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# Outline and Shape Reconstruction in 2D

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**Abstract.** Outline and shape reconstruction from unstructured points in a plane is a fundamental problem with many applications that have generated research interest for decades. Involved aspects like handling open, sharp, multiple and non-manifold outlines, run-time and provability, and potential extension to 3D for surface reconstruction have led to many different algorithms. This multitude of reconstruction methods with quite different strengths and focus makes it difficult for users to choose a suitable algorithm for their specific problem. In this tutorial, we present proximity graphs, graph-based algorithms, and algorithms with sampling guarantees, all in detail. Then, we show algorithms targeted at specific problem classes, such as reconstructing from noise, outliers, or sharp corners. Examples of the evaluation will show how its results can guide users in selecting an appropriate algorithm for their input data. As a special application, we show the reconstruction of lines in the context of sketch completion and sketch simplification. Shape characterization of dot patterns will be shown as an additional field closely related to boundary reconstruction.

**Keywords:** Curve reconstruction, Sketching, Boundary reconstruction

## 1 Introduction

Reconstruction of curves from unorganized points is a fundamental task in computer graphics/vision, with many applications such as silhouette or slice reconstruction of 3D models in reverse engineering, connecting feature points in medical imaging or facial recognition, all of these possessing varying artefacts and requirements.

In this tutorial, we tell the story of the development of curve reconstruction algorithms based on proximity graphs, further specialized algorithms, and our taxonomy. As an application, we include line reconstruction from sketches and outline reconstruction from dot patterns as a related field.

We show how the evaluation of the different methods based on input and output criteria helps users to select a suitable algorithm for specific problems, and we guide users through the process of integrating new algorithms into our open-source benchmark framework using a comprehensive test data set (<https://gitlab.com/stefango74/curve-benchmark>). Course notes and slides will be made available to the attendees.

## 2 Presenters

**Stefan Ohrhallinger** is a postdoc researcher at the Institute of Visual Computing and Human-Centered Technology at TU Wien, Austria. In 2013 he obtained his PhD from Concordia University, Montréal, Canada. Since October 2012, he has been a research associate at TU Wien, working mainly on curve/surface reconstruction, geometry processing and point-based graphics. He has first-authored six peer-reviewed papers in the domain of curve and surface reconstruction.

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**Amal Dev Parakkat** is an assistant professor in the Information Processing and Communication Laboratory (LTCl) of Telecom Paris, Institut Polytechnique de Paris, France. He finished his PhD degree from the Indian Institute of Technology Madras, India, in 2019. Previously, he was an assistant professor at the Indian Institute of Technology Guwahati, India, and also worked as a postdoctoral researcher at TU Delft, Netherlands and Ecole Polytechnique, France. His current research interests include Geometry Processing and Interactive Computer Graphics, focusing on Sketch-based interfaces.

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**Jiju Peethambaran** is currently an assistant professor in the Department of Math and Computing Science, Saint Mary's University, Halifax, Canada. He received his PhD degree in computational geometry from the Indian Institute of Technology Madras, Chennai, India. He has held postdoc positions at University of Victoria, Canada and the University of Calgary, Canada. He has (co)authored peer-reviewed articles on/related to shape and curve reconstruction from 2D/ 3D point sets and their applications. His current research interests include Computer graphics, 3D computer vision, Geometric deep learning, and related applications, including LiDAR-based modeling of real-world scenes.

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The authors have presented both a STAR [15] and a tutorial [19,28] at the Eurographics conference. This tutorial includes about 50% new materials tailored to the computer vision community.

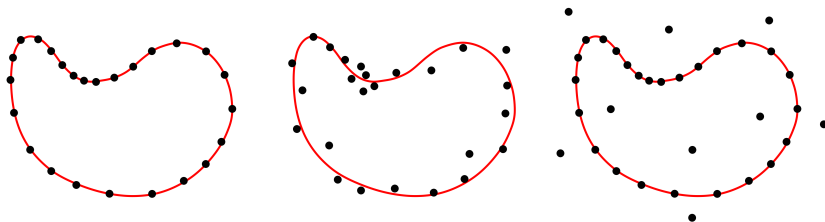
This tutorial will be presented as a half-day (3 hours) remote session. We will target an intermediate and advanced audience who is close to this fundamental field or are using these algorithms and anticipate 30-50 attendees. We are unaware of any related tutorials or courses appearing at CVPR/ICCV/ECCV or other international vision conferences in the previous three years.

## 3 Curve Reconstruction from Points

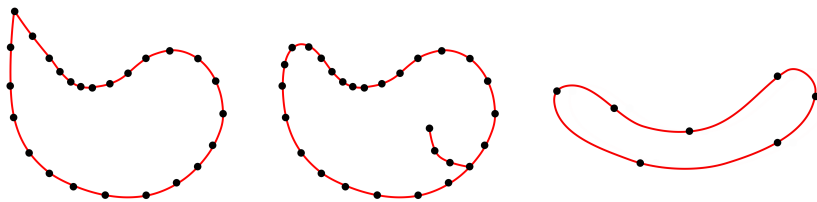
We will show some motivating examples with their varying requirements. These requirements result in specific challenges of input data such as sampling density, noise or outliers, but also intersections, and open- or closedness (see Figure 1).

Session title	Presenter	Duration
Intro & Proximity graphs	Stefan Ohrhallinger	0:00 - 0:25
Curve reconstruction	Stefan Ohrhallinger	0:25 - 0:50
<i>Questions &amp; Answers</i>	<i>Stefan Ohrhallinger</i>	<i>0:50 - 0:55</i>
Benchmark & Demo	Amal Dev Parakkat	0:55 - 1:20
<i>Break: 15 Minutes</i>		<i>1:20 - 1:35</i>
Sketch reconstruction	Amal Dev Parakkat	1:35 - 2:00
<i>Questions &amp; Answers</i>	<i>Amal Dev Parakkat</i>	<i>2:00 - 2:05</i>
Visual Perception of Shapes	Jiju Peethambaran	2:05 - 2:30
Shape Characterization	Jiju Peethambaran	2:30 - 2:55
<i>Questions &amp; Answers</i>	<i>Jiju Peethambaran</i>	<i>2:55 - 3:00</i>

**Table 1.** Sessions with title, presenter and duration.



**Fig. 1.** Sample points (left) with noise (middle) and outliers (right)



**Fig. 2.** Curve with sharp corner (left), non-manifold curve (middle), sparsely sampled curve (right)

We show why these configurations cannot be handled well by any single algorithm but that there exist specific tools addressing all of these challenges. Helping users to choose a suitable algorithm for their problem also depends on desired output properties such as manifoldness, open curves, sharp corners, guarantees on time and sampling conditions (see Figure 2). We will list 14 curve reconstruction algorithms available as open source that were evaluated thoroughly in our benchmark to highlight their respective strengths and weaknesses. We categorize a total of 36 curve reconstruction algorithms and relate their historical development into seven categories as follows (some examples referenced):

- Graph-based algorithms [7,27,26,12]
- Algorithms relying on feature size criteria [2,18]

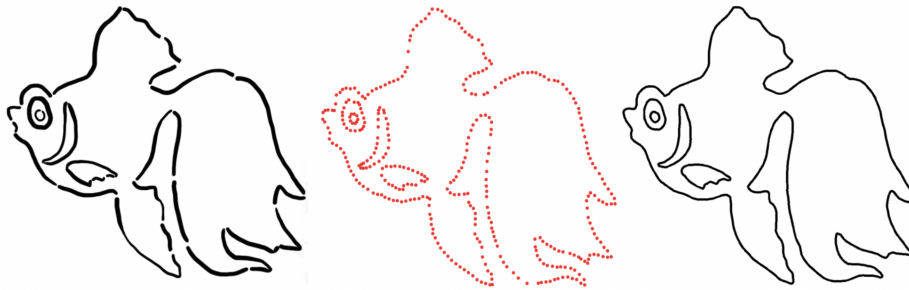
- Curve fitting based algorithms for noisy points [16,17]
- Algorithms designed for handling sharp corners [5]
- Traveling salesman based methods [10,1]
- Algorithms that can handle self-intersections [25]
- Algorithms based on human visual system [14]

Finally, we explain the basic definitions of curves and sampling.

## 4 Line Reconstruction from Sketches

Another closely related application for the generic curve reconstruction problem is reconstructing lines from sketches. In the broad area of sketch-based modelling, we can relate curve reconstruction into two important sub-domains:

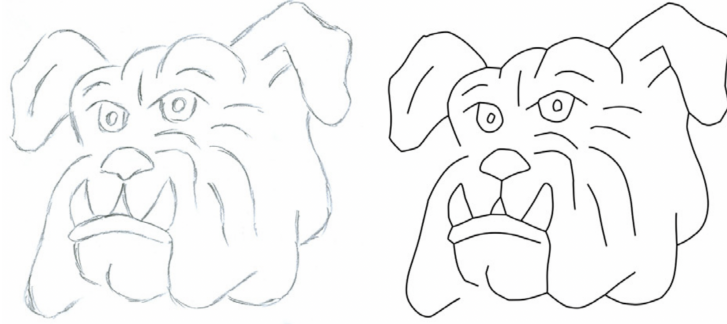
- Sketch completion: Where the input is a set of disconnected sketch strokes that is required to appropriately connect (in other words, filling the gaps in a line art).
- Sketch simplification: In this case, similar to reconstruction from noisy samples, the input will be a noisy sketch (also called multi-stroke sketches - where the input will be a set of unordered strokes approximating the required drawing) generated by expert artists, and the expected output would be a simplified representation.



**Fig. 3.** Left: Sample sketch with gaps, Middle: Sampled points, Right: Contour closed sketch generated by [26]

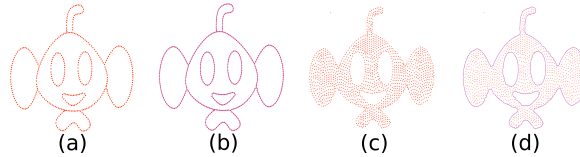
**Sketch Completion:** Filling gaps in a sketch represented by a set of disconnected strokes (a.k.a contour closing problem) is an important pre-processing step required for various applications including sketch-based 3D modeling [11] and sketch coloring [22,24]. If we sample the sketch strokes, our objective becomes similar to the classical curve reconstruction problem - where the “appropriate” connection of points gives us the information about which strokes connect

(for example, Figure 3). Pivoting on that, in this section, we will explore the most relevant and related works starting from 1994 [8] to the latest work [24]. Though the contour closing problem is closely related to curve reconstruction, the former is more difficult since there is no generic rule. This means that two sets of strokes exhibiting the same properties do not guarantee that they will be treated similarly. Hence, we will also discuss how well-suited the existing curve reconstruction algorithms are to this task.



**Fig. 4.** Left: A sketch drawn in multi-stroke style, Right: Its simplified result of [20]

**Sketch Simplification:** Because of the increased freedom and flexibility, expert artists usually prefer drawing in a multi-stroke style. Since these sketches drawn in multi-stroke style cannot be directly used for many other applications (e.g., for animations or illustrations), in most cases, this is accompanied by a sketch simplification module (which is mostly done manually). If we sample all the sketch strokes, the problem reduces to reconstruction from noisy point clouds (for example, see Figure 4). Not only are there sophisticated algorithms that directly work on strokes by exploiting additional information, such as stroke ordering [3], but also a few methods that pose this problem as a variant of curve reconstruction [4,20,21]. This part will quickly go through the related works and discuss how they addressed this complex problem.



**Fig. 5.** Two common types of inputs to the 2D reconstruction algorithms. (a) Boundary sample (b) Reconstructed curves (c) Dot pattern (or area samples) (d) Reconstruction from area samples.

## 5 Shape Characterization of Dot Patterns

Shape characterization is the problem of constructing the polygonal boundary of a set of points distributed over a 2D region or sampled from a 2D object, commonly referred to as *dot patterns* or *area samples*. Figure 5 illustrates the distinction between *boundary samples* and *dot patterns* and the corresponding reconstruction results. This part of the tutorial will mainly focus on the human visual perception of the dot patterns, various criteria for characterizing the shapes, prominent algorithms, sampling models, e.g.,  $r$ -regular sampling, important theoretical results on shape characterization and the evaluation practices in this domain. We will also present unified algorithms [13,6,9,29,30] that handle sampled boundaries, as well as dot patterns. Since there is a considerable body of literature on reconstruction from dot patterns (or area samples), only the most important algorithms and results will be provided in this section. A discussion on various sampling tools for shape characterization, different metrics used for evaluating the shape characterization algorithms and available datasets [15] will also be provided. The section will discuss future directions (including [23]), presenting the open problems around 2D shape reconstruction. Though this is a mature field, we still consider some directions to be worthwhile for future work, mostly building on the fundamental results published so far. Some potential topics include sampling conditions for non-smooth and self-intersecting curves, deep learning for curve generation, and kinetic shapes of points.

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