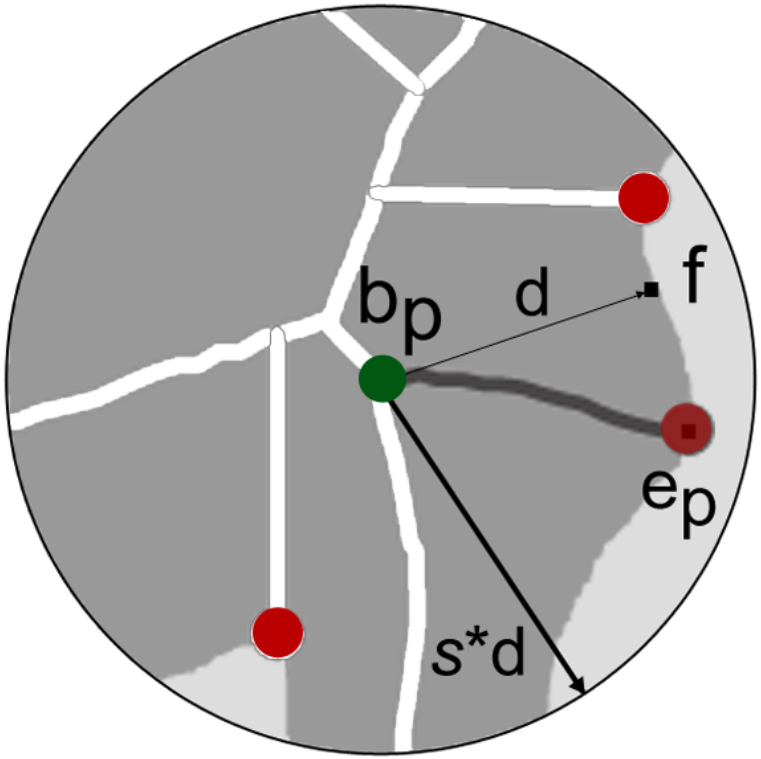

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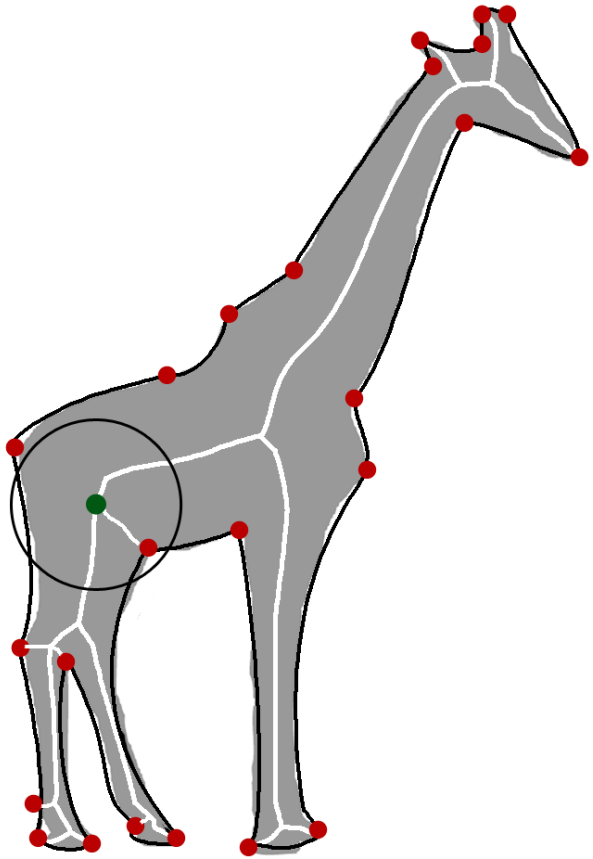

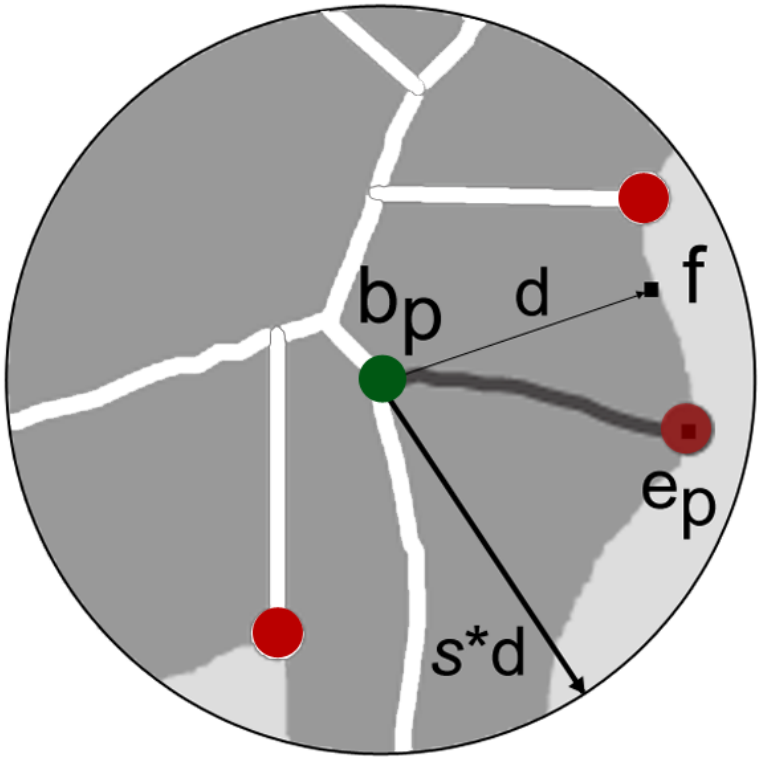

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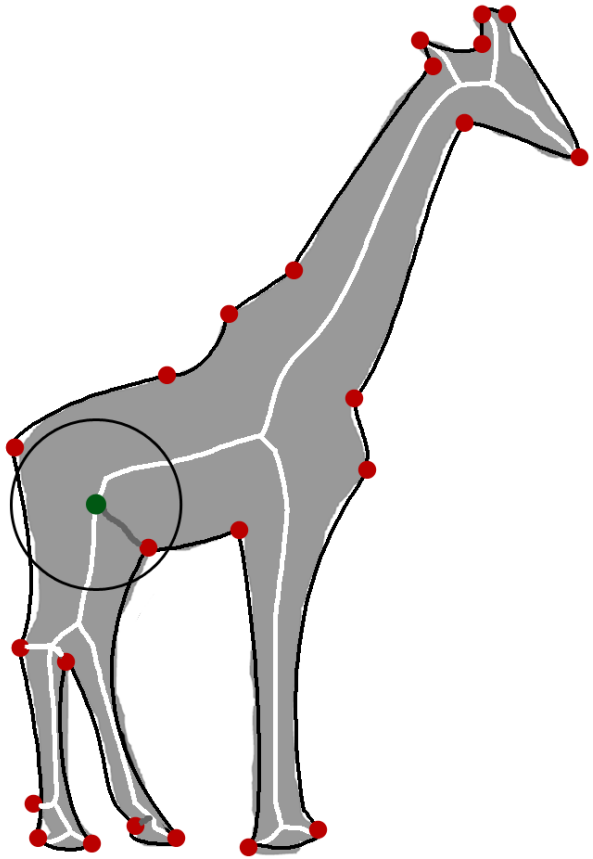

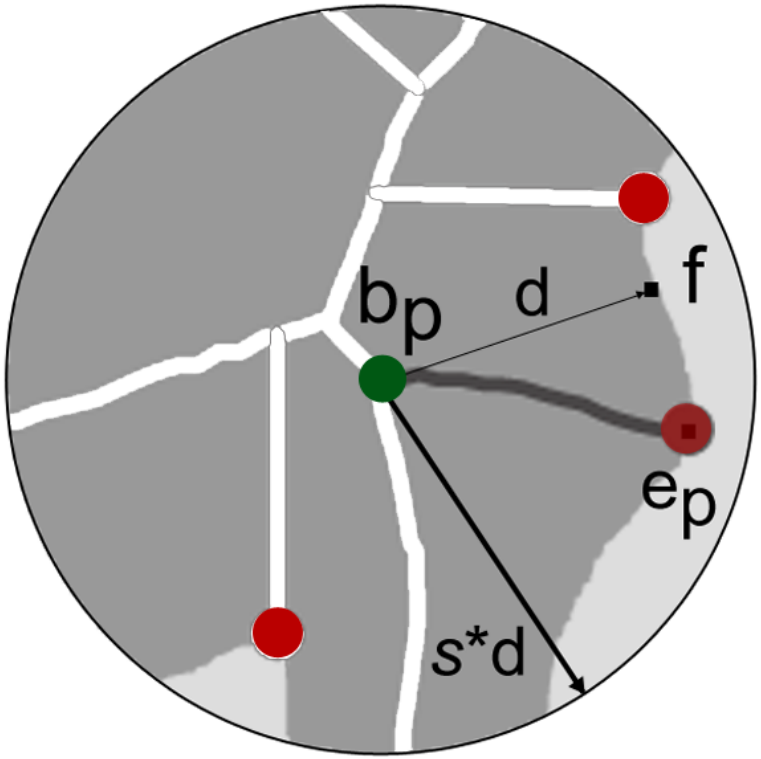

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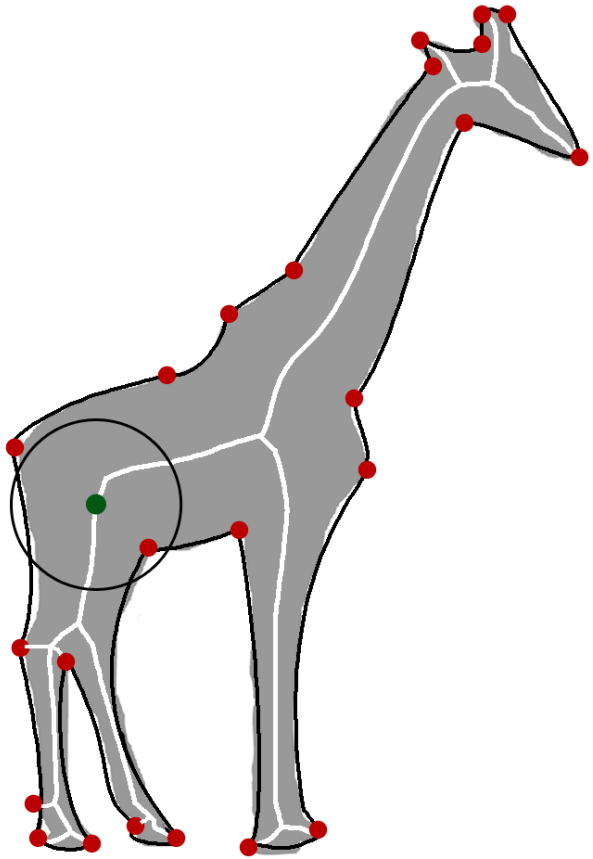

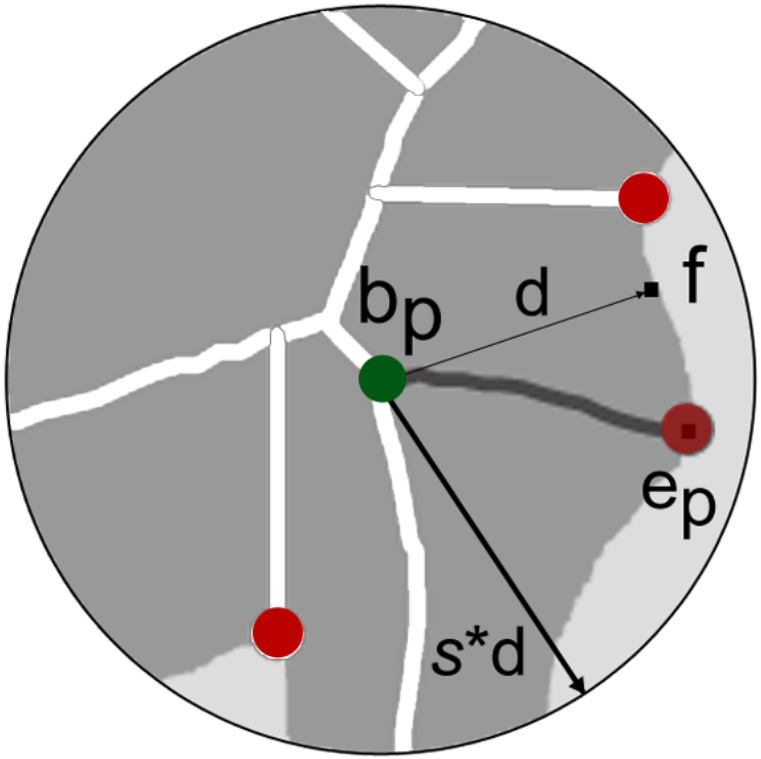

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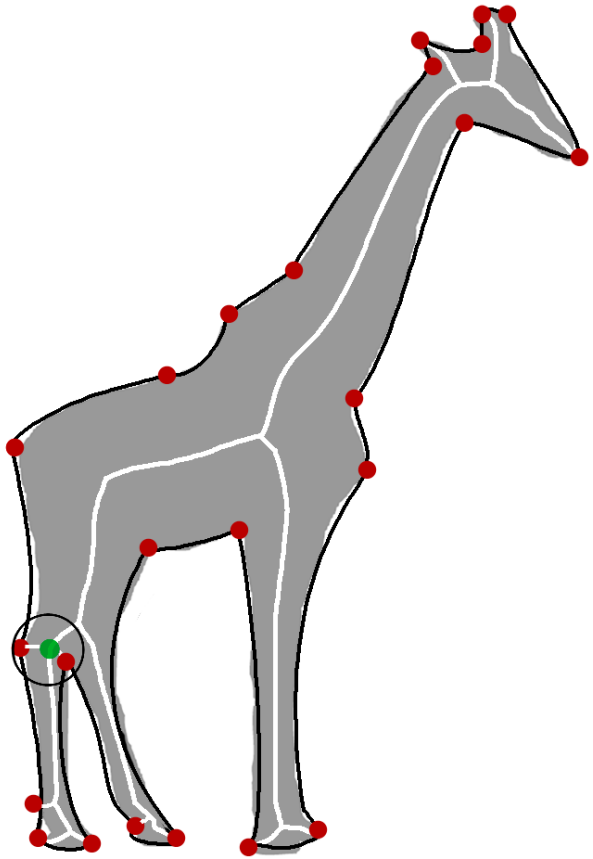
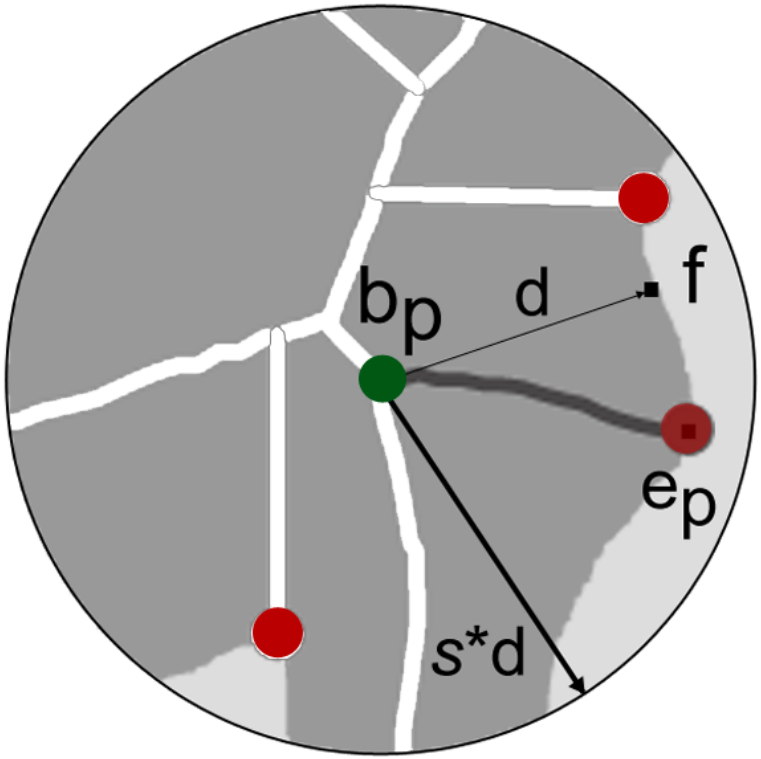
n: skeleton pixels

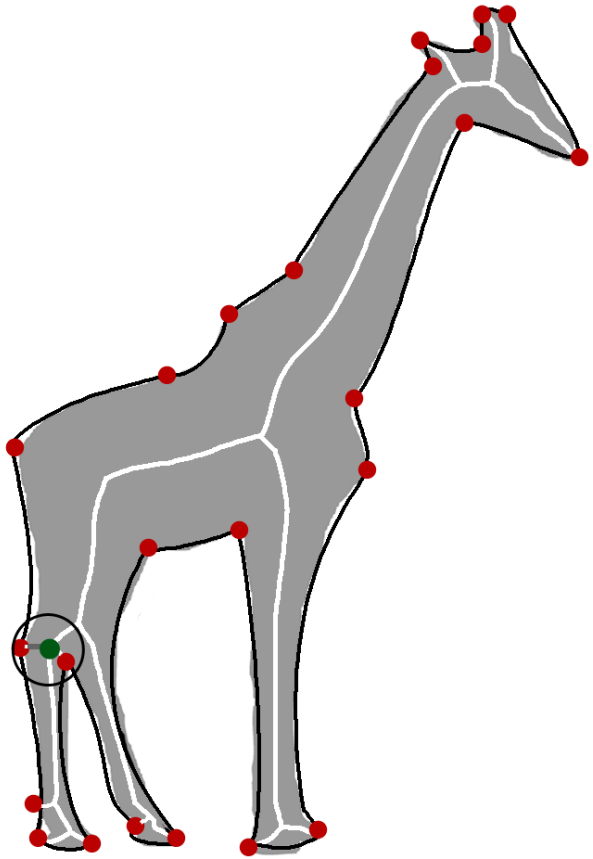
3. Check every branch chain for removal

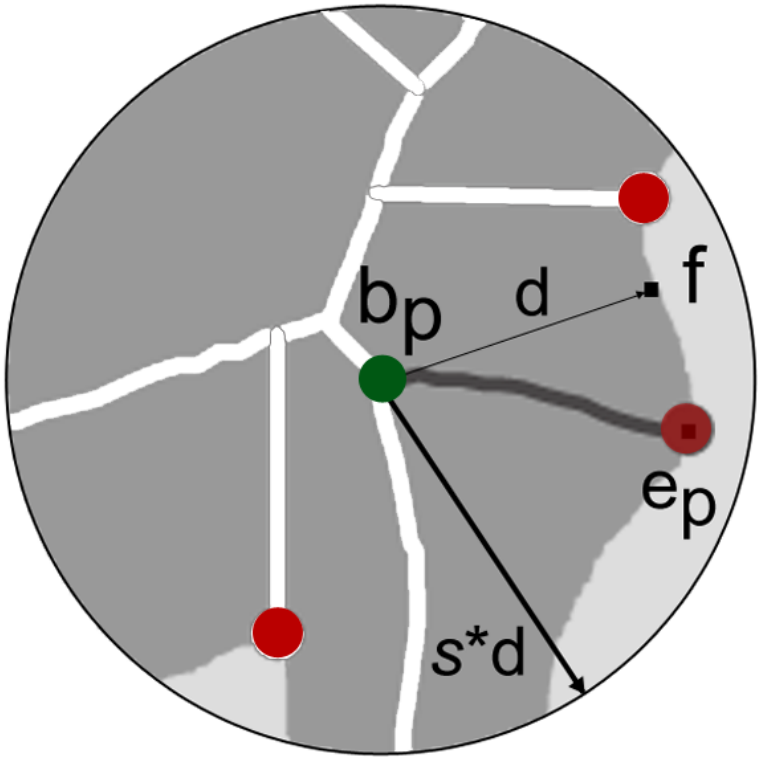




Time complexity: O(n)
n: skeleton pixels

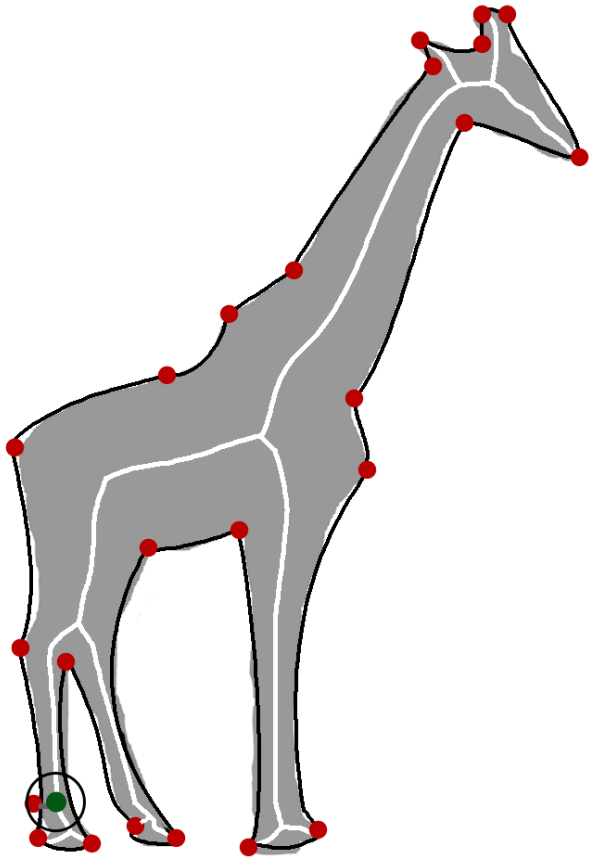
3. Check every branch chain for removal

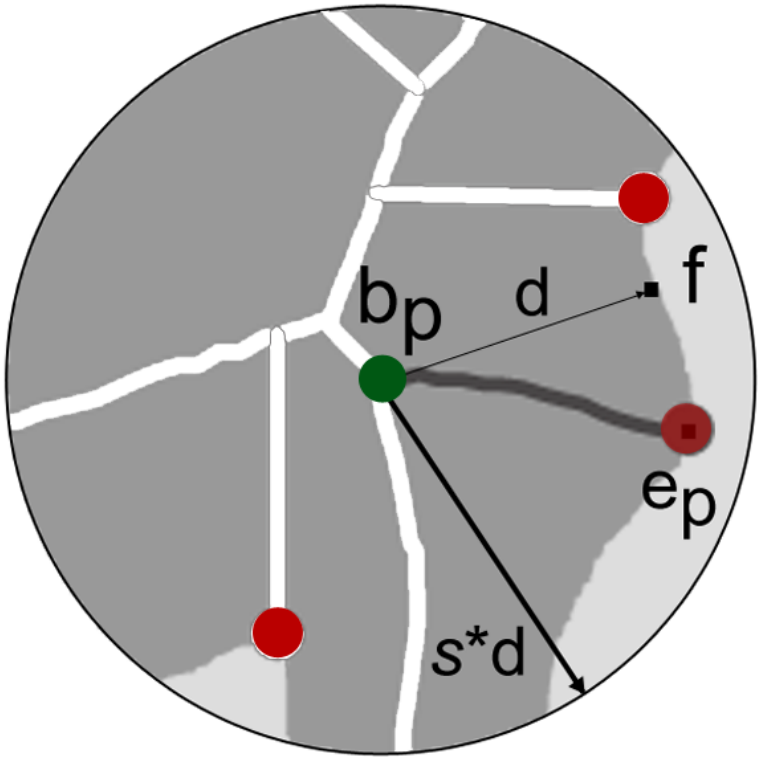




Time complexity: O(n)
n: skeleton pixels

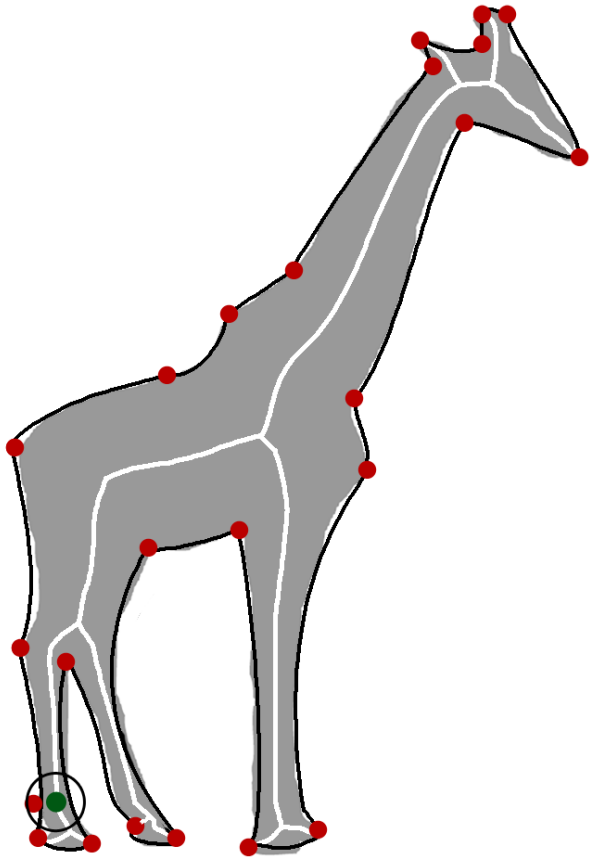
3. Check every branch chain for removal

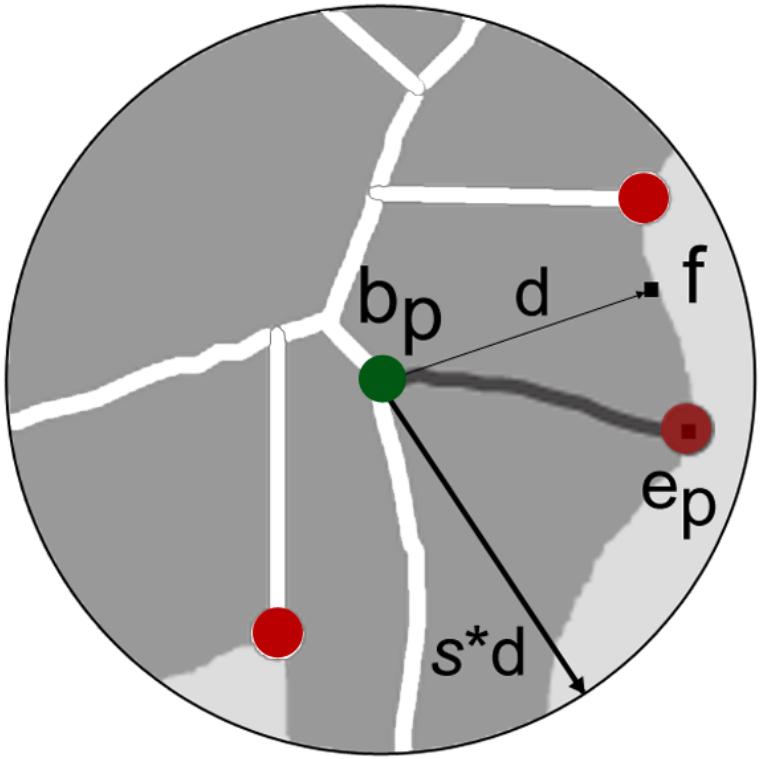




Time complexity: O(n)
n: skeleton pixels

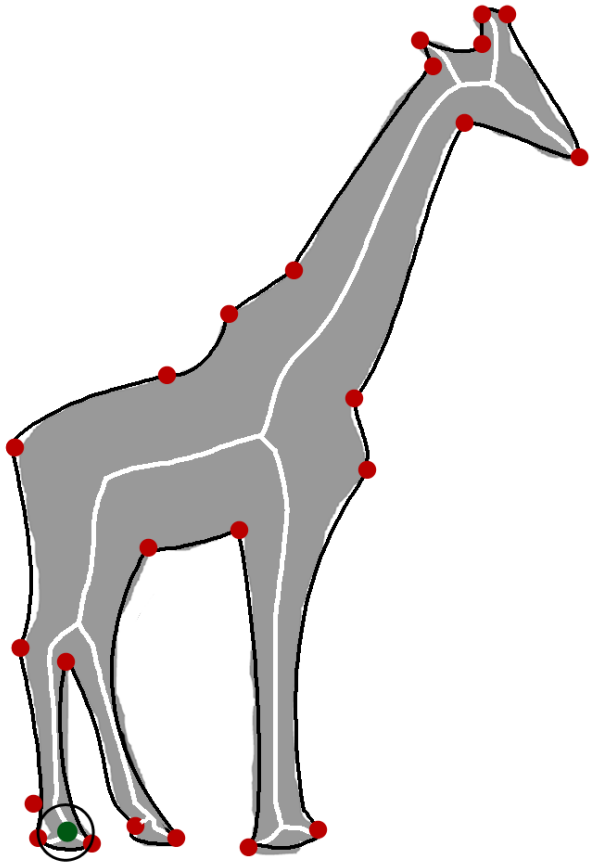
3. Check every branch chain for removal

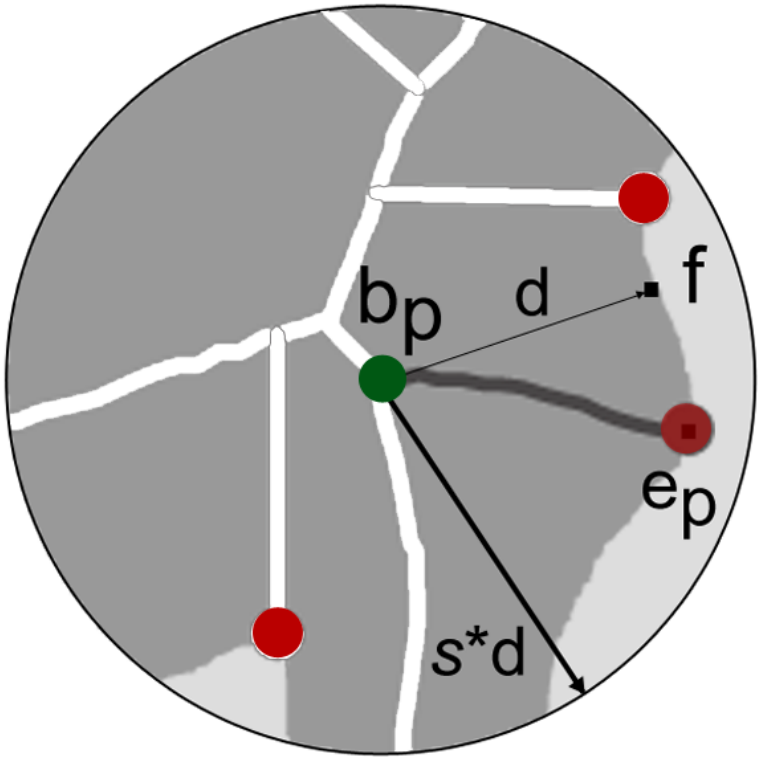




Time complexity: O(n)
n: skeleton pixels

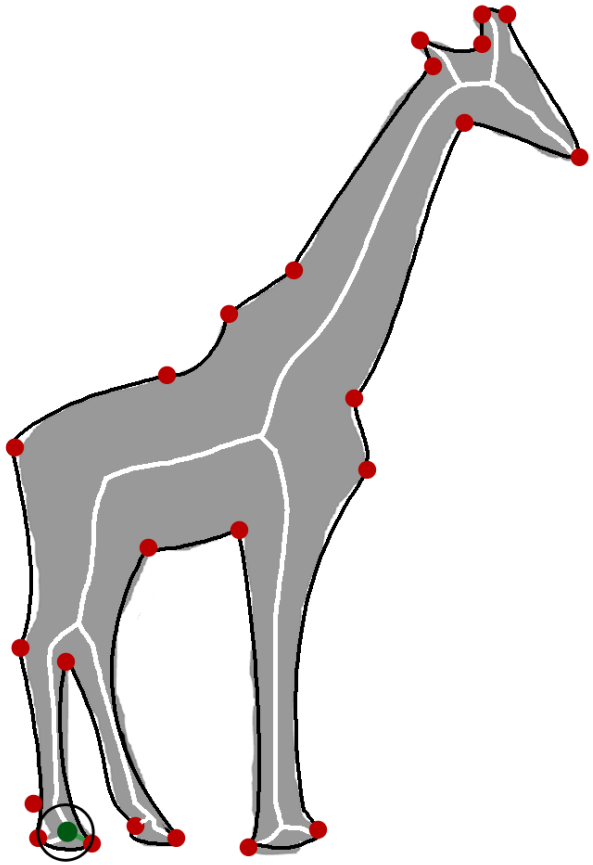
3. Check every branch chain for removal

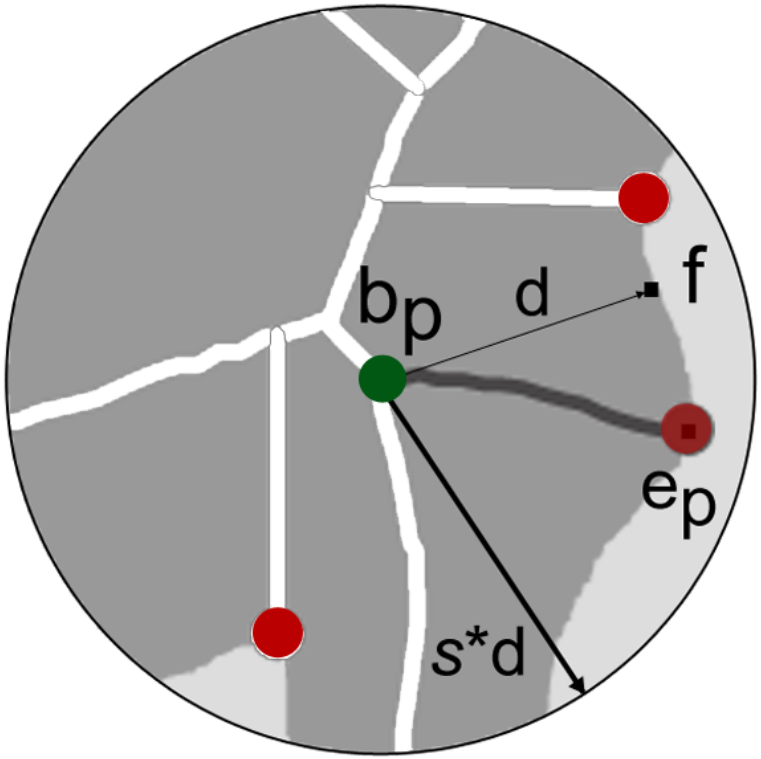




Time complexity: O(n)
n: skeleton pixels

3. Check every branch chain for removal





Time complexity: O(n)
n: skeleton pixels

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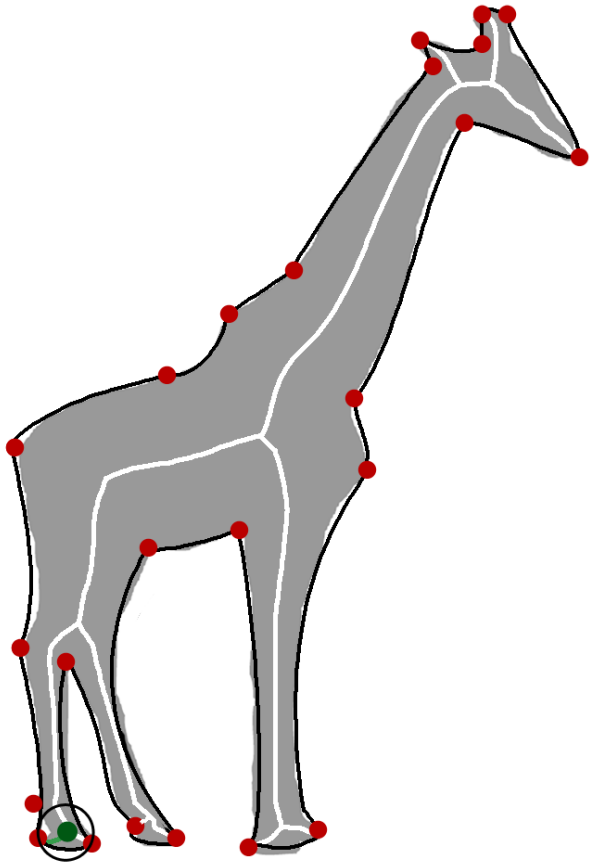
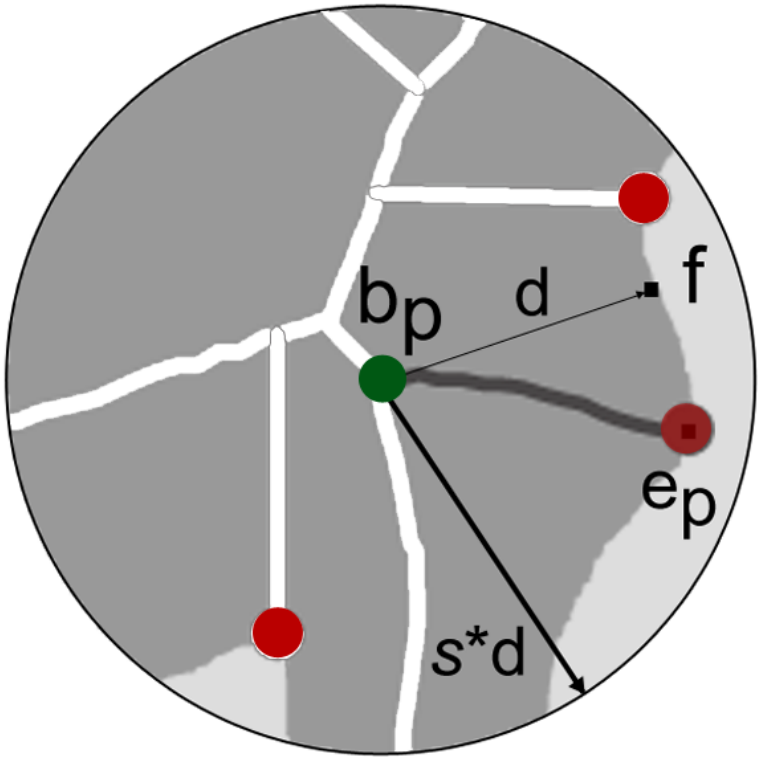
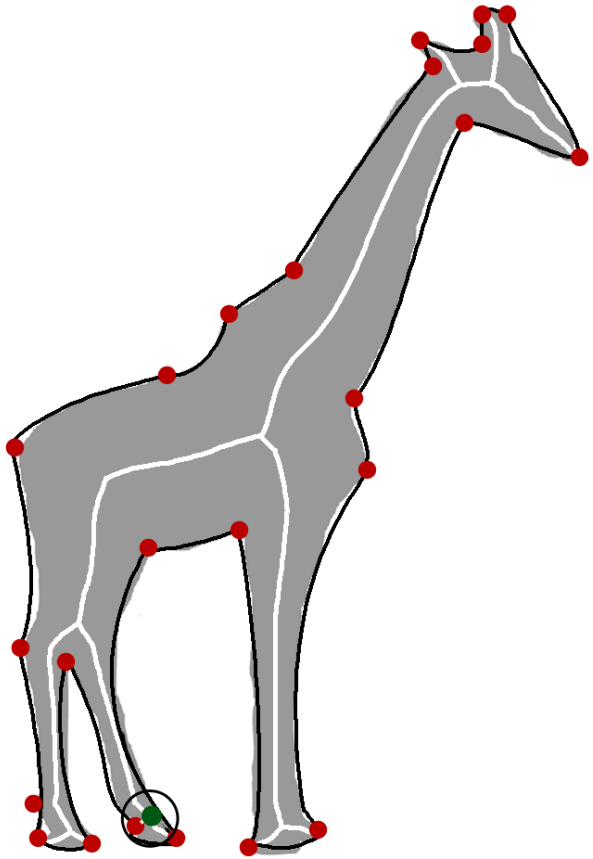
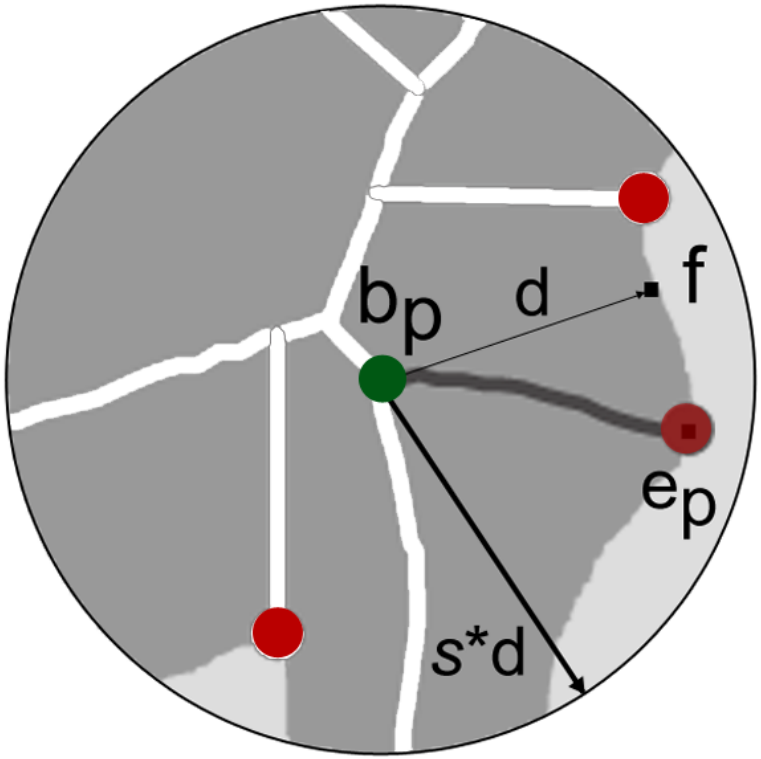




Time complexity: O(n)
n: skeleton pixels

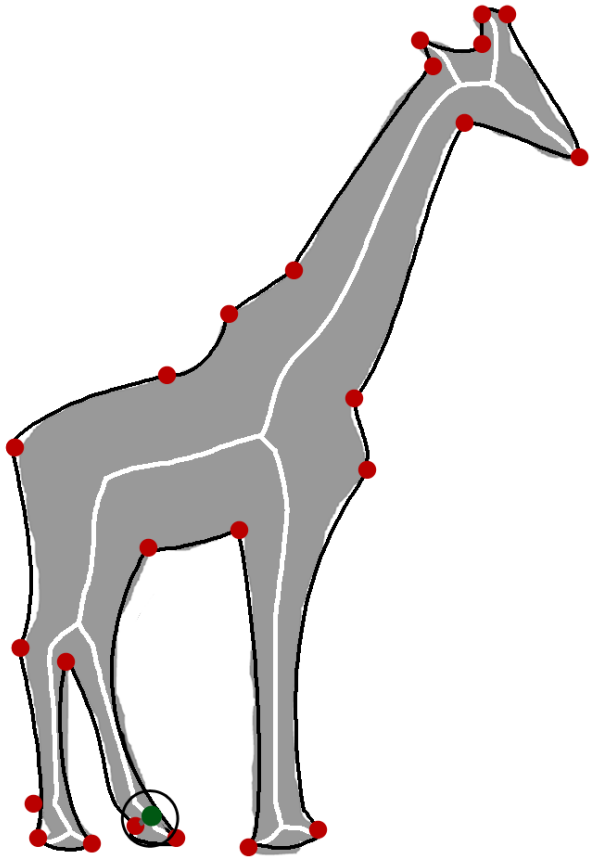
3. Check every branch chain for removal

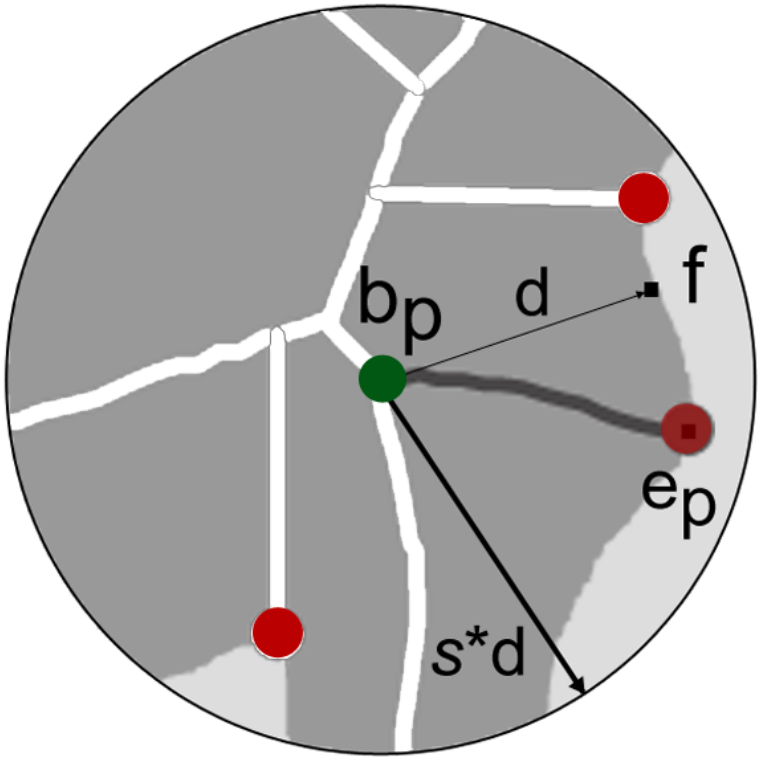




Time complexity: O(n)
n: skeleton pixels

3. Check every branch chain for removal





Time complexity: O(n)
n: skeleton pixels

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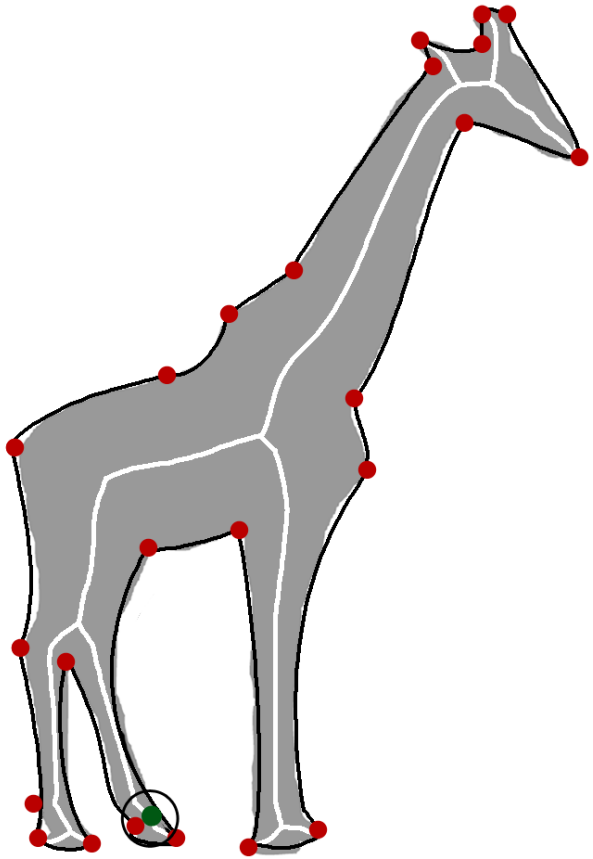

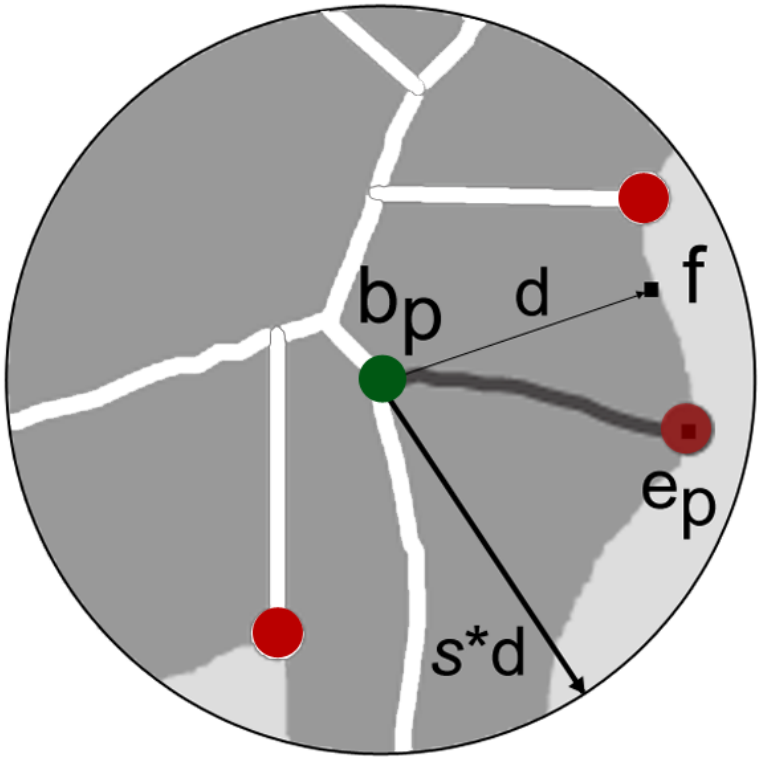

Time complexity: O(n)
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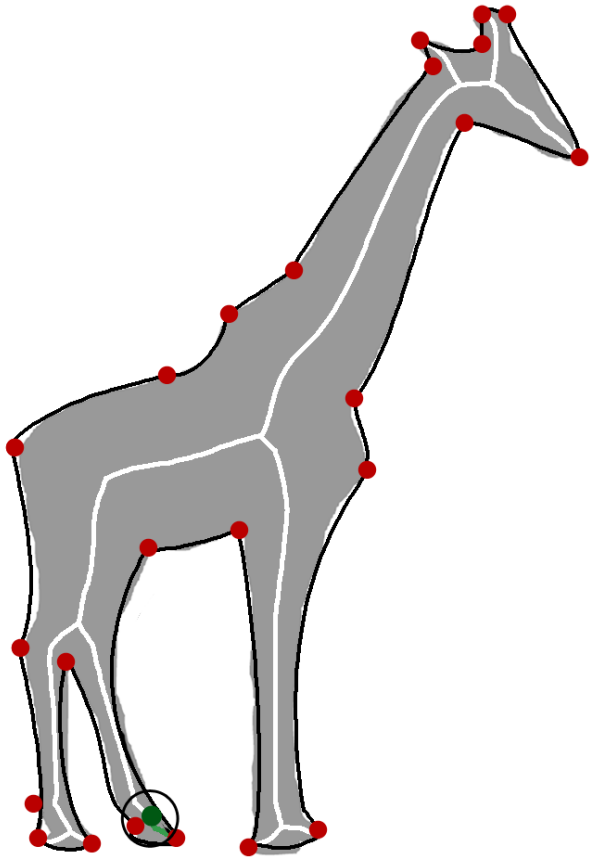
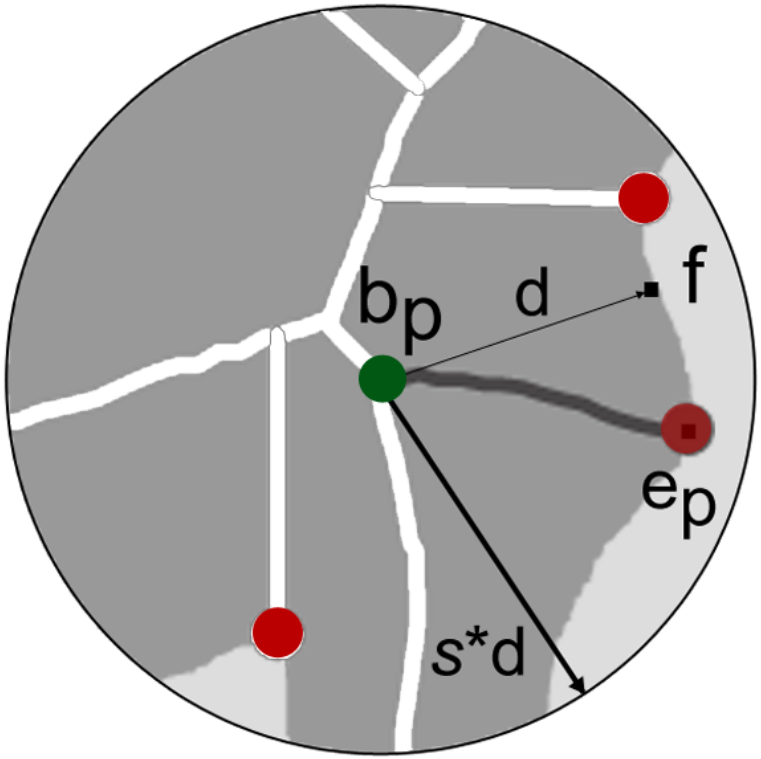
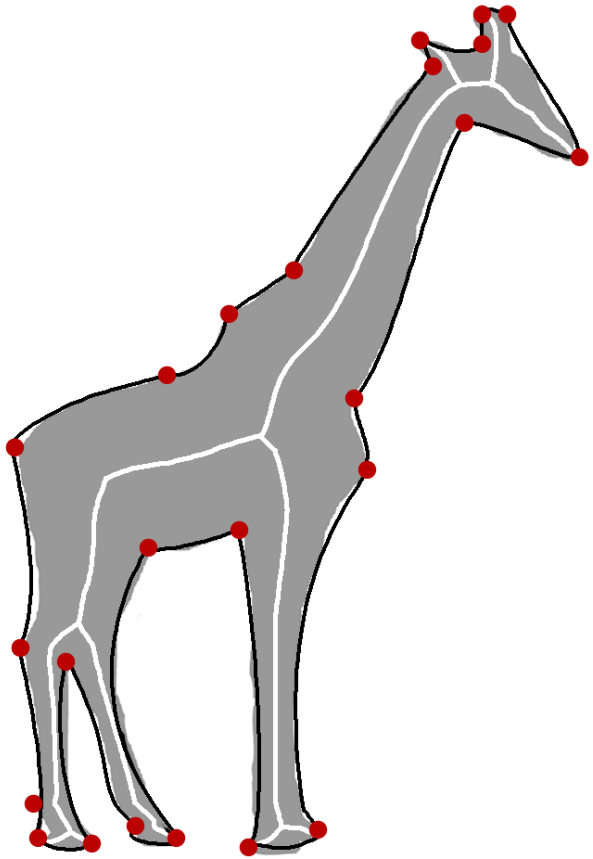
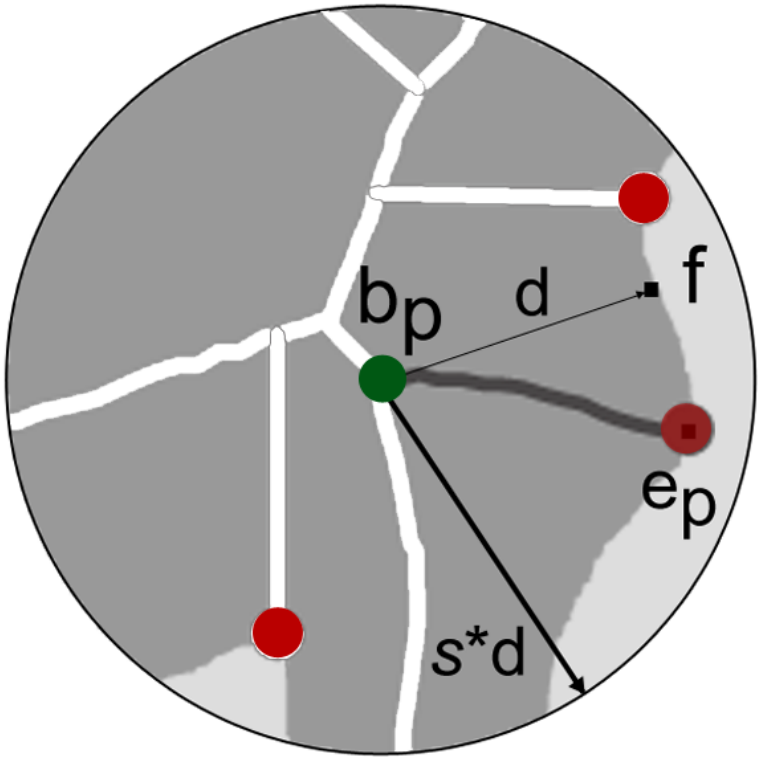




Time complexity: O(n)
n: skeleton pixels

3. Check every branch chain for removal





Time complexity: O(n)
n: skeleton pixels

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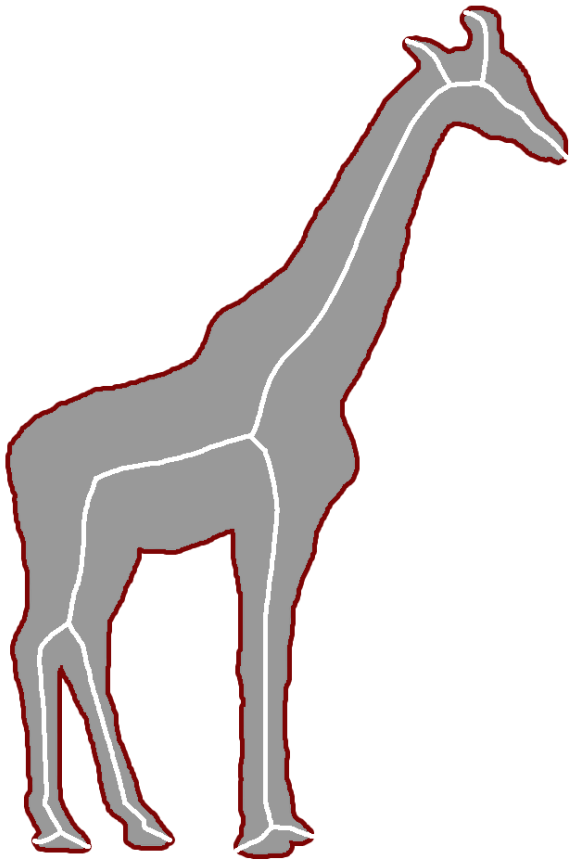

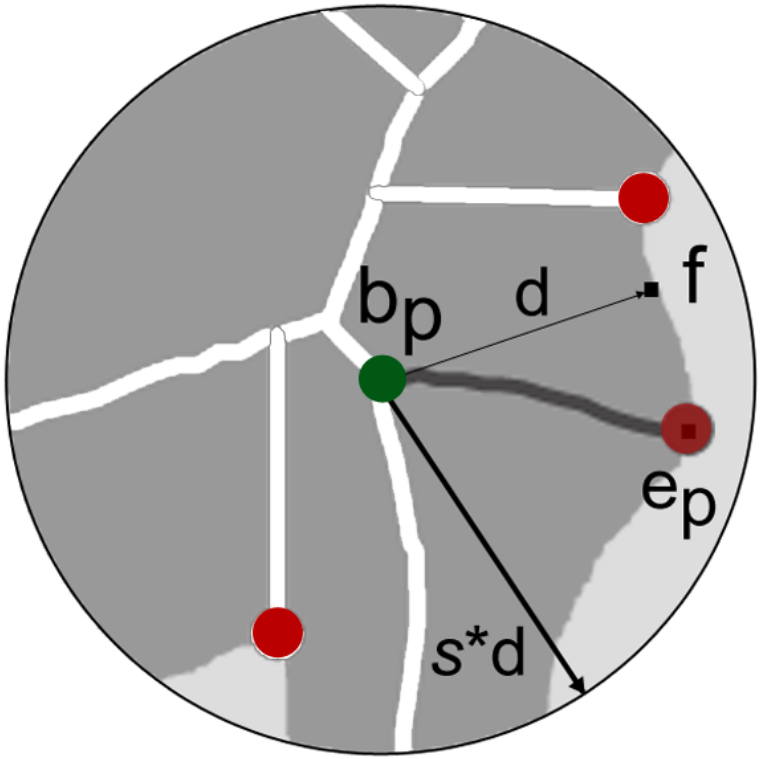

Time complexity: O(n)
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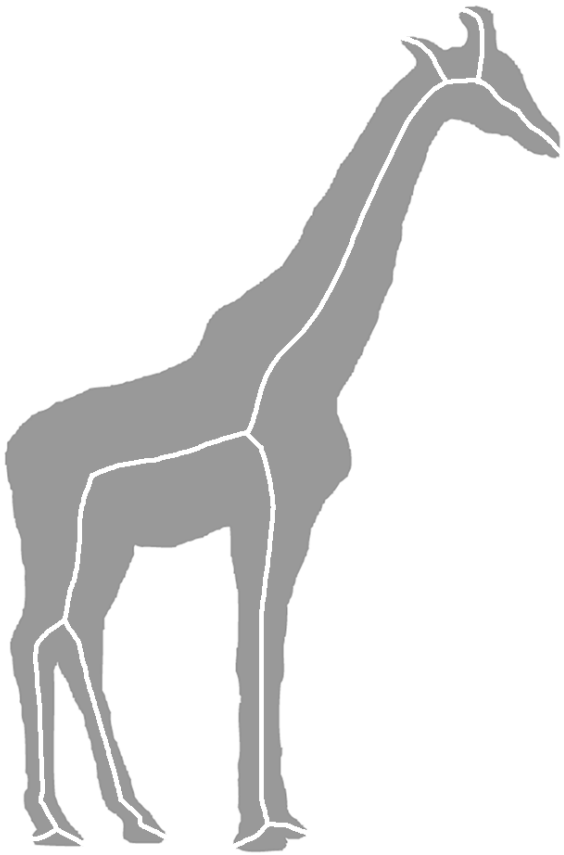
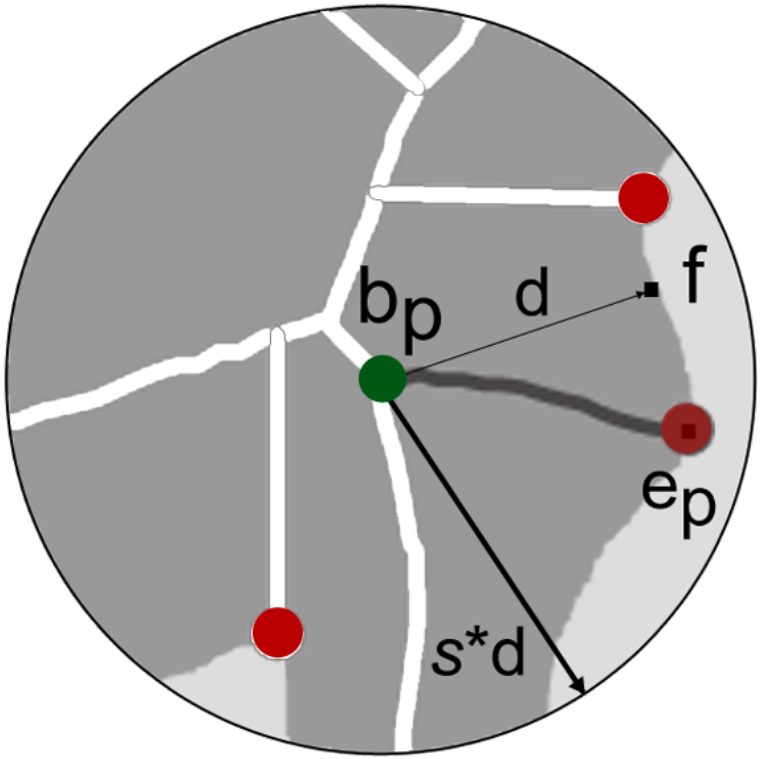
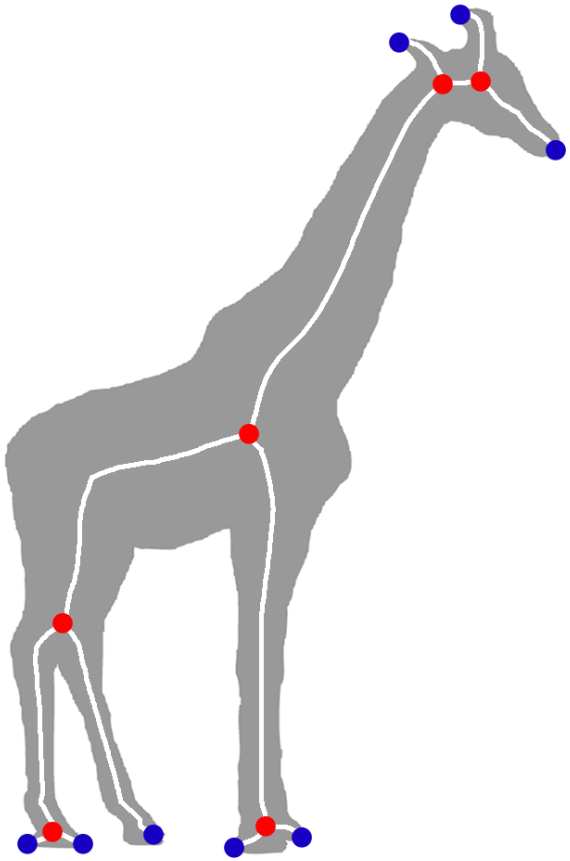
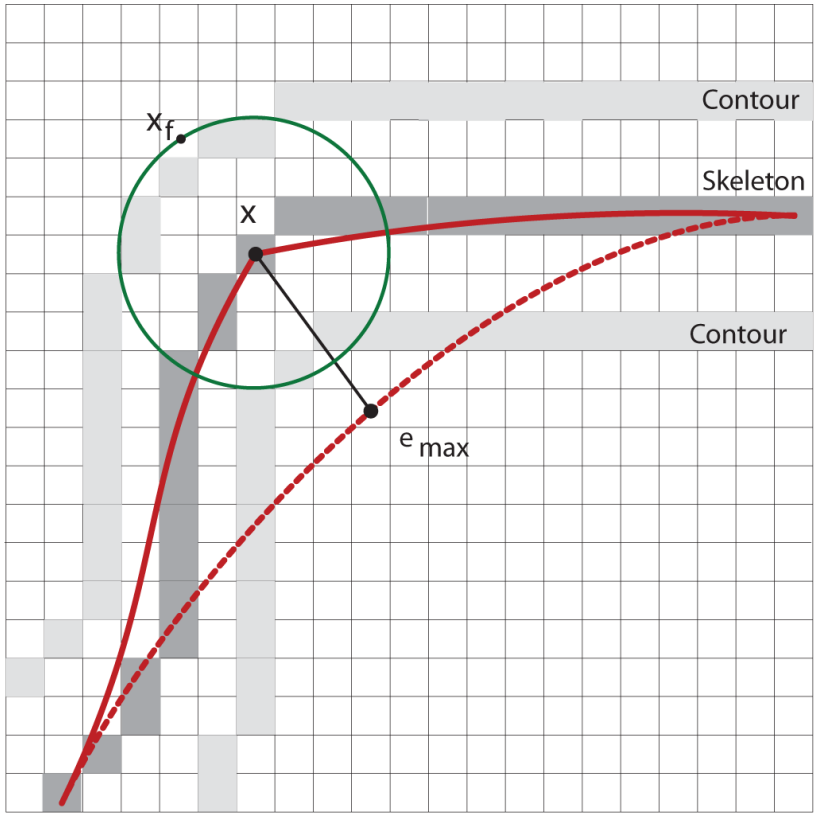




Time complexity: O(n)
n: skeleton pixels

4. Vectorize skeleton

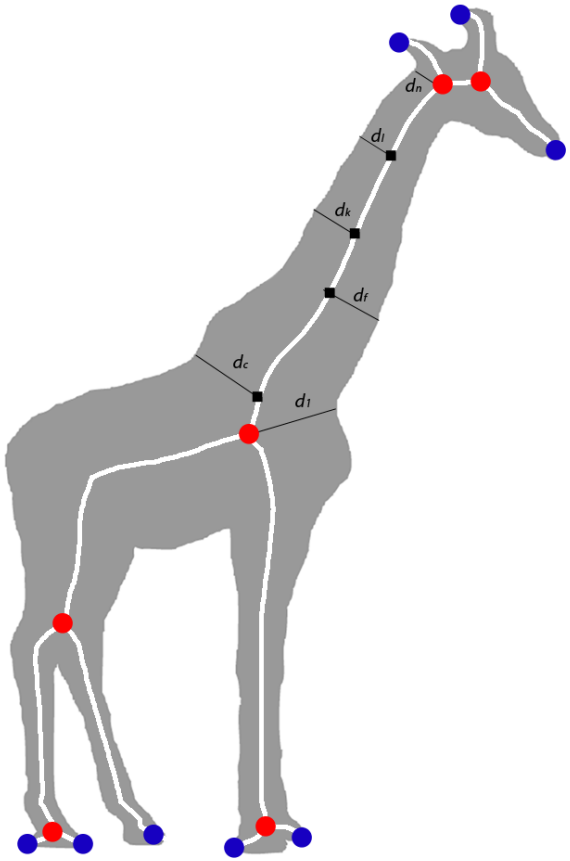


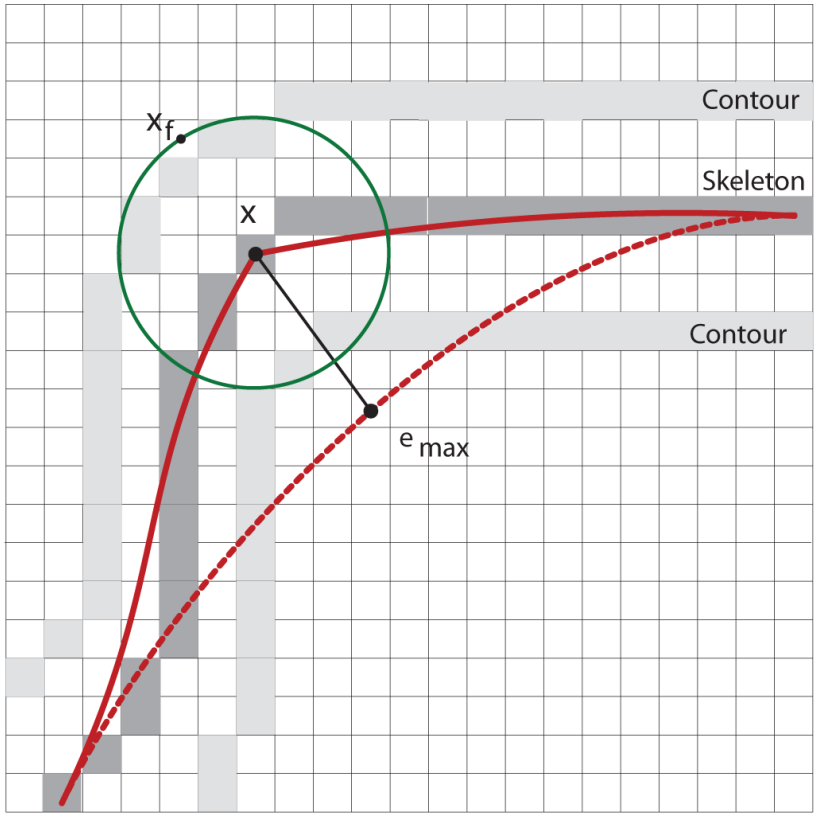


$$\| x_f - x \| < e_{max} < T$$

Time complexity: O(kn)
k: number of knots
n: skeleton pixels

4. Vectorize skeleton

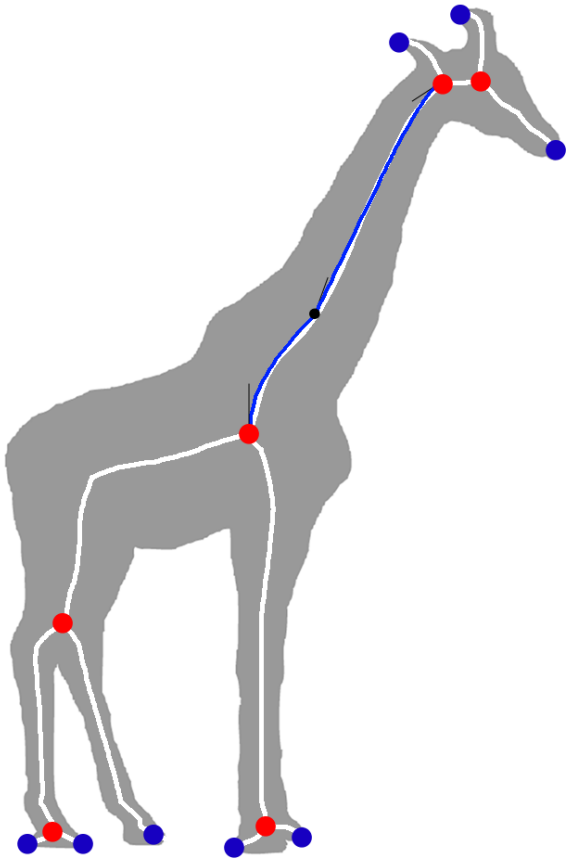


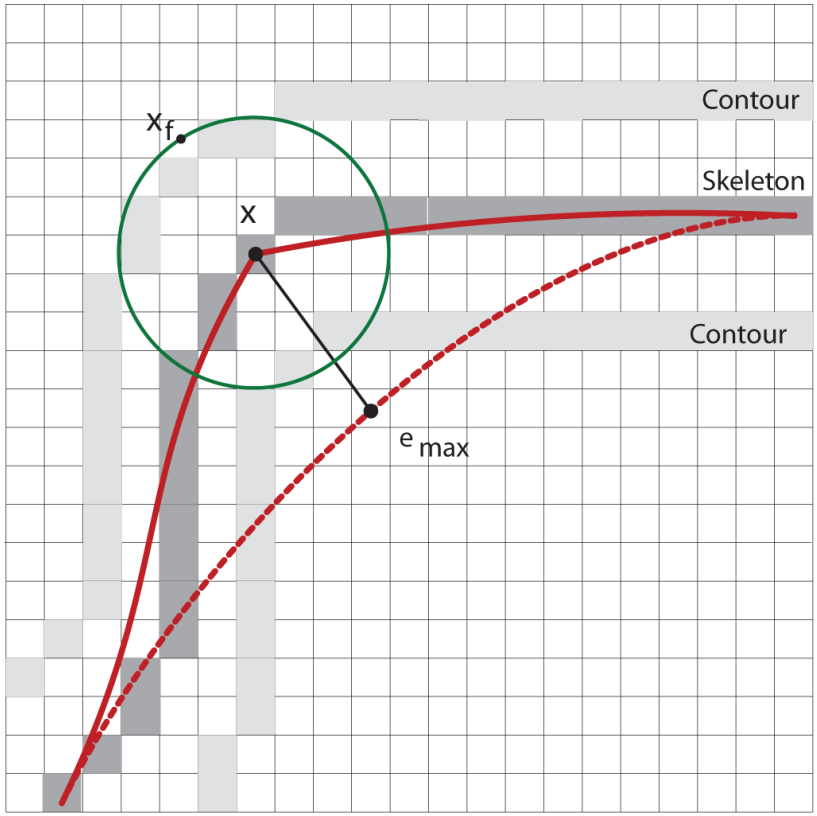


$$\| x_f - x \| < e_{max} < T$$

Time complexity: O(kn)
k: number of knots
n: skeleton pixels

4. Vectorize skeleton

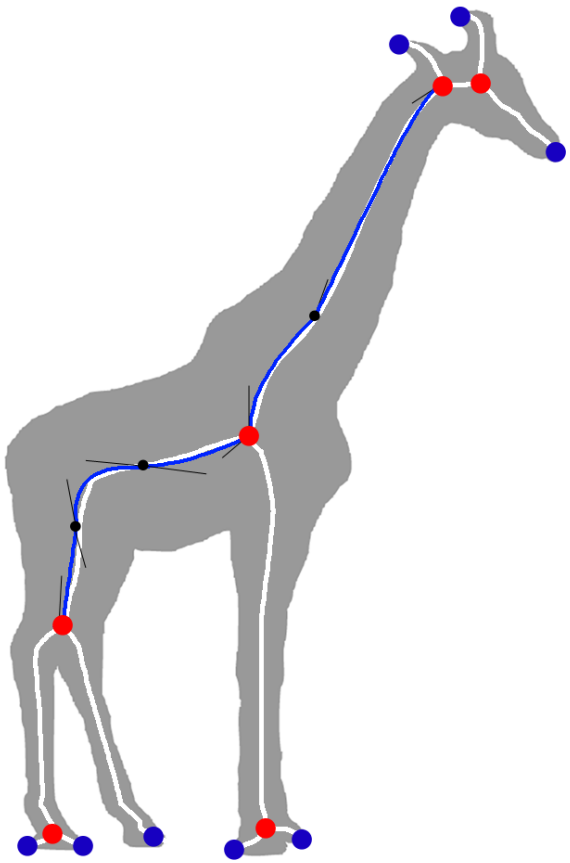


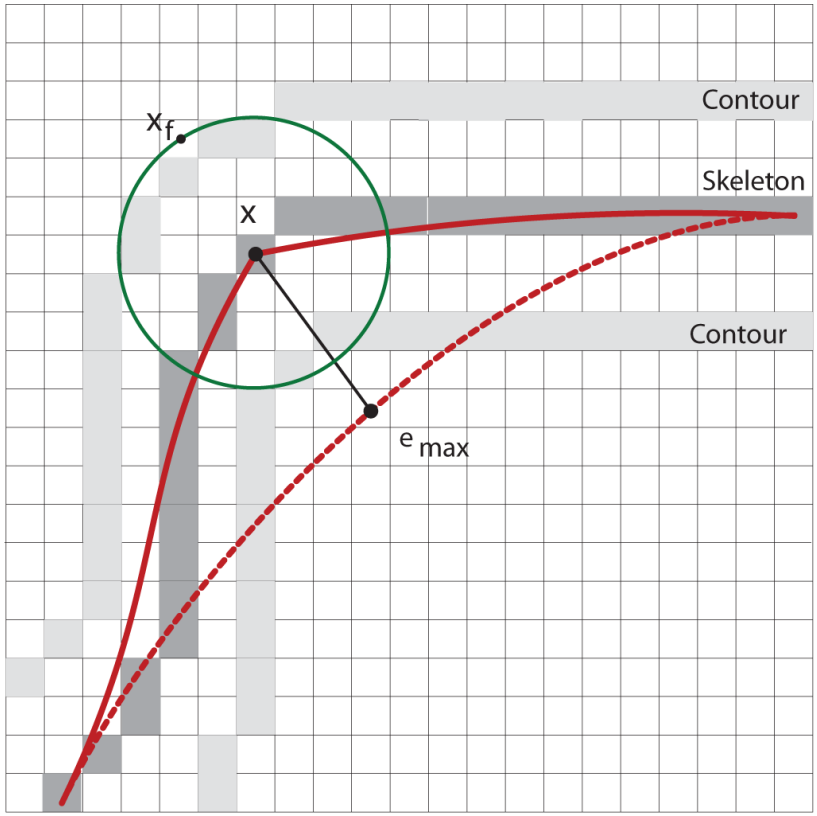


$$\| x_f - x \| < e_{max} < T$$

Time complexity: O(kn)
k: number of knots
n: skeleton pixels

4. Vectorize skeleton





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Time complexity: O(kn)
k: number of knots
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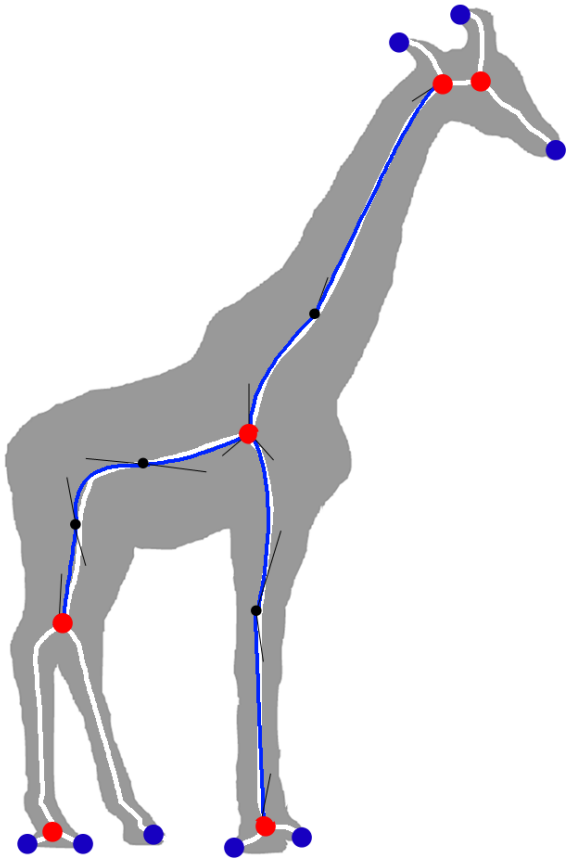
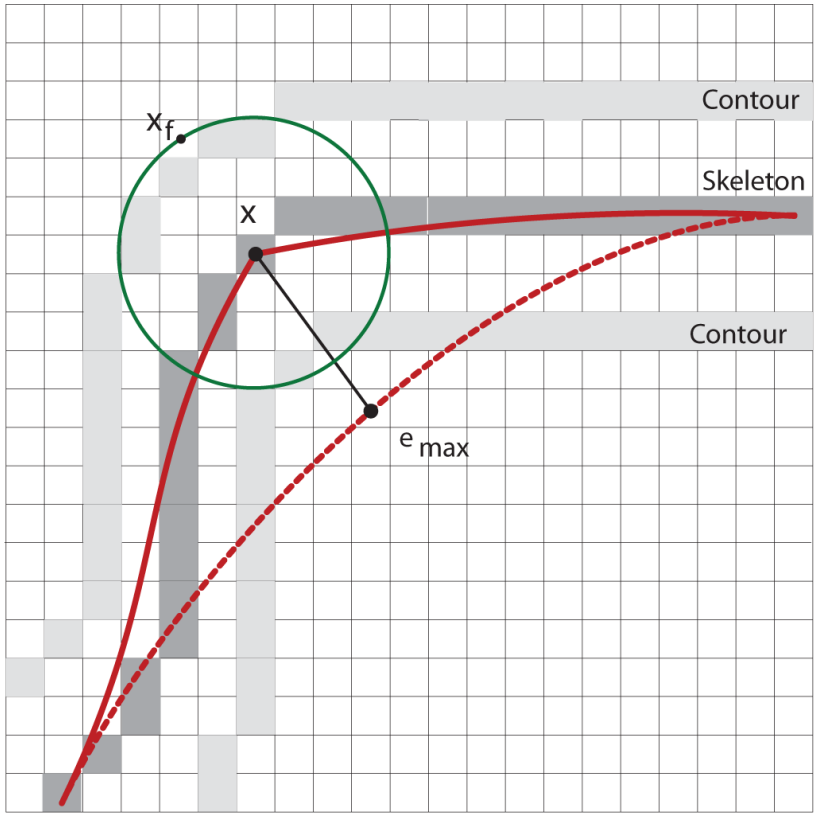
4. Vectorize skeleton





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Time complexity: O(kn)
k: number of knots
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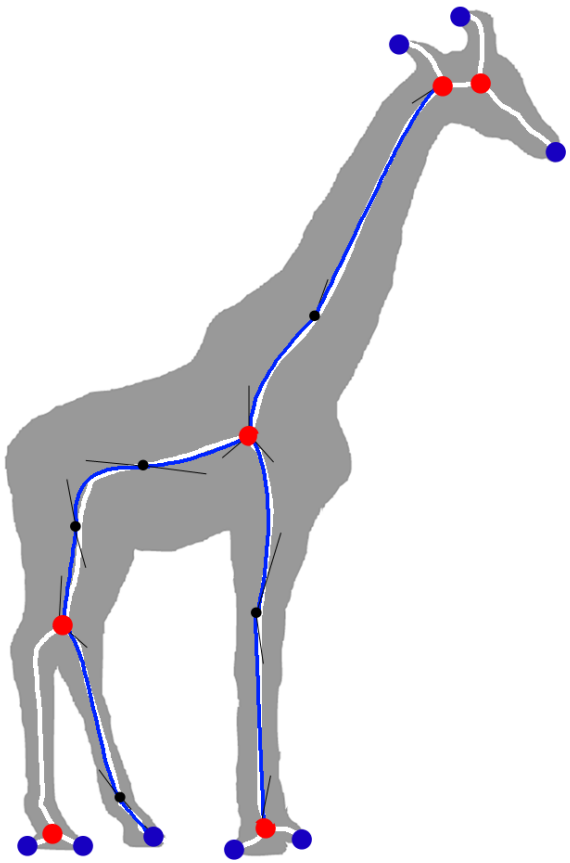
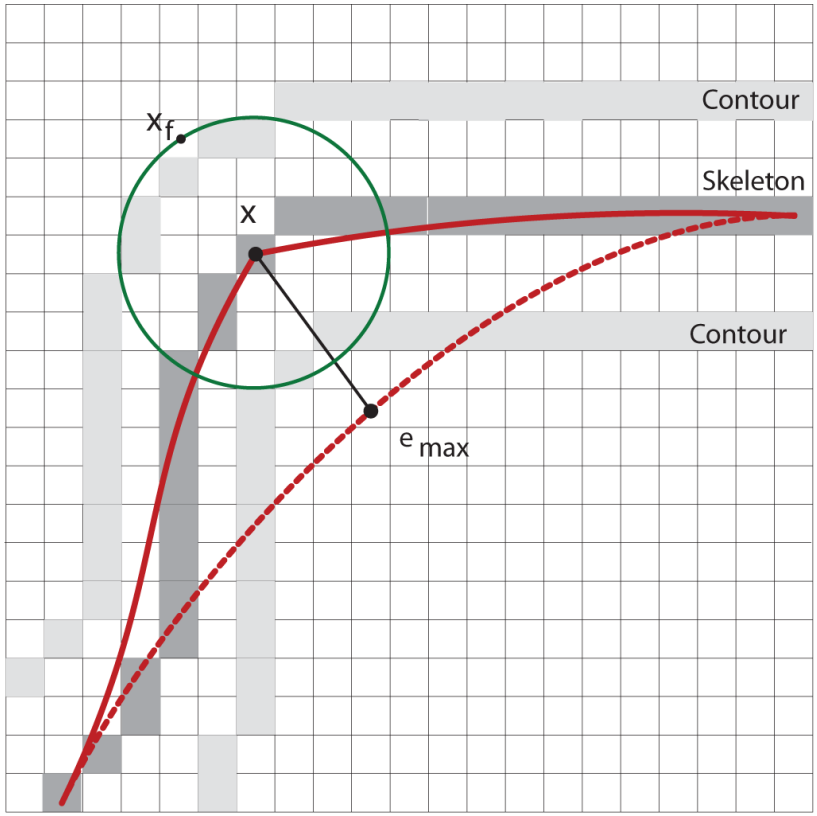
4. Vectorize skeleton





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Time complexity: O(kn)
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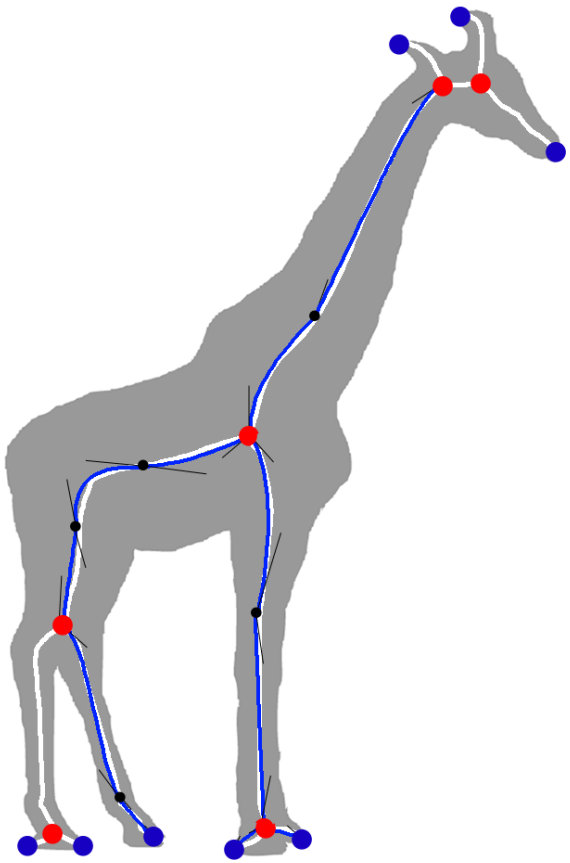

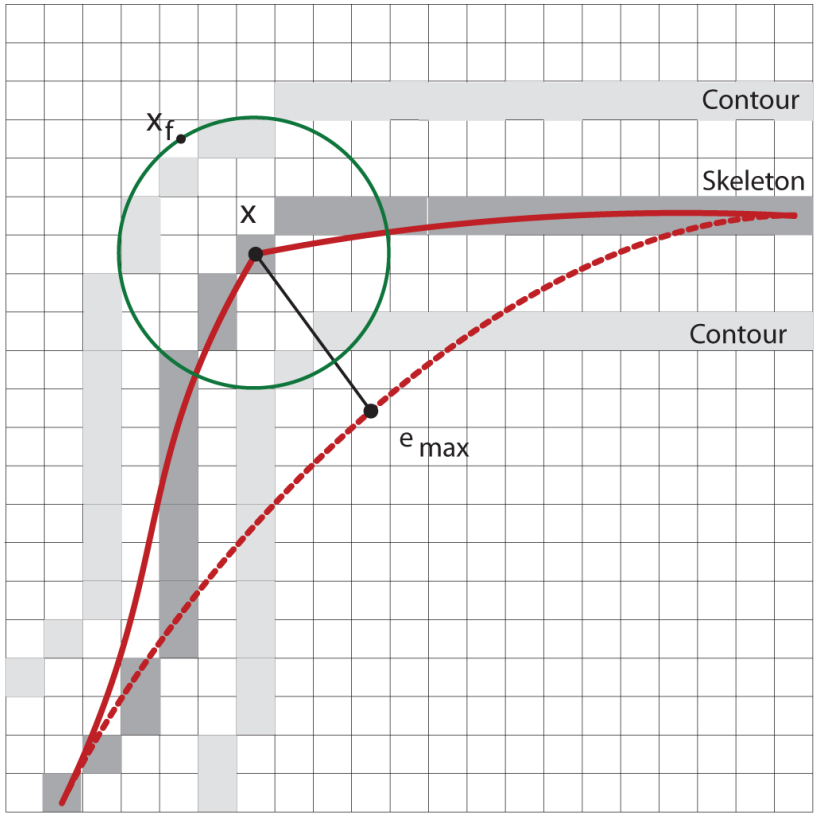

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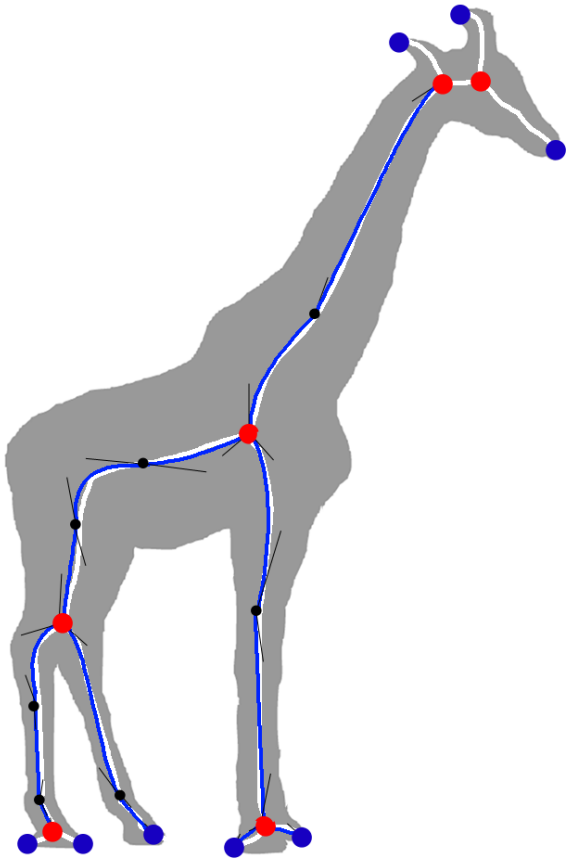

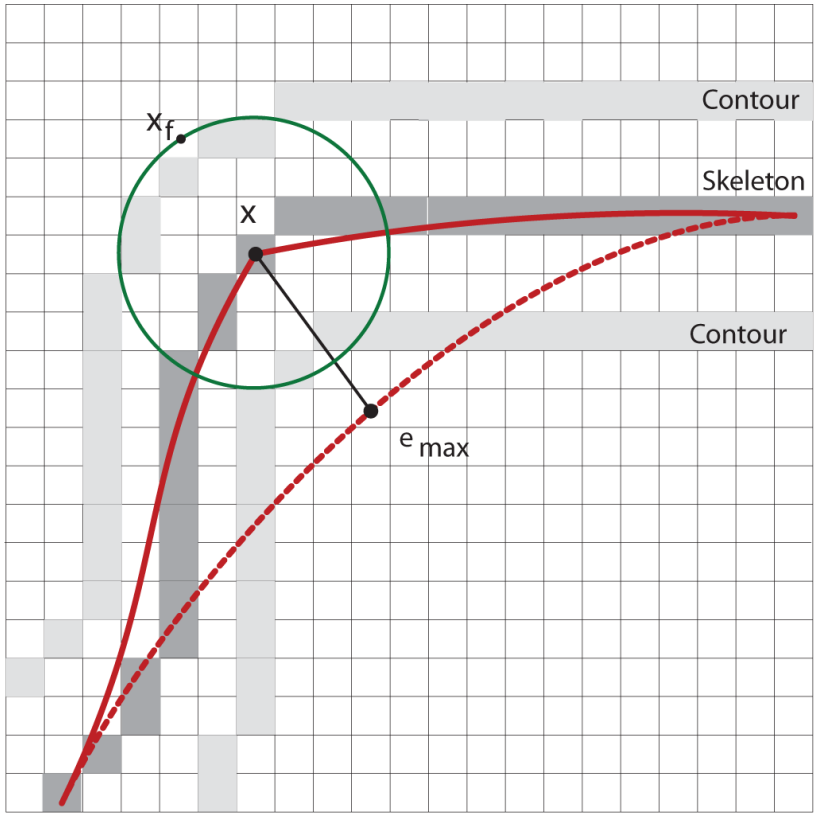

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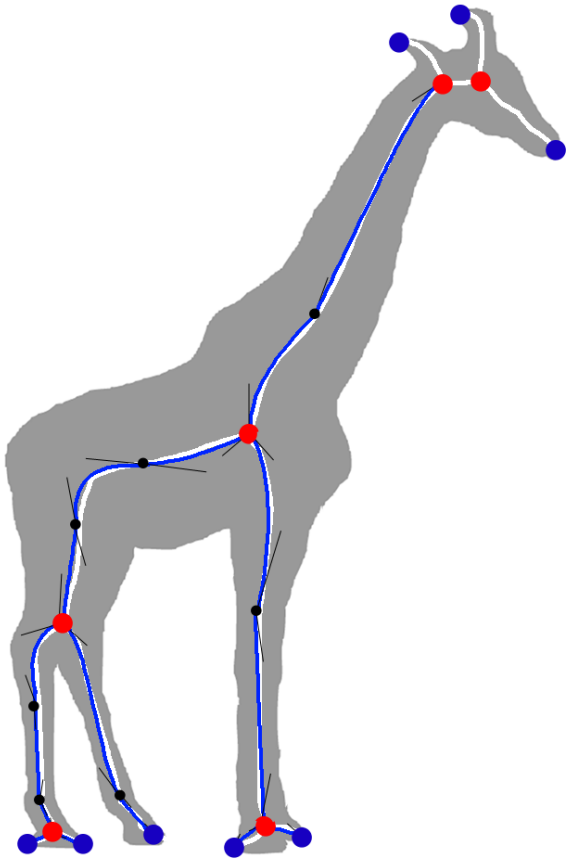

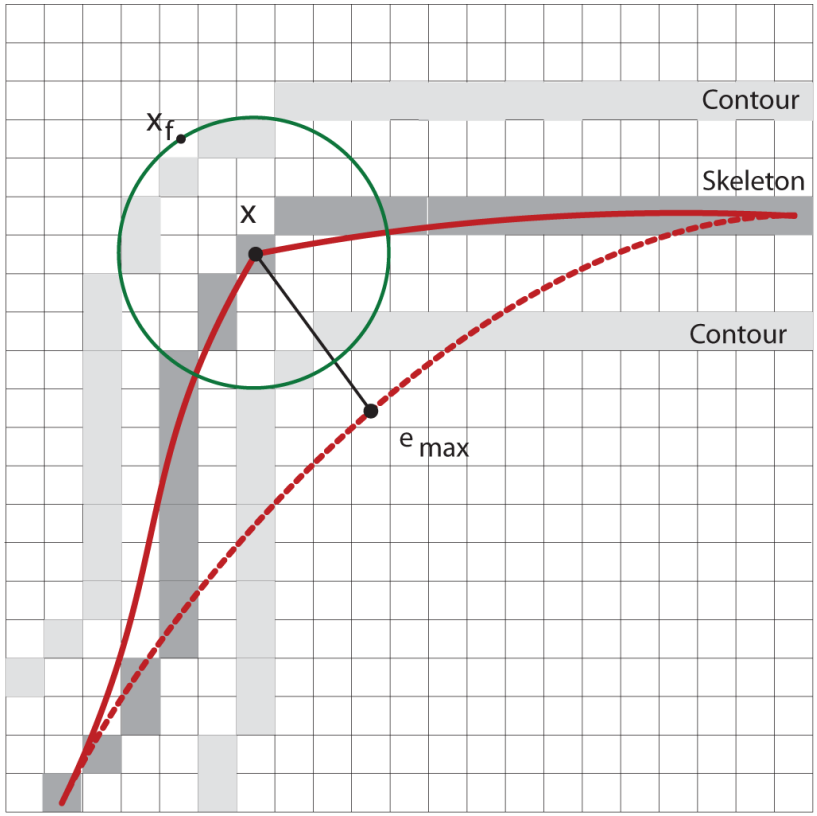

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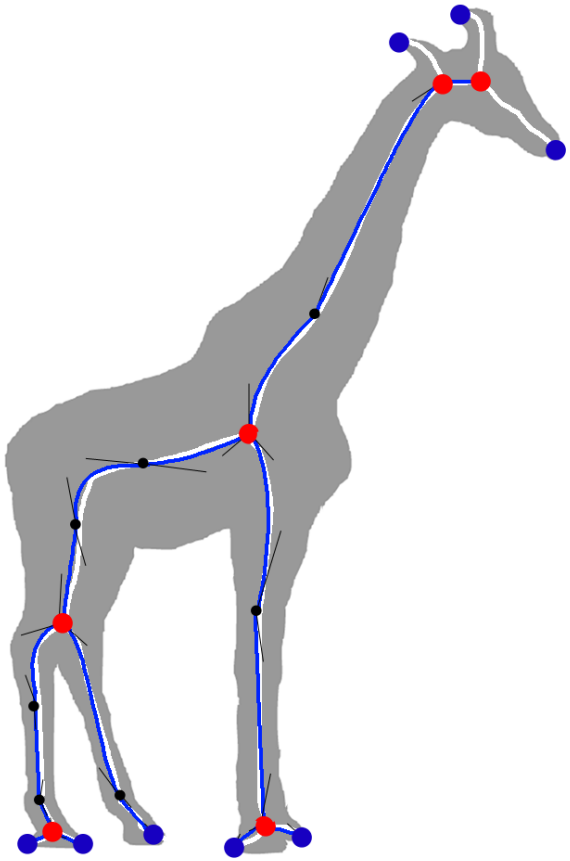

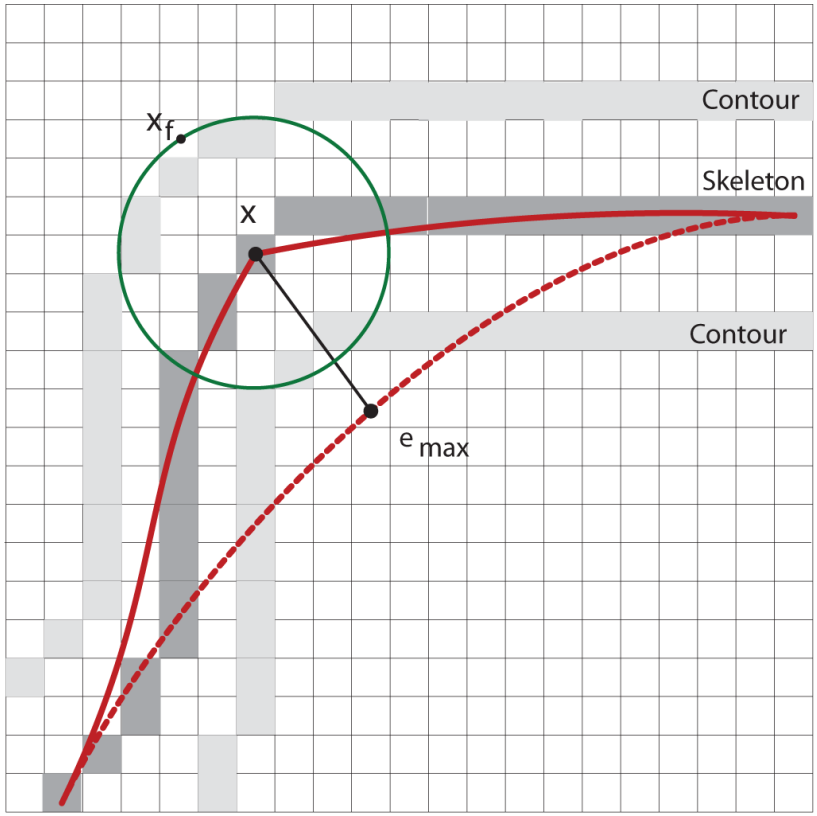

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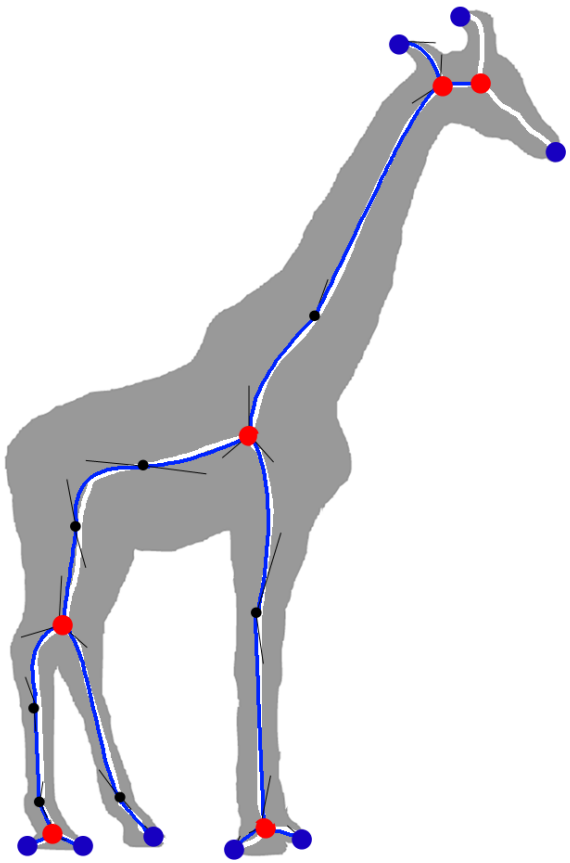
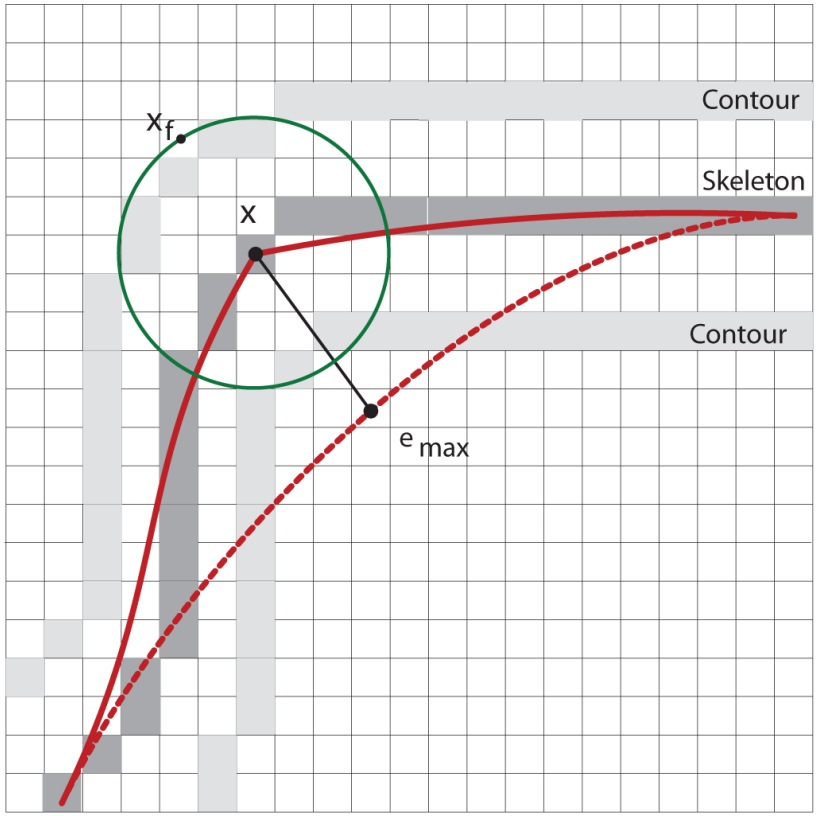
4. Vectorize skeleton

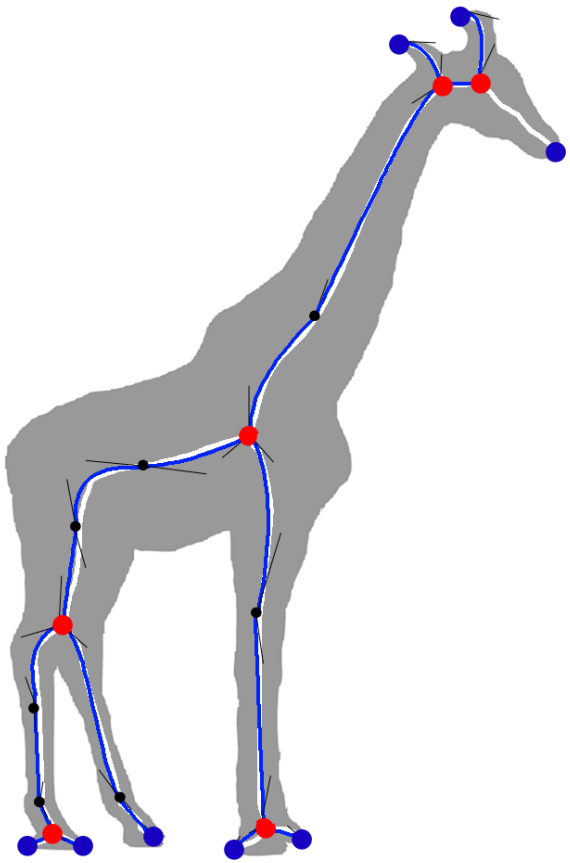


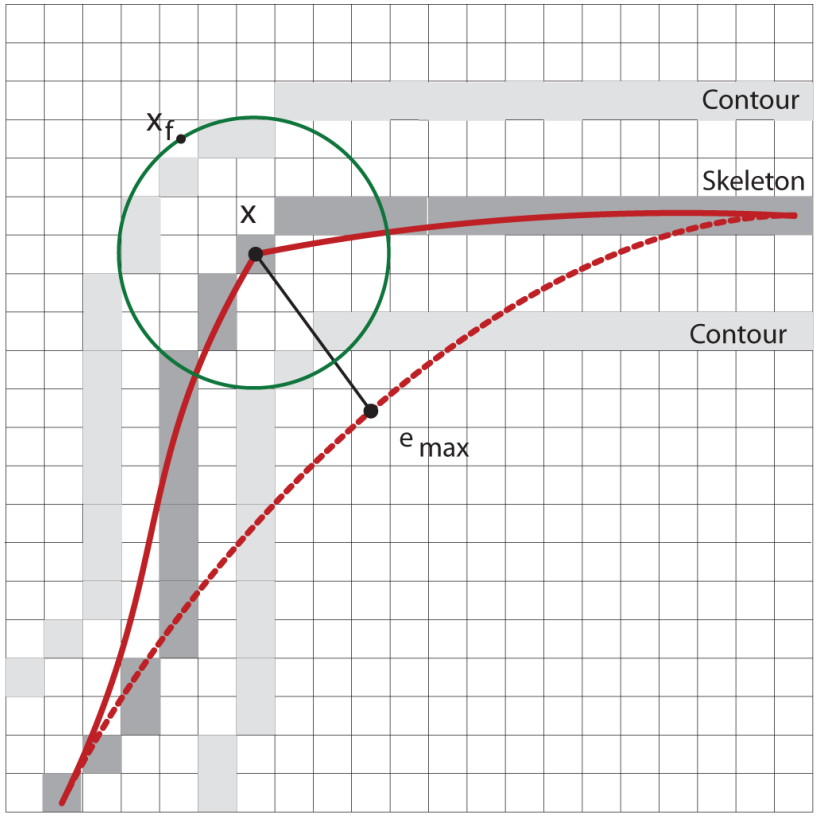


$$\| x_f - x \| < e_{max} < T$$

Time complexity: O(kn)
k: number of knots
n: skeleton pixels

4. Vectorize skeleton





$$\| x_f - x \| < e_{max} < T$$

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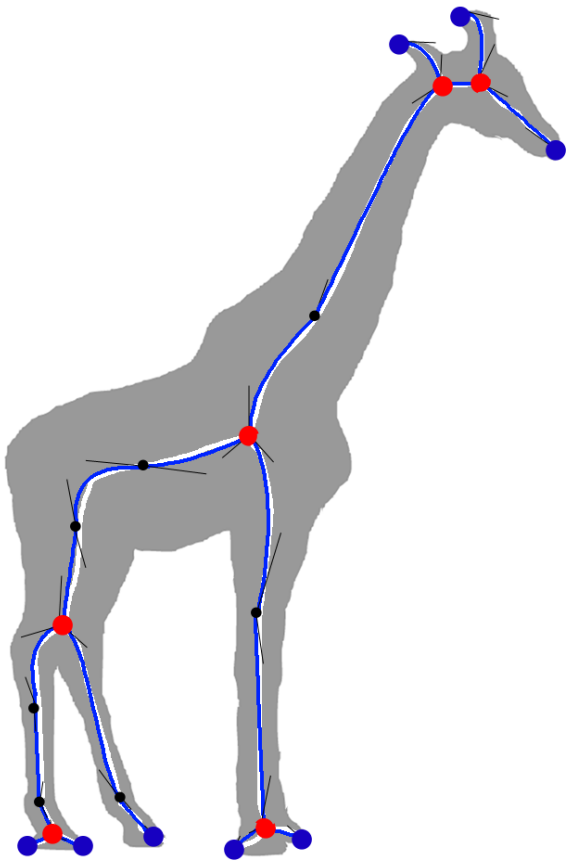
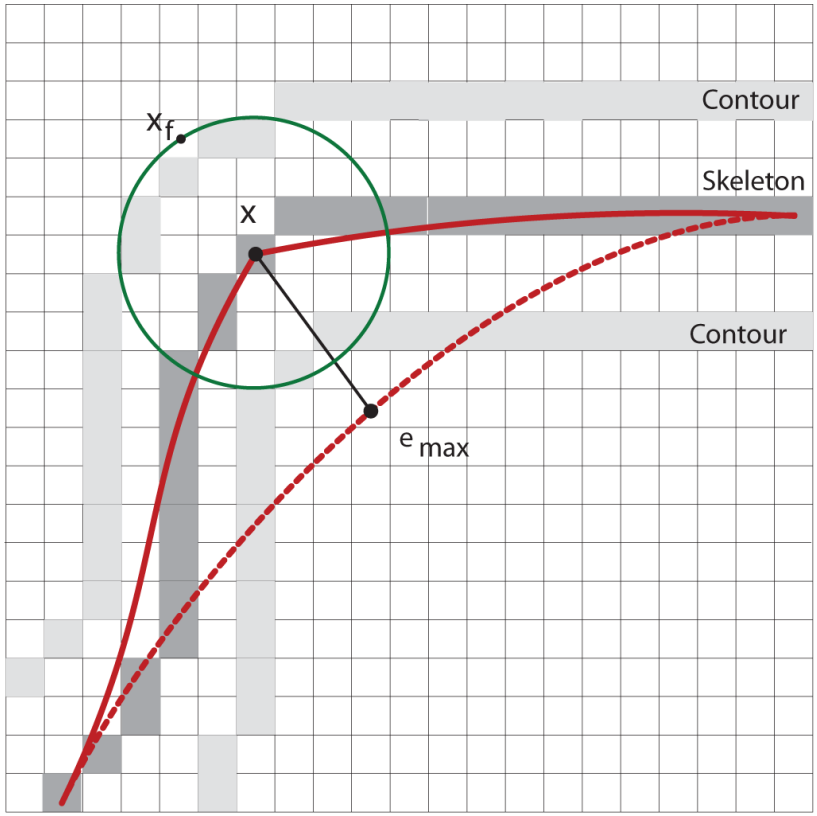
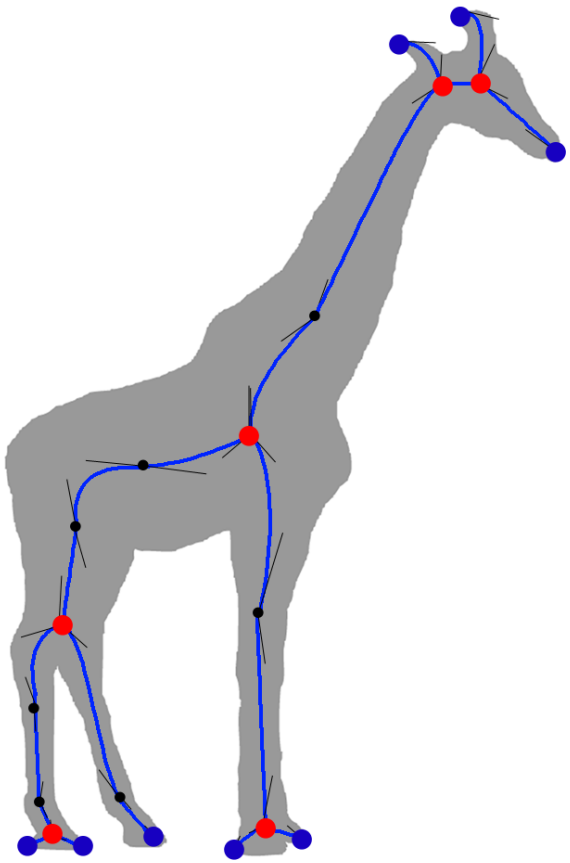


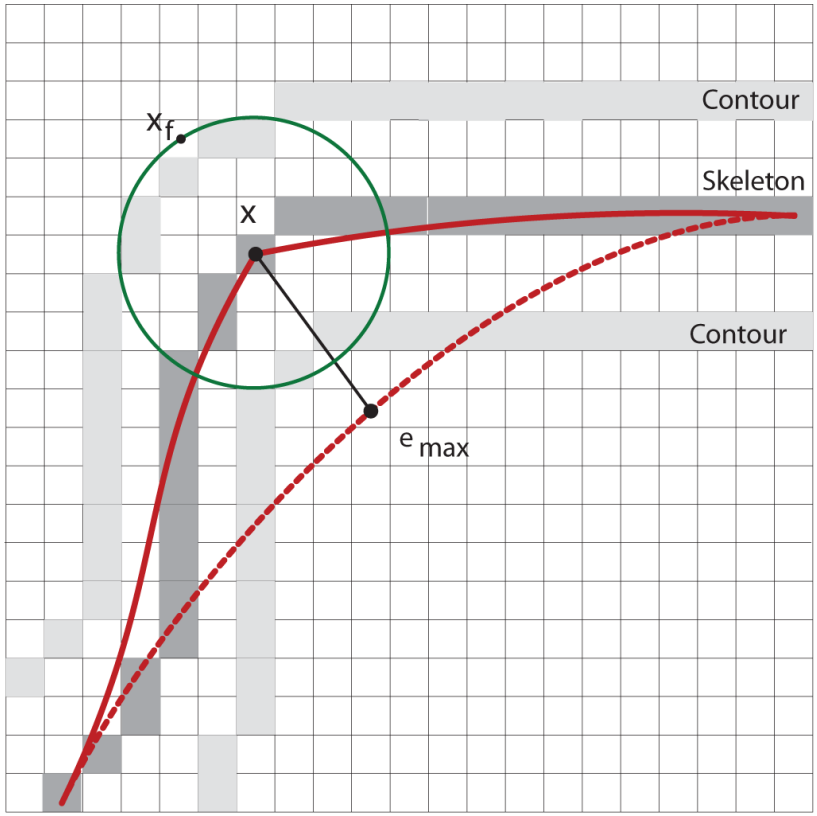


$$\| x_f - x \| < e_{max} < T$$

Time complexity: O(kn)
k: number of knots
n: skeleton pixels

4. Vectorize skeleton





$$\| x_f - x \| < e_{max} < T$$

Time complexity: O(kn)
k: number of knots
n: skeleton pixels

Experiment

Dataset

Experiments were done on the mpeg-7 dataset (1401 images), testing for accuracy, running time, connectivity, shape reconstruction, rotation invariance, noise sensitivity, and parameter selection.

Resolution of Images

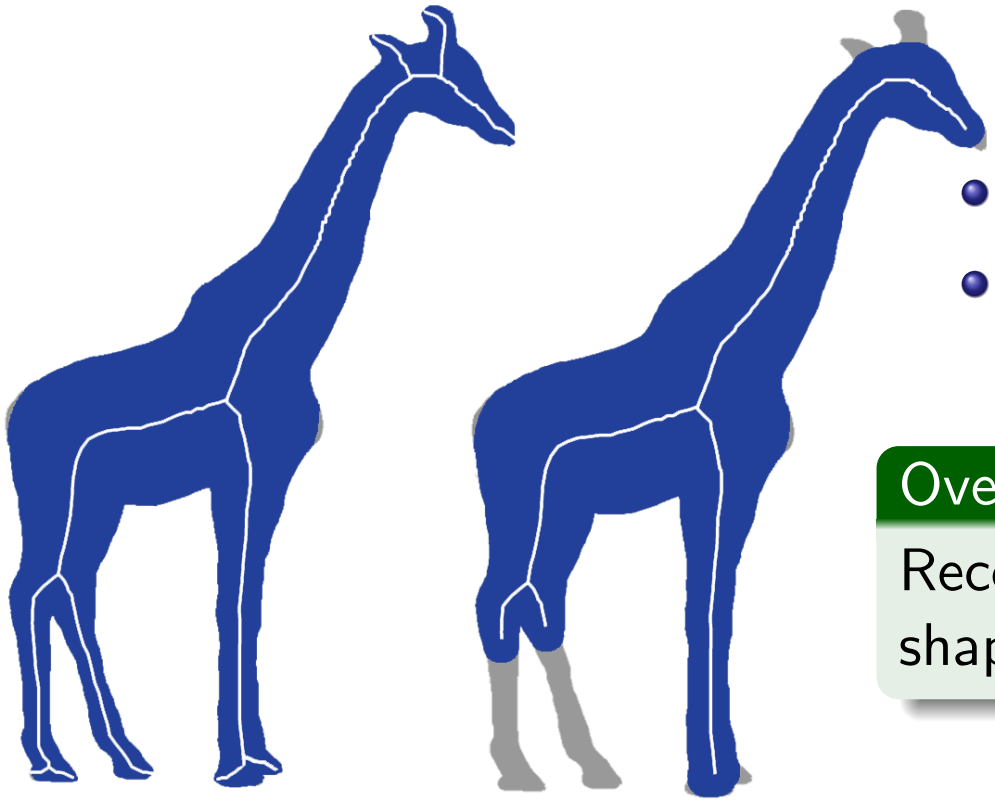
Image resolutions ranged from [256x256] to [950x800]

Experimental Results

Running Time

Algorithm	95% Confidence Interval
IMA+D,A	0.08 ± 0.01 sec
Linear	0.09 ± 0.004 sec
Cubic	0.10 ± 0.009 sec
Scale Axis Transform	0.17 ± 0.013 sec
Thinning	0.35 ± 0.018 sec
Voronoi	0.68 ± 0.021 sec
DCE	5.13 ± 0.518 sec

Experimental Results — Shape reconstruction

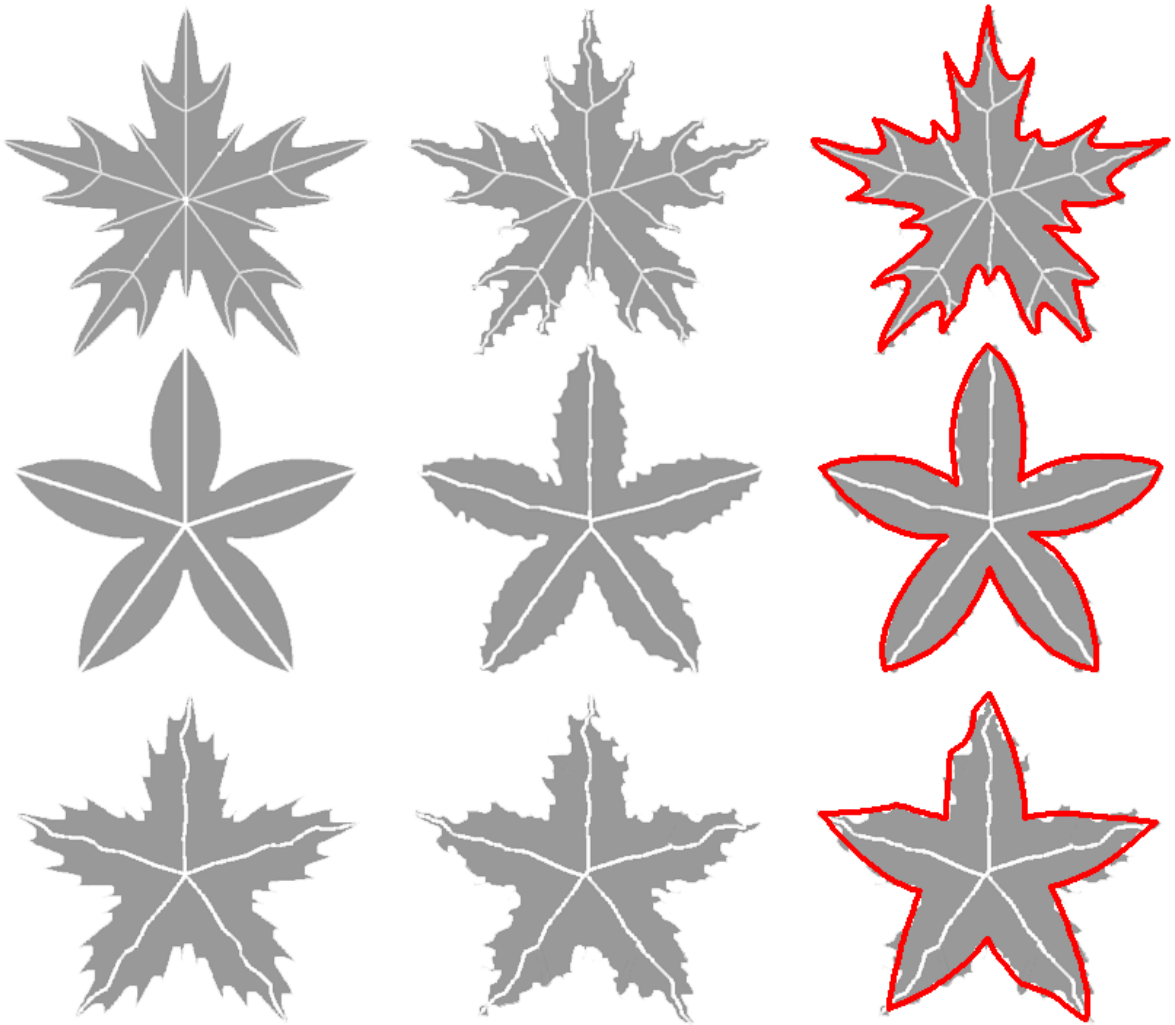


- Left: Our solution.
- Right: IMA + Angular Pruning.

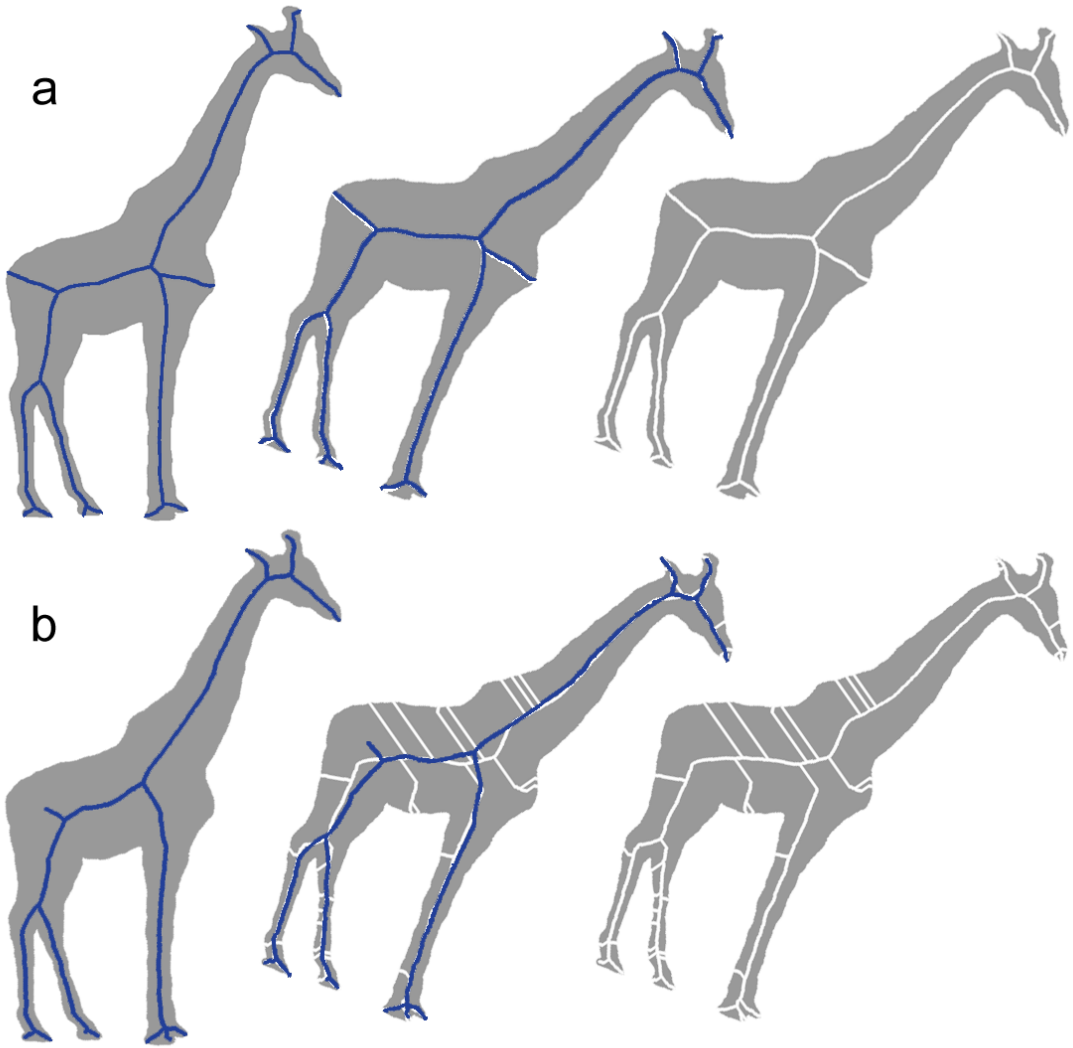
Overall

Reconstruction of the original shape 98 % (average) in area.

Experimental Results — Noise invariant

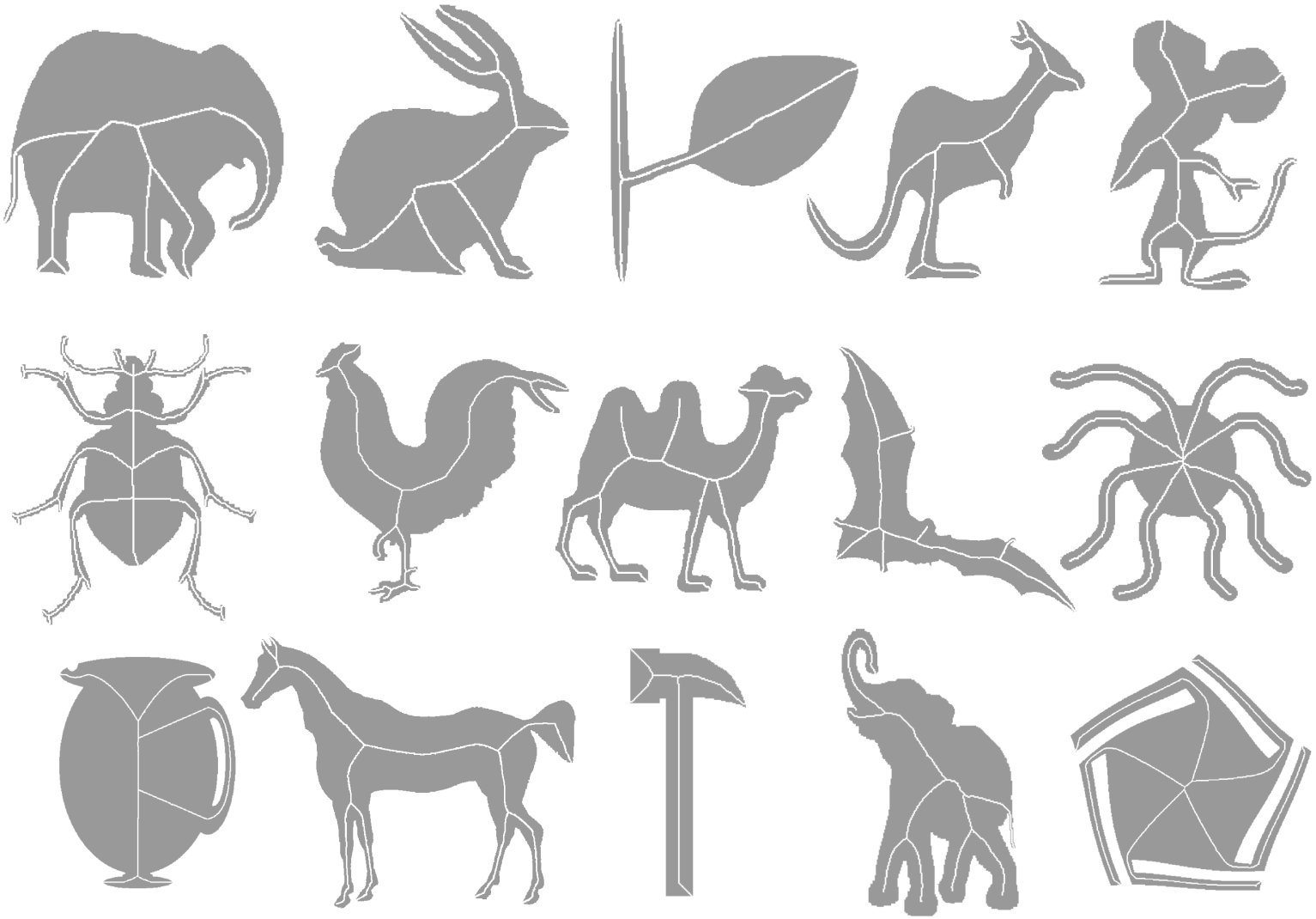


Experimental Results — Rotation Invariance

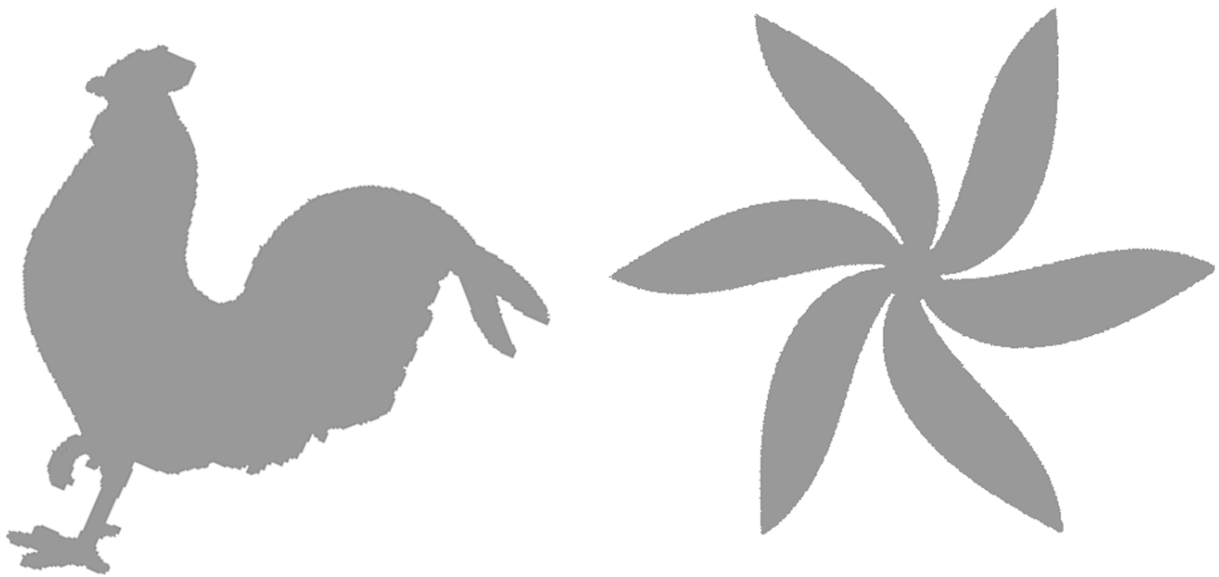


Experimental Results — Complex shapes

Experimental Results — Parameter Selection

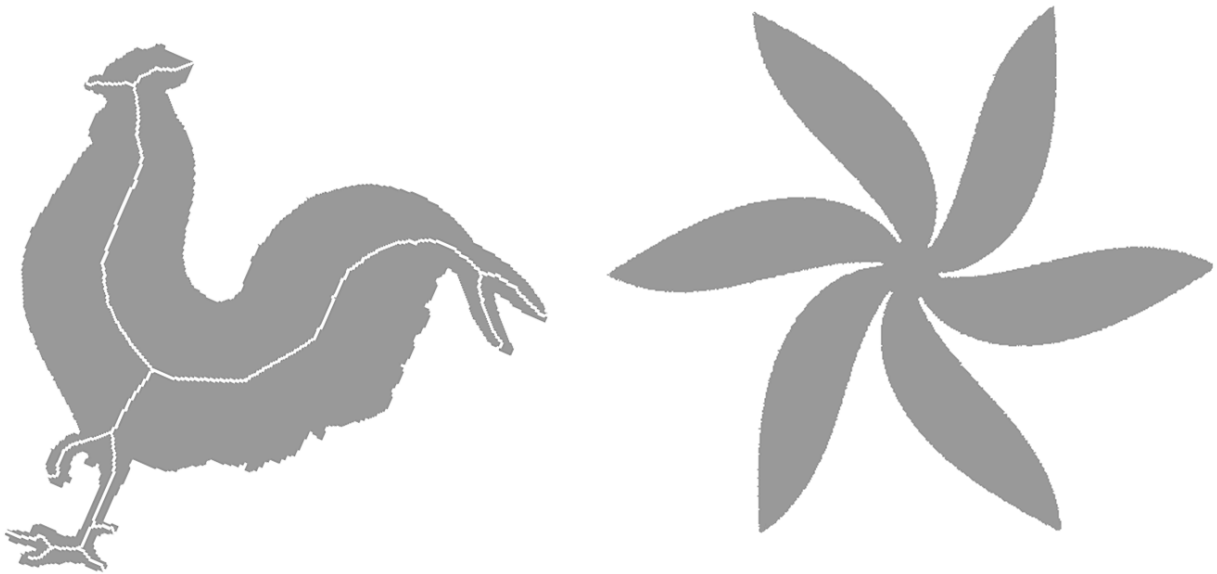


More Examples



The selected input parameters are the same

More Examples



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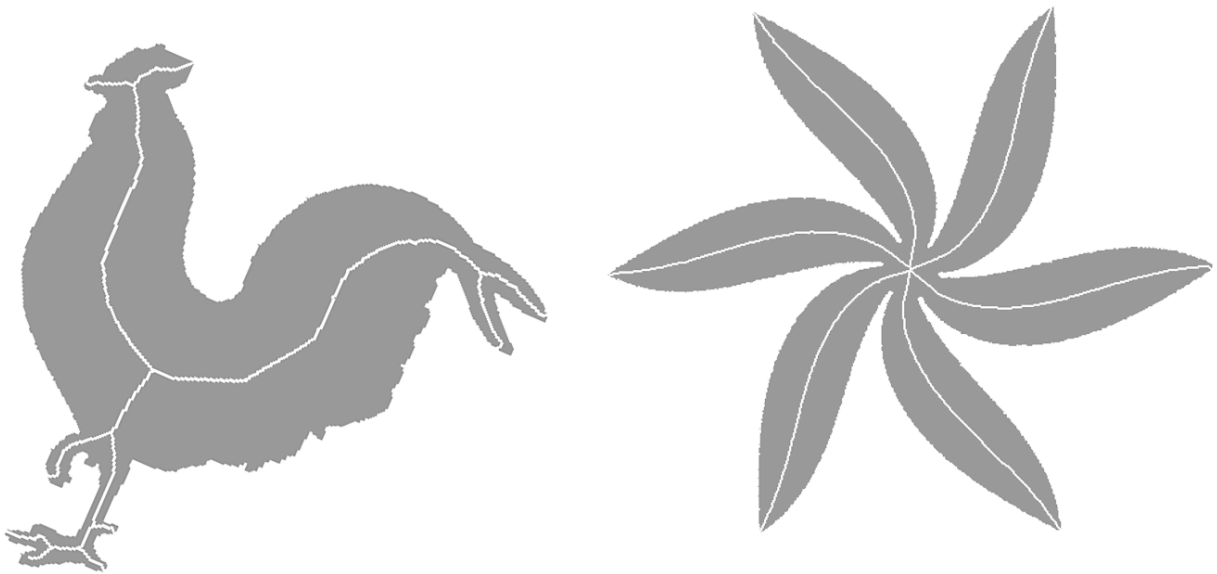
More Examples



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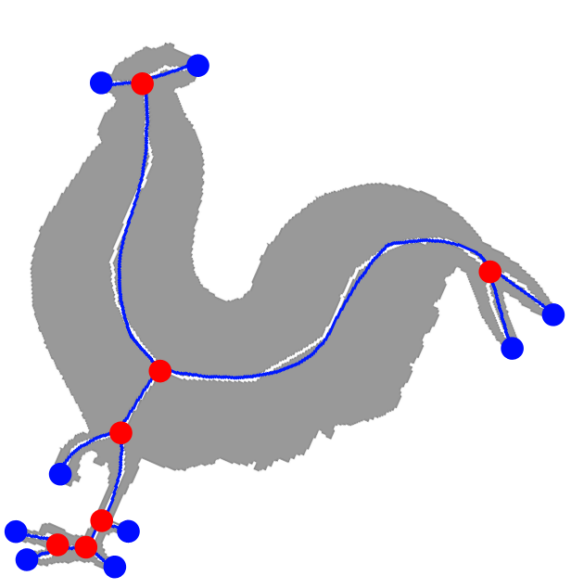
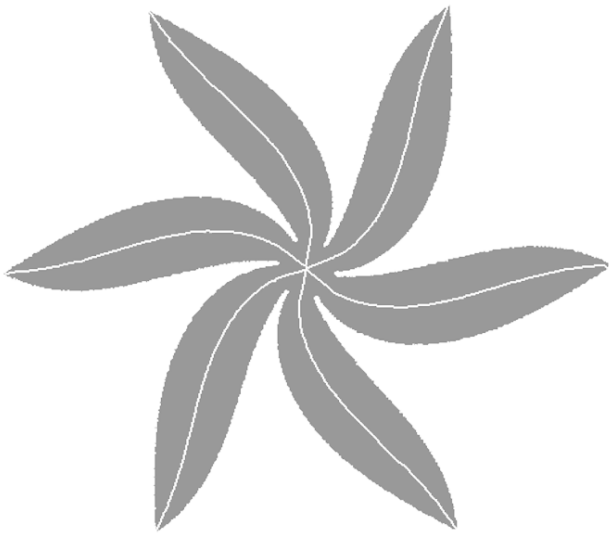
More Examples





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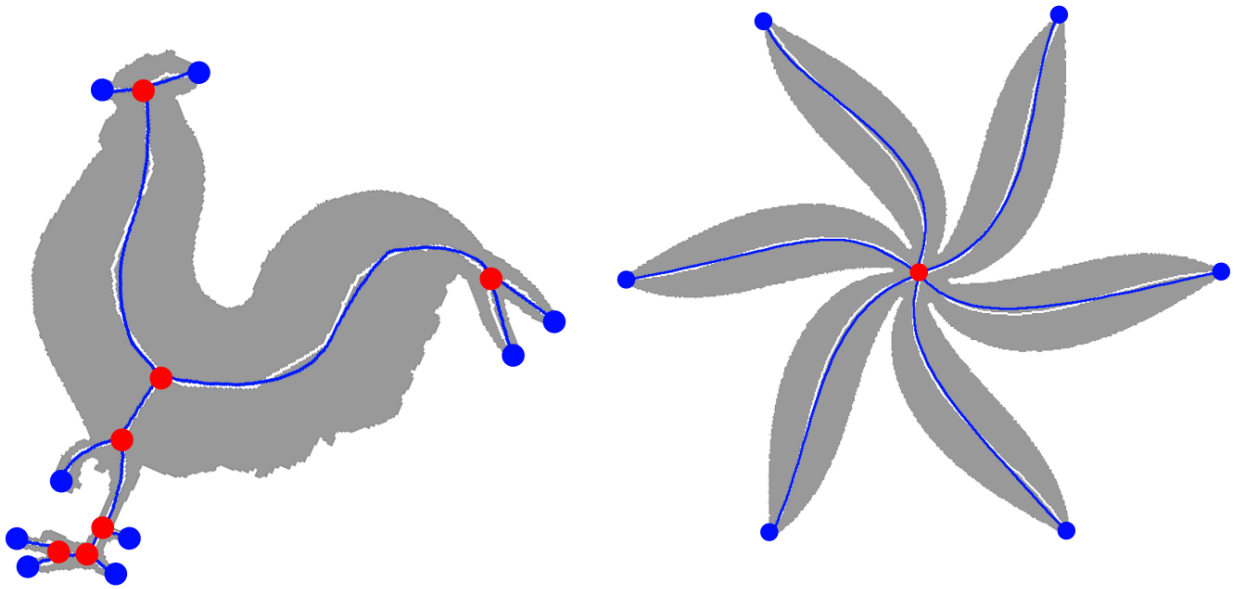
More Examples



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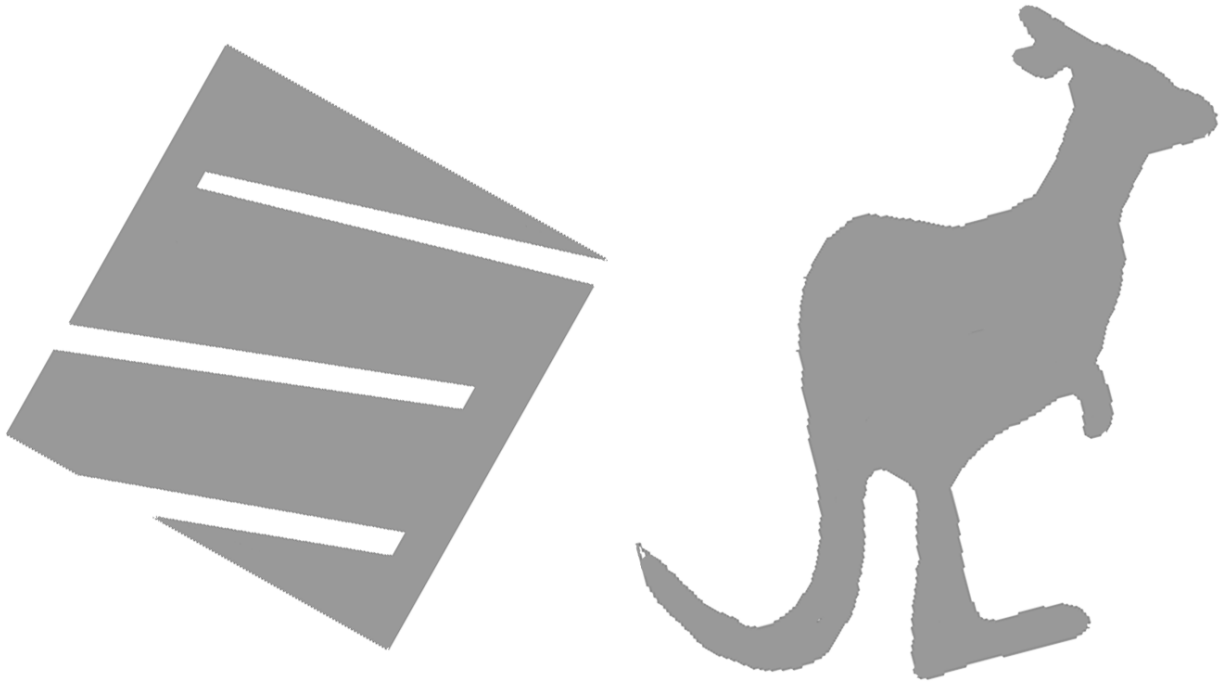
More Examples



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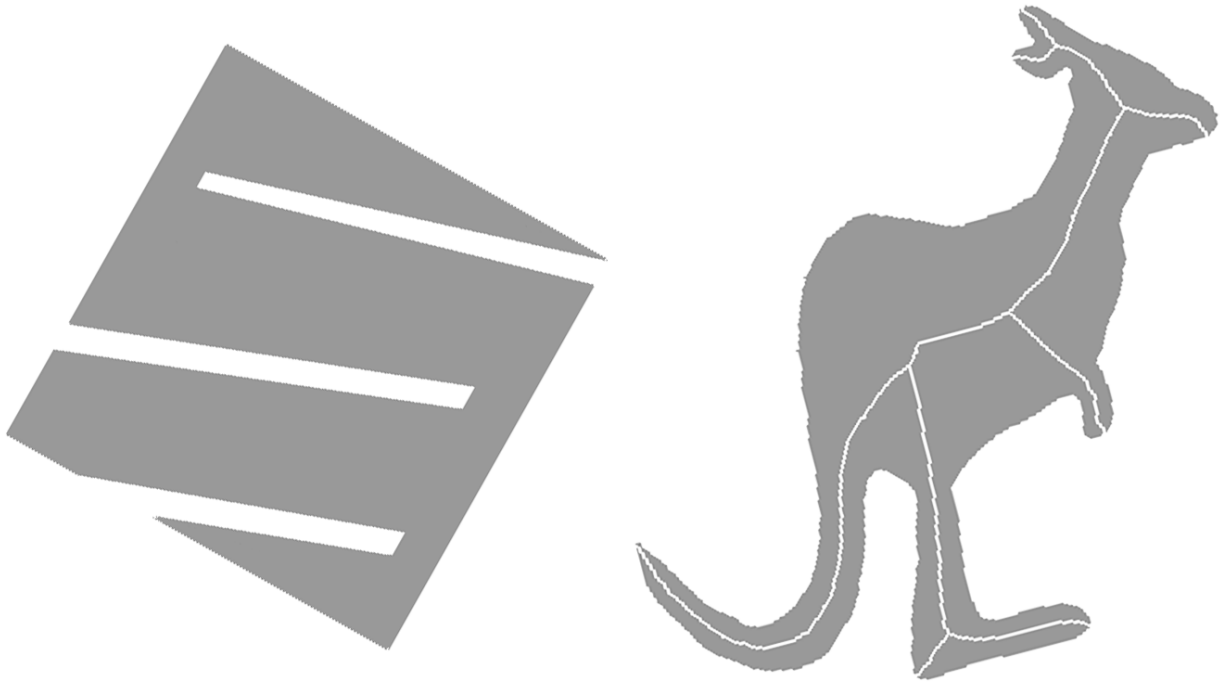
More Examples



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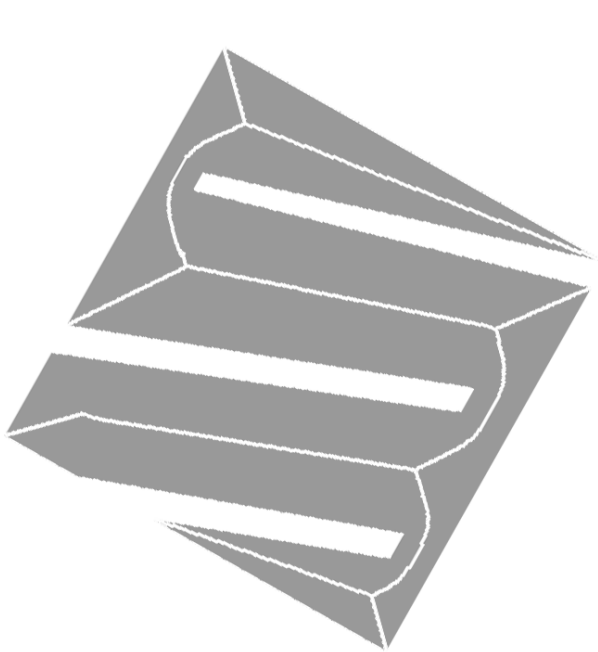
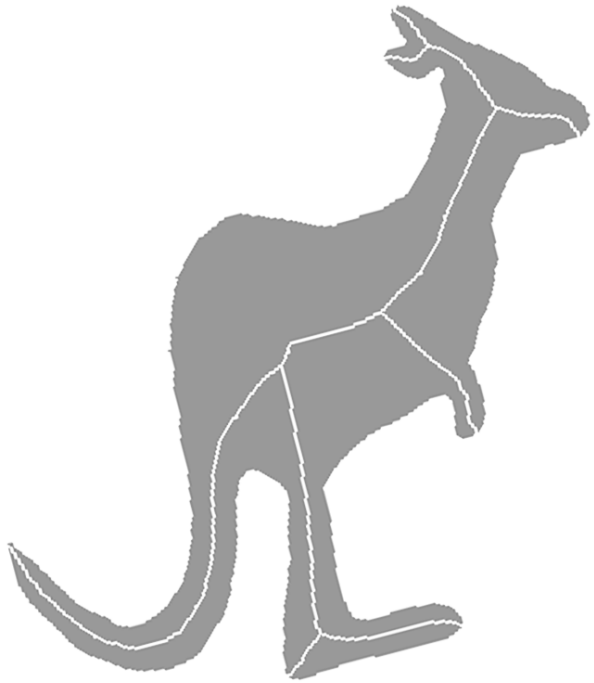
More Examples





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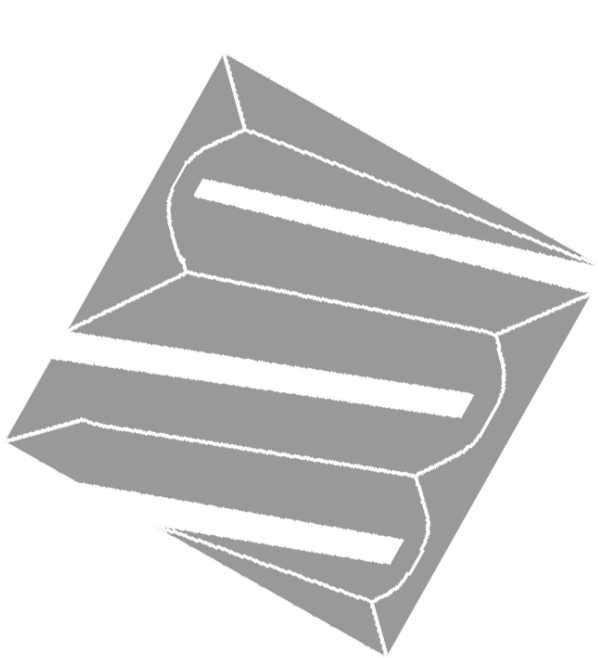
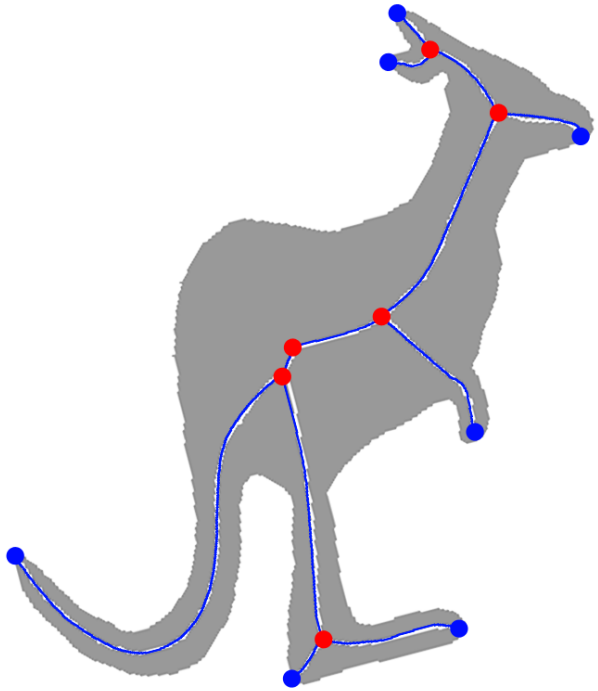
More Examples





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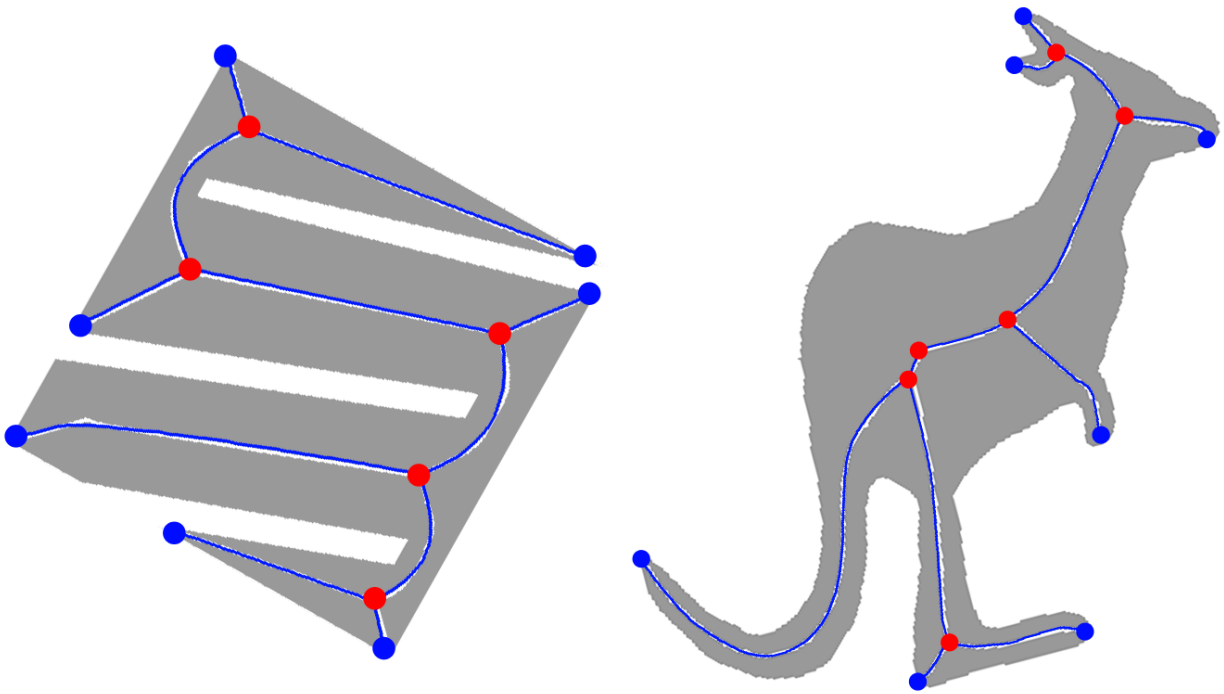

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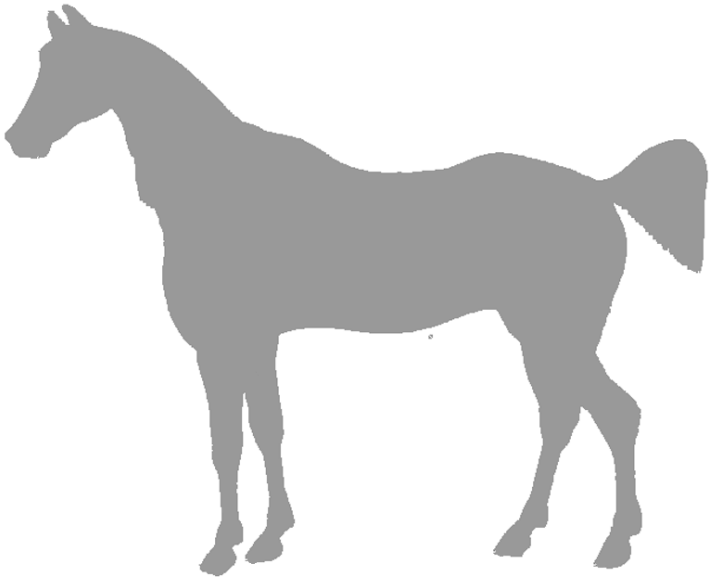
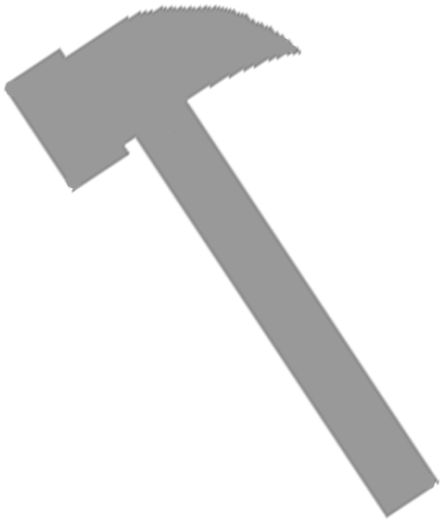
More Examples





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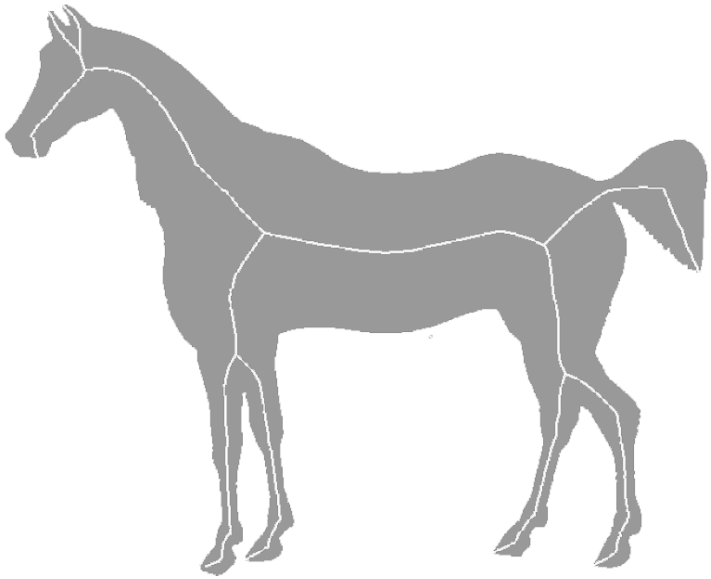
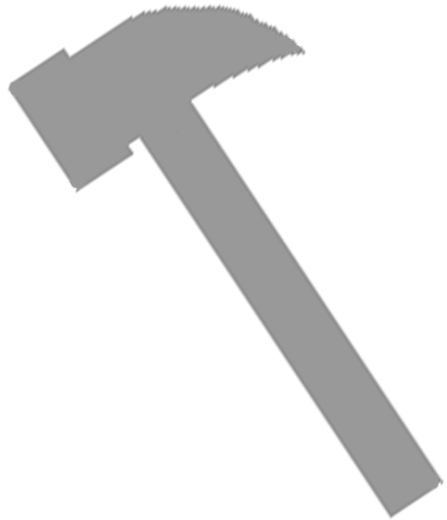
More Examples





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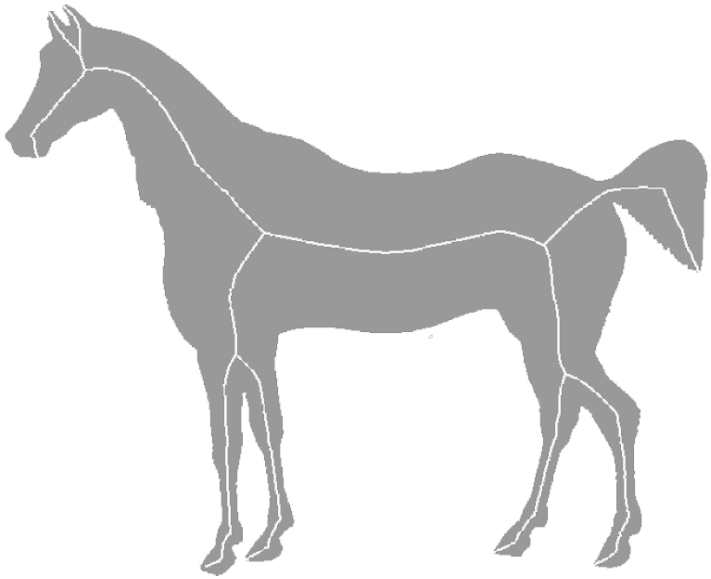
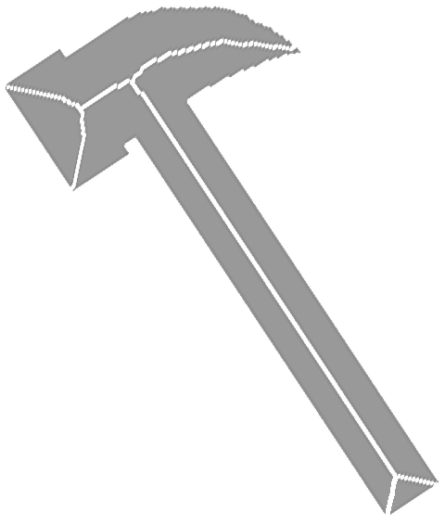
More Examples





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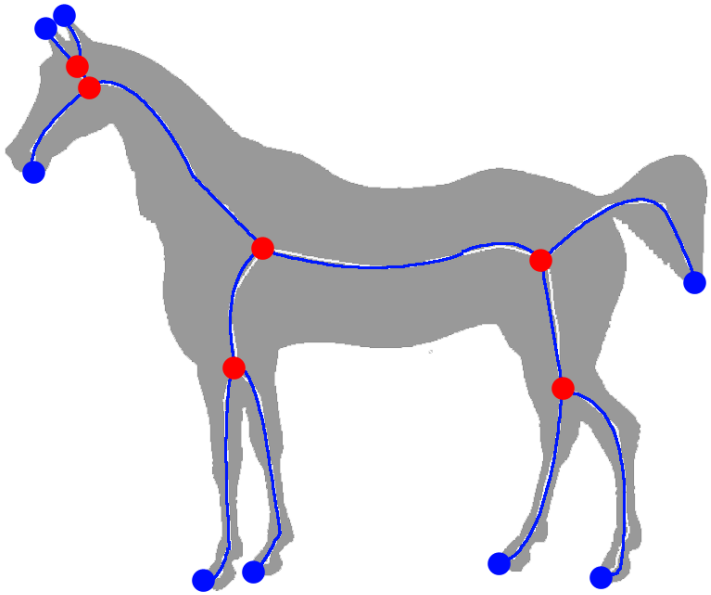
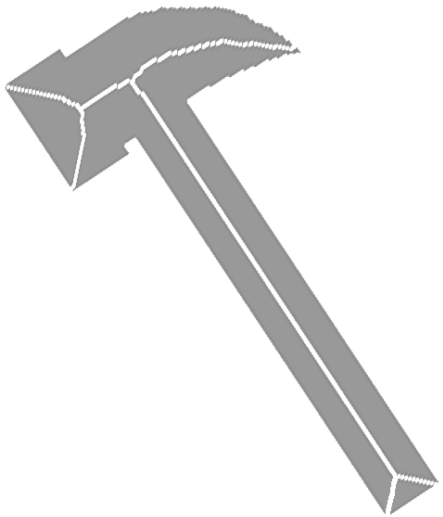
More Examples





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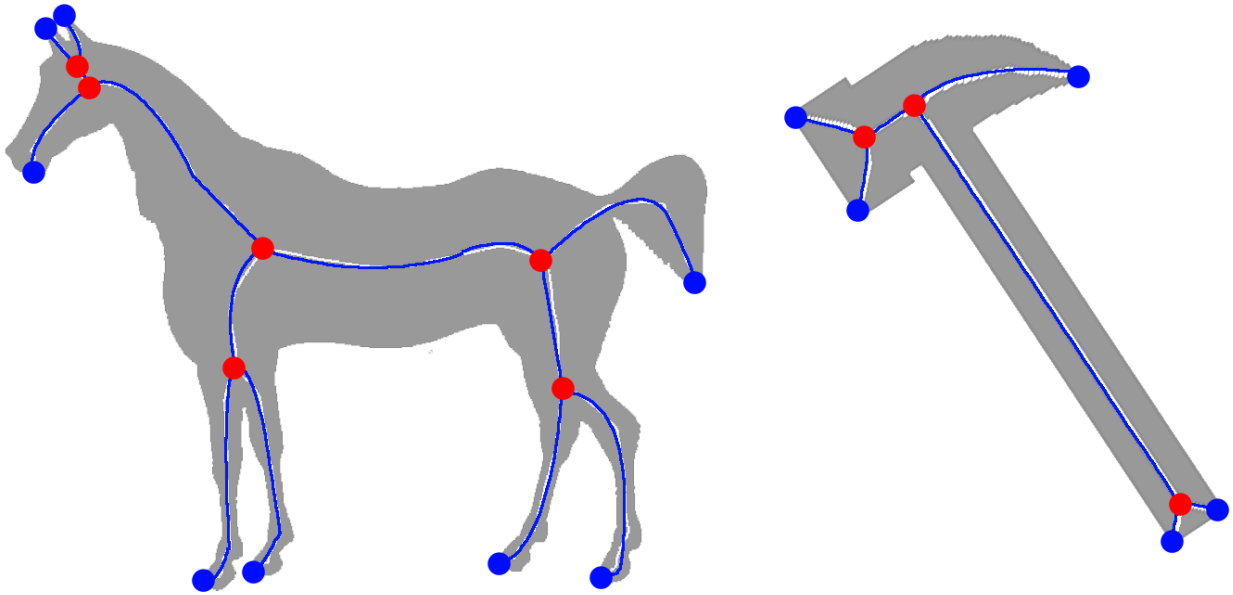

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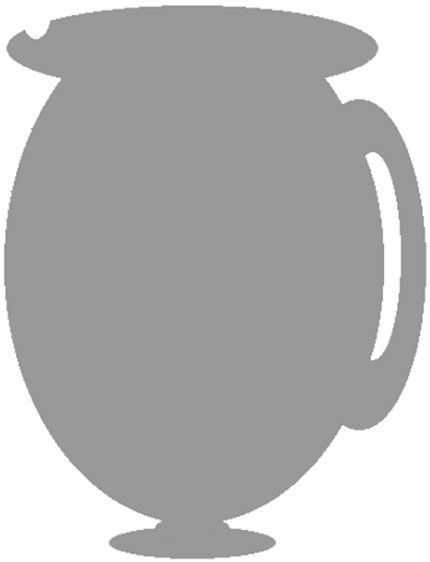
More Examples



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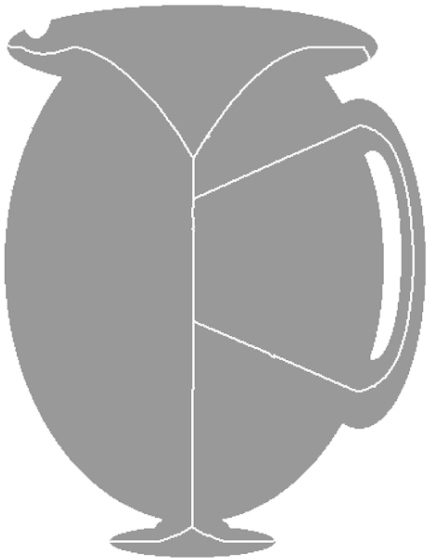
More Examples



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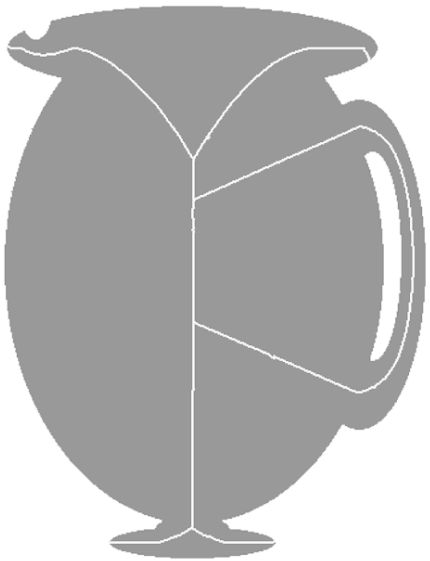

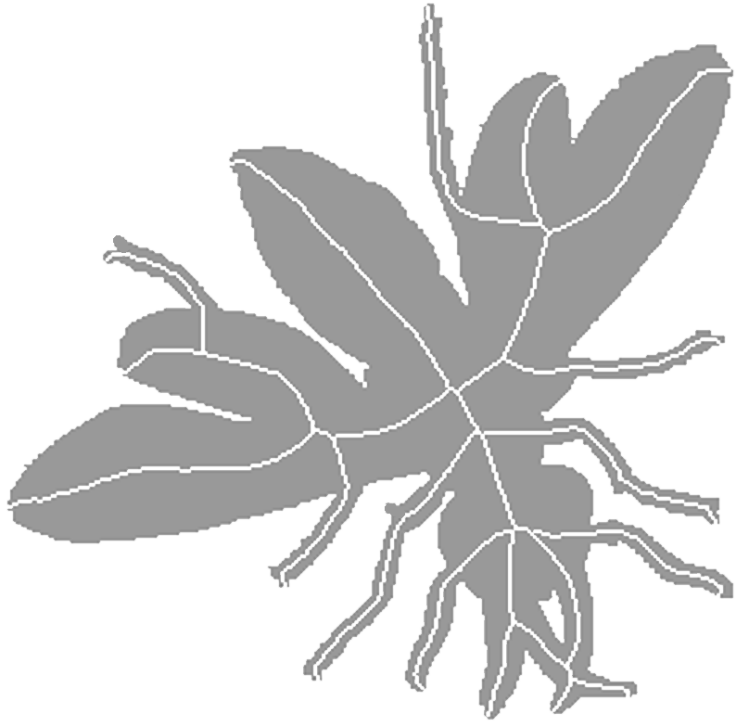

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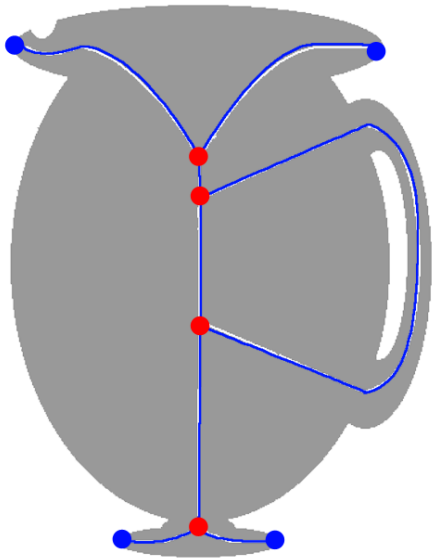
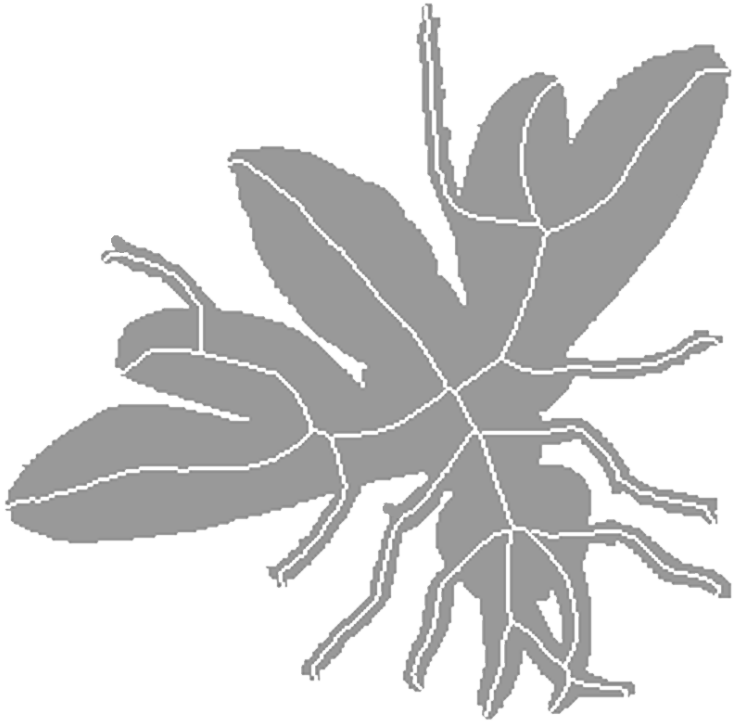
More Examples





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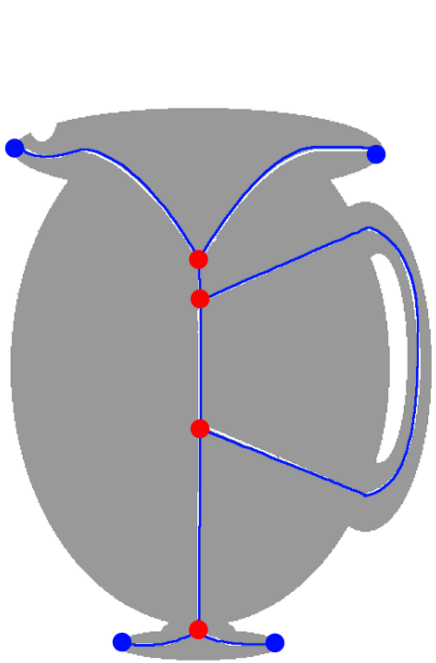
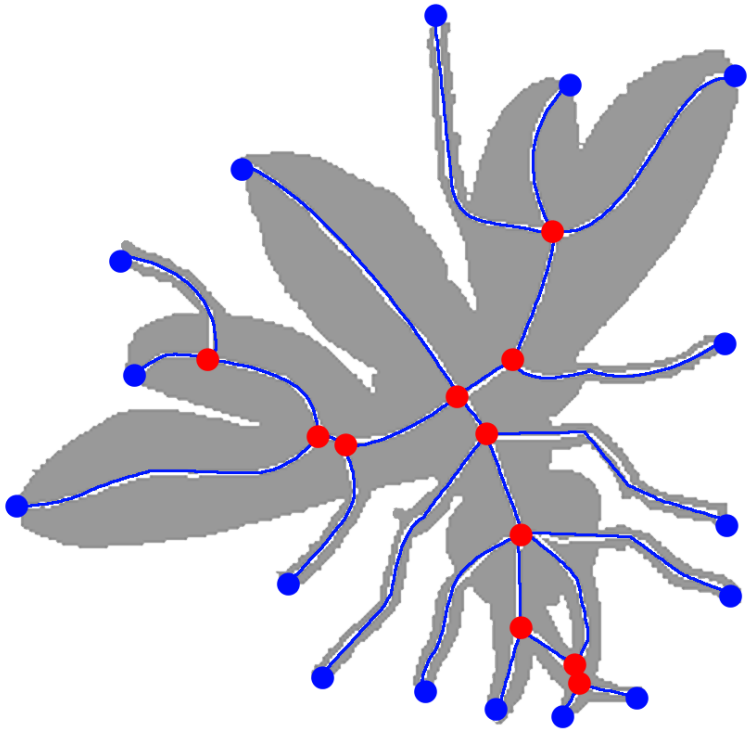
More Examples





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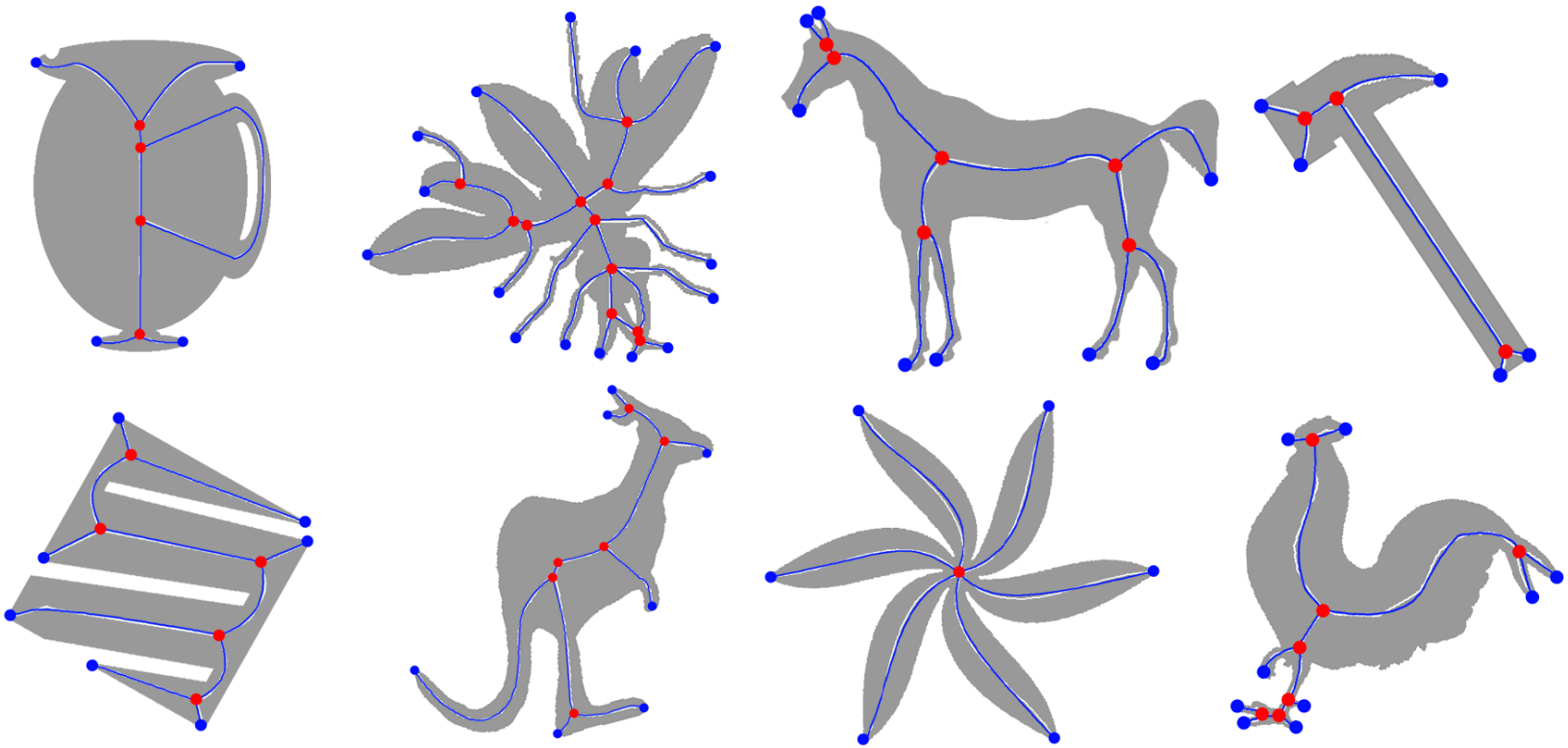
More Examples



The selected input parameters are the same

Conclusion

- The pruning algorithm presented is fast and gives good results.
- It proved to be very stable with the parameter selection and always preserved connectivity.
- Reconstruction of the original shape area was 98% in average.
- It returns a subset of the medial axis, robust to image rotations and boundary noise.
- It handles complex shapes (i.e. holes).

Thanks

Questions?