



IN PARTNERSHIP WITH:
Université de Lorraine

Activity Report 2018

Project-Team GAMBLE

Geometric Algorithms & Models Beyond the
Linear & Euclidean realm

IN COLLABORATION WITH: Laboratoire lorrain de recherche en informatique et ses applications (LORIA)

RESEARCH CENTER
Nancy - Grand Est

THEME
**Algorithmics, Computer Algebra and
Cryptology**

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Project-Team GAMBLE

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Computer Science and Digital Science:

A5.5.1. - Geometrical modeling
A5.10.1. - Design
A7.1. - Algorithms
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A8.3. - Geometry, Topology
A8.4. - Computer Algebra

Other Research Topics and Application Domains:

B1.1.1. - Structural biology
B1.2.3. - Computational neurosciences
B2.6. - Biological and medical imaging
B3.3. - Geosciences
B5.5. - Materials
B5.6. - Robotic systems
B5.7. - 3D printing
B6.2.2. - Radio technology

1. Team, Visitors, External Collaborators

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2. Overall Objectives

2.1. Overall Objectives

Starting in the eighties, the emerging computational geometry community has put a lot of effort into designing and analyzing algorithms for geometric problems. The most commonly used framework was to study the worst-case theoretical complexity of geometric problems involving linear objects (points, lines, polyhedra...) in Euclidean spaces. This so-called *classical computational geometry* has some known limitations:

- Objects: dealing with objects only defined by linear equations.
- Ambient space: considering only Euclidean spaces.
- Complexity: worst-case complexities often do not capture realistic behaviour.
- Dimension: complexities are often exponential in the dimension.
- Robustness: ignoring degeneracies and rounding errors.

Even if these limitations have already got some attention from the community [36], a quick look at the flagship conference SoCG¹ proceedings shows that these topics still need a big effort.

It should be stressed that, in this document, the notion of certified algorithms is to be understood with respect to robustness issues. In other words, certification does not refer to programs that are proven correct with the help of mechanical proof assistants such as Coq, but to algorithms that are proven correct on paper even in the presence of degeneracies and computer-induced numerical rounding errors.

We address several of the above limitations:

- **Non-linear computational geometry.** Curved objects are ubiquitous in the world we live in. However, despite this ubiquity and decades of research in several communities, curved objects are far from being robustly and efficiently manipulated by geometric algorithms. Our work on, for instance, quadric intersections and certified drawing of plane curves has proven that dramatic improvements can be accomplished when the right mathematics and computer science concepts are put into motion. In this direction, many problems are fundamental and solutions have potential industrial impact in Computer Aided Design and Robotics for instance. Intersecting NURBS (Non-uniform rational basis spline) and meshing singular surfaces in a certified manner are important examples of such problems.

- **Non-Euclidean computational geometry.** Triangulations are central geometric data structures in many areas of science and engineering. Traditionally, their study has been limited to the Euclidean setting. Needs for triangulations in non-Euclidean settings have emerged in many areas dealing with objects whose sizes range from the nuclear to the astrophysical scale, and both in academia and in industry. It has become timely to extend the traditional focus on \mathbb{R}^d of computational geometry and encompass non-Euclidean spaces.

- **Probability in computational geometry.** The design of efficient algorithms is driven by the analysis of their complexity. Traditionally, worst-case input and sometimes uniform distributions are considered and many results in these settings have had a great influence on the domain. Nowadays, it is necessary to be more subtle and to prove new results in between these two extreme settings. For instance, smoothed analysis, which was introduced for the simplex algorithm and which we applied successfully to convex hulls, proves that such promising alternatives exist.

¹Symposium on Computational Geometry. <http://www.computational-geometry.org/>.

3. Research Program

3.1. Non-linear computational geometry



Figure 1. Two views of the Whitney umbrella (on the left, the “stick” of the umbrella, i.e., the negative z -axis, is missing). Right picture from [Wikipedia], left picture from [Lachaud et al.].

As mentioned above, curved objects are ubiquitous in real world problems and in computer science and, despite this fact, there are very few problems on curved objects that admit robust and efficient algorithmic solutions without first discretizing the curved objects into meshes. Meshing curved objects induces a loss of accuracy which is sometimes not an issue but which can also be most problematic depending on the application. In addition, discretization induces a combinatorial explosion which could cause a loss in efficiency compared to a direct solution on the curved objects (as our work on quadrics has demonstrated with flying colors [42], [43], [44], [46], [51]). But it is also crucial to know that even the process of computing meshes that approximate curved objects is far from being resolved. As a matter of fact there is no algorithm capable of computing in practice meshes with certified topology of even rather simple singular 3D surfaces, due to the high constants in the theoretical complexity and the difficulty of handling degenerate cases. Even in 2D, meshing an algebraic curve with the correct topology, that is in other words producing a correct drawing of the curve (without knowing where the domain of interest is), is a very difficult problem on which we have recently made important contributions [29], [30], [52].

It is thus to be understood that producing practical robust and efficient algorithmic solutions to geometric problems on curved objects is a challenge on all and even the most basic problems. The basicness and fundamentality of two problems we mentioned above on the intersection of 3D quadrics and on the drawing in a topologically certified way of plane algebraic curves show rather well that the domain is still in its infancy. And it should be stressed that these two sets of results were not anecdotal but flagship results produced during the lifetime of the VEGAS team.

There are many problems in this theme that are expected to have high long-term impacts. Intersecting NURBS (Non-uniform rational basis spline) in a certified way is an important problem in computer-aided design and manufacturing. As hinted above, meshing objects in a certified way is important when topology matters. The 2D case, that is essentially drawing plane curves with the correct topology, is a fundamental problem with far-reaching applications in research or R&D. Notice that on such elementary problems it is often difficult to predict the reach of the applications; as an example, we were astonished by the scope of the applications of our software on 3D quadric intersection ² which was used by researchers in, for instance, photochemistry, computer vision, statistics and mathematics.

3.2. Non-Euclidean computational geometry

²QI: <http://vegas.loria.fr/qi/>.



Figure 2. Left: 3D mesh of a gyroid (triple periodic surface) [54]. Right: Simulation of a periodic Delaunay triangulation of the hyperbolic plane [24].

Triangulations, in particular Delaunay triangulations, in the *Euclidean space* \mathbb{R}^d have been extensively studied throughout the 20th century and they are still a very active research topic. Their mathematical properties are now well understood, many algorithms to construct them have been proposed and analyzed (see the book of Aurenhammer *et al.* [23]). Some members of GAMBLE have been contributing to these algorithmic advances (see, e.g. [28], [62], [39], [27]); they have also contributed robust and efficient triangulation packages through the state-of-the-art Computational Geometry Algorithms Library CGAL,³ whose impact extends far beyond computational geometry. Application fields include particle physics, fluid dynamics, shape matching, image processing, geometry processing, computer graphics, computer vision, shape reconstruction, mesh generation, virtual worlds, geophysics, and medical imaging.⁴

It is fair to say that little has been done on non-Euclidean spaces, in spite of the large number of questions raised by application domains. Needs for simulations or modeling in a variety of domains⁵ ranging from the infinitely small (nuclear matter, nano-structures, biological data) to the infinitely large (astrophysics) have led us to consider 3D periodic Delaunay triangulations, which can be seen as Delaunay triangulations in the 3D *flat torus*, quotient of \mathbb{R}^3 under the action of some group of translations [34]. This work has already yielded a fruitful collaboration with astrophysicists [47], [63] and new collaborations with physicists are emerging. To the best of our knowledge, our CGAL package [33] is the only publicly available software that computes Delaunay triangulations of a 3D flat torus, in the special case where the domain is cubic. This case, although restrictive is already useful.⁶ We have also generalized this algorithm to the case of general d -dimensional compact flat manifolds [35]. As far as non-compact manifolds are concerned, past approaches, limited to the two-dimensional case, have stayed theoretical [53].

Interestingly, even for the simple case of triangulations on the *sphere*, the software packages that are currently available are far from offering satisfactory solutions in terms of robustness and efficiency [32].

Moreover, while our solution for computing triangulations in hyperbolic spaces can be considered as ultimate [24], the case of *hyperbolic manifolds* has hardly been explored. Hyperbolic manifolds are quotients of a hyperbolic space by some group of hyperbolic isometries. Their triangulations can be seen as hyperbolic periodic triangulations. Periodic hyperbolic triangulations and meshes appear for instance in geometric modeling [55], neuromathematics [37], or physics [58]. Even the simplest possible case (a surface homeomorphic to the torus with two handles) shows strong mathematical difficulties [25], [60].

³<http://www.cgal.org/>

⁴See <http://www.cgal.org/projects.html> for details.

⁵See <http://www.loria.fr/~teillaud/PeriodicSpacesWorkshop/>, <http://www.lorentzcenter.nl/lc/web/2009/357/info.php3?wsid=357>,

<http://neg15.loria.fr/> and <http://gerschroeder-turk.org/2015/06/17/shape-up-2015-exercises-in-materials-geometry-and-topology/>.

⁶See examples at <http://www.cgal.org/projects.html>

3.3. Probability in computational geometry

In most computational geometry papers, algorithms are analyzed in the worst-case setting. This often yields too pessimistic complexities that arise only in pathological situations that are unlikely to occur in practice. On the other hand, probabilistic geometry provides analyses with great precision [56], [57], [31], but using hypotheses with much more randomness than in most realistic situations. We are developing new algorithmic designs improving state-of-the-art performance in random settings that are not overly simplified and that can thus reflect many realistic situations.

Twelve years ago, smooth analysis was introduced by Spielman and Teng analyzing the simplex algorithm by averaging on some noise on the data [61] (and they won the Gödel prize). In essence, this analysis smoothes the complexity around worst-case situations, thus avoiding pathological scenarios but without considering unrealistic randomness. In that sense, this method makes a bridge between full randomness and worst case situations by tuning the noise intensity. The analysis of computational geometry algorithms within this framework is still embryonic. To illustrate the difficulty of the problem, we started working in 2009 on the smooth analysis of the size of the convex hull of a point set, arguably the simplest computational geometry data structure; then, only one very rough result from 2004 existed [38] and we only obtained in 2015 breakthrough results, but still not definitive [41], [40], [45].

Another example of problem of different flavor concerns Delaunay triangulations, which are rather ubiquitous in computational geometry. When Delaunay triangulations are computed for reconstructing meshes from point clouds coming from 3D scanners, the worst-case scenario is, again, too pessimistic and the full randomness hypothesis is clearly not adapted. Some results exist for “good samplings of generic surfaces” [21] but the big result that everybody wishes for is an analysis for random samples (without the extra assumptions hidden in the “good” sampling) of possibly non-generic surfaces.

Trade-offs between full randomness and worst case may also appear in other forms such as dependent distributions, or random distributions conditioned to be in some special configurations. Simulating these kinds of geometric distributions is currently out of reach for more than a few hundred points [48] although it has practical applications in physics or networks.

4. Application Domains

4.1. Applications of computational geometry

Many domains of science can benefit from the results developed by GAMBLE. Curves and surfaces are ubiquitous in all sciences to understand and interpret raw data as well as experimental results. Still, the non-linear problems we address are rather basic and fundamental, and it is often difficult to predict the impact of solutions in that area. The short-term industrial impact is likely to be small because, on basic problems, industries have used ad hoc solutions for decades and have thus got used to it. The example of our work on quadric intersection is typical: even though we were fully convinced that intersecting 3D quadrics is such an elementary/fundamental problem that it ought to be useful, we were the first to be astonished by the scope of the applications of our software ⁷ (which was the first and still is the only one —to our knowledge— to compute robustly and efficiently the intersection of 3D quadrics) which has been used by researchers in, for instance, photochemistry, computer vision, statistics, and mathematics. Our work on certified drawing of plane (algebraic) curves falls in the same category. It seems obvious that it is widely useful to be able to draw curves correctly (recall also that part of the problem is to determine where to look in the plane) but it is quite hard to come up with specific examples of fields where this is relevant. A contrario, we know that certified meshing is critical in mechanical-design applications in robotics, which is a non-obvious application field. There, the singularities of a manipulator often have degrees higher than 10 and meshing the singular locus in a certified way is currently out of reach. As a result, researchers in robotics can only build physical prototypes for validating, or not, the approximate solutions given by non-certified numerical algorithms.

⁷QI: <http://vegas.loria.fr/qi/>.

The fact that several of our pieces of software for computing non-Euclidean triangulations have already been requested by users long before they become public is a good sign for their wide future impact once in CGAL. This will not come as a surprise, since most of the questions that we have been studying followed from discussions with researchers outside computer science and pure mathematics. Such researchers are either users of our algorithms and software, or we meet them in workshops. Let us only mention a few names here. We have already referred above to our collaboration with Rien van de Weijgaert [47], [63] (astrophysicist, Groningen, NL). Michael Schindler [59] (theoretical physicist, ENSPCI, CNRS, France) is using our prototype software for 3D periodic weighted triangulations. Stephen Hyde and Vanessa Robins (applied mathematics and physics at Australian National University) have recently signed a software license agreement with INRIA that allows their group to use our prototype for 3D periodic meshing. Olivier Faugeras (neuromathematics, Inria Sophia Antipolis) had come to us and mentioned his needs for good meshes of the Bolza surface [37] before we started to study them. Such contacts are very important both to get feedback about our research and to help us choose problems that are relevant for applications. These problems are at the same time challenging from the mathematical and algorithmic points of view. Note that our research and our software are generic, i.e., we are studying fundamental geometric questions, which do not depend on any specific application. This recipe has made the success of the CGAL library.

Probabilistic models for geometric data are widely used to model various situations ranging from cell phone distribution to quantum mechanics. The impact of our work on probabilistic distributions is twofold. On the one hand, our studies of properties of geometric objects built on such distributions will yield a better understanding of the above phenomena and has potential impact in many scientific domains. On the other hand, our work on simulations of probabilistic distributions will be used by other teams, more maths oriented, to study these distributions.

5. Highlights of the Year

5.1. Highlights of the Year

Given a set of possibly intersecting polygons in 3D, we presented a breakthrough result on the problem of computing a set of interior-disjoint triangles whose geometry is close to that of the input and such that the output vertices have coordinates of fixed precision, typically integers or floating-point numbers of bounded precision (eg. int, float, double). This problem is important in academic and industrial contexts because many 3D digital models contain self intersections and many applications require models without self intersections. Despite the theoretical and practical relevance of this problem, there was almost no literature on the subject and we presented its first satisfactory solution [12].

6. New Software and Platforms

6.1. ISOTOP

Topology and geometry of planar algebraic curves

KEYWORDS: Topology - Curve plotting - Geometric computing

FUNCTIONAL DESCRIPTION: Isotop is a Maple software for computing the topology of an algebraic plane curve, that is, for computing an arrangement of polylines isotopic to the input curve. This problem is a necessary key step for computing arrangements of algebraic curves and has also applications for curve plotting. This software has been developed since 2007 in collaboration with F. Rouillier from Inria Paris - Rocquencourt.

NEWS OF THE YEAR: In 2018, an engineer from Inria Nancy (Benjamin Dexheimer) finished the implementation of the web server to improve the diffusion of our software.

- Participants: Luis Penaranda, Marc Pouget and Sylvain Lazard
- Contact: Marc Pouget
- Publications: [Rational Univariate Representations of Bivariate Systems and Applications - Separating Linear Forms for Bivariate Systems - On The Topology of Planar Algebraic Curves - New bivariate system solver and topology of algebraic curves - Improved algorithm for computing separating linear forms for bivariate systems - Solving bivariate systems using Rational Univariate Representations - On the topology of planar algebraic curves - On the topology of real algebraic plane curves - Bivariate triangular decompositions in the presence of asymptotes - Separating linear forms and Rational Univariate Representations of bivariate systems](#)
- URL: <https://isotop.gamble.loria.fr/>

6.2. SubdivisionSolver

KEYWORDS: Numerical solver - Polynomial or analytical systems

SCIENTIFIC DESCRIPTION: The goal underlying the developpement of RealSolver is the ability to solve large polynomial systems with certified results using adaptive multi-precision arithmetic for efficiency.

The software is based on a classic branch and bound algorithm using interval arithmetic: an initial box is subdivided until its sub-boxes are certified to contain either no solution or a unique solution of the input system. Evaluation is performed with a centered evaluation at order two, and existence and uniqueness of solutions is verified thanks to the Krawczyk operator.

RealSolver uses two implementations of interval arithmetic: the C++ boost library that provides a fast arithmetic when double precision is enough, and otherwise the C mpfi library that allows to work in arbitrary precision. Considering the subdivision process as a breadth first search in a tree, the boost interval arithmetic is used as deeply as possible before a new subdivision process using higher precision arithmetic is performed on the remaining forest.

The software is can be interfaced with sage and the library Fast_Polynomial that allows to solve systems of polynomials that are large in terms of degree, number of monomials and bit-size of coefficients.

FUNCTIONAL DESCRIPTION: The software RealSolver solves square systems of analytic equations on a compact subset of a real space. RealSolver is a subdivision solver using interval arithmetic and multiprecision arithmetic to achieve certified results. If the arithmetic precision required to isolate solutions is known, it can be given as an input parameter of the process, otherwise the precision is increased on-the-fly. In particular, RealSolver can be interfaced with the Fast_Polynomial library (<https://bil.inria.fr/en/software/view/2423/tab#1A>) to solve polynomial systems that are large in terms of degree, number of monomials and bit-size of coefficients.

NEWS OF THE YEAR: In 2018, Mohamed Eissa was recruited on a FastTrack contract for porting the code to python.

- Contact: Rémi Imbach

6.3. CGAL Package : 2D hyperbolic triangulations

KEYWORDS: Geometry - Delaunay triangulation - Hyperbolic space

FUNCTIONAL DESCRIPTION: This package implements the construction of Delaunay triangulations in the Poincaré disk model.

NEWS OF THE YEAR: This package has been submitted to the CGAL Editorial Board for future integration into the library.

- Participants: Mikhail Bogdanov, Olivier Devillers, Iordan Iordanov and Monique Teillaud
- Contact: Monique Teillaud
- Publication: [Hyperbolic Delaunay Complexes and Voronoi Diagrams Made Practical](#)
- URL: https://github.com/CGAL/cgal-public-dev/tree/Periodic_4_hyperbolic_triangulation_2-Iordanov

6.4. CGAL Package : 2D periodic hyperbolic triangulations

KEYWORDS: Geometry - Delaunay triangulation - Hyperbolic space

FUNCTIONAL DESCRIPTION: This module implements the computation of Delaunay triangulations of the Bolza surface.

NEWS OF THE YEAR: This package has been submitted to the CGAL Editorial Board for future integration into the library.

- Authors: Iordan Iordanov and Monique Teillaud
- Contact: Monique Teillaud
- Publication: [Implementing Delaunay Triangulations of the Bolza Surface](#)
- URL: https://github.com/CGAL/cgal-public-dev/tree/Periodic_4_hyperbolic_triangulation_2-Iordanov

6.5. CGAL package: 3D periodic mesh generation

KEYWORDS: Flat torus - CGAL - Geometry - Delaunay triangulation - Mesh generation - Tetrahedral mesh - Mesh

FUNCTIONAL DESCRIPTION: This package of CGAL (Computational Geometry Algorithms Library <http://www.cgal.org>) allows to build and handle volumic meshes of shapes described through implicit functional boundaries over the 3D flat torus whose fundamental domain is a cube.

NEWS OF THE YEAR: This new package has been released in CGAL 4.13

- Participants: Mikhail Bogdanov, Aymeric Pellé, Mael Rouxel-Labbe and Monique Teillaud
- Contact: Monique Teillaud
- Publications: [CGAL periodic volume mesh generator - Periodic meshes for the CGAL library](#)
- URL: https://doc.cgal.org/latest/Manual/packages.html#PkgPeriodic_3_mesh_3Summary

7. New Results

7.1. Non-Linear Computational Geometry

Participants: Sény Diatta, Laurent Dupont, George Krait, Sylvain Lazard, Guillaume Moroz, Marc Pouget.

7.1.1. *Reliable location with respect to the projection of a smooth space curve*

Consider a plane curve \mathcal{B} defined as the projection of the intersection of two analytic surfaces in \mathbb{R}^3 or as the apparent contour of a surface. In general, \mathcal{B} has node or cusp singular points and thus is a singular curve. Our main contribution [6] is the computation of a data structure for answering point location queries with respect to the subdivision of the plane induced by \mathcal{B} . This data structure is composed of an approximation of the space curve together with a topological representation of its projection \mathcal{B} . Since \mathcal{B} is a singular curve, it is challenging to design a method only based on reliable numerical algorithms.

In a previous work [49], we have shown how to describe the set of singularities of \mathcal{B} as regular solutions of a so-called ball system suitable for a numerical subdivision solver. Here, the space curve is first enclosed in a set of boxes with a certified path-tracker to restrict the domain where the ball system is solved. Boxes around singular points are then computed such that the correct topology of the curve inside these boxes can be deduced from the intersections of the curve with their boundaries. The tracking of the space curve is then used to connect the smooth branches to the singular points. The subdivision of the plane induced by \mathcal{B} is encoded as an extended planar combinatorial map allowing point location. We experimented our method and showed that our reliable numerical approach can handle classes of examples that are not reachable by symbolic methods.

7.1.2. *Workspace, Joint space and Singularities of a family of Delta-Like Robots*

Our paper [7] presents the workspace, the joint space and the singularities of a family of delta-like parallel robots by using algebraic tools. The different functions of the SIROPA library are introduced and used to estimate the complexity representing the singularities in the workspace and the joint space. A Groebner based elimination is used to compute the singularities of the manipulator and a Cylindrical Algebraic Decomposition algorithm is used to study the workspace and the joint space. From these algebraic objects, we propose some certified three-dimensional plotting tools describing the shape of the workspace and of the joint space which will help engineers or researchers to decide the most suited configuration of the manipulator they should use for a given task. Also, the different parameters associated with the complexity of the serial and parallel singularities are tabulated, which further enhance the selection of the different configurations of the manipulator by comparing the complexity of the singularity equations.

In collaboration with Ranjan Jha, Damien Chablat, Luc Baron and Fabrice Rouillier.

7.2. Non-Euclidean Computational Geometry

Participants: Vincent Despré, Jordan Iordanov, Monique Teillaud.

7.2.1. *Delaunay Triangulations of Symmetric Hyperbolic Surfaces*

We have worked on extending our previous results on the computation of Delaunay triangulations of the Bolza surface [50] (see also the section New Software above), which is the most symmetric surface of genus 2. Elaborating further on previous work [26], we are now considering symmetric hyperbolic surfaces of higher genus, for which we study mathematical properties [14] that allow us to propose algorithms [13].

In collaboration with Gert Vegter and Matthijs Ebbens (University of Groningen).

7.3. Probabilistic Analysis of Geometric Data Structures and Algorithms

Participants: Olivier Devillers, Charles Duménil, Fernand Kuiebove Pefireko.

7.3.1. *Stretch Factor in a Planar Poisson-Delaunay Triangulation with a Large Intensity*

Let $X := X_n \cup \{(0, 0), (1, 0)\}$, where X_n is a planar Poisson point process of intensity n . Our paper [4] provides a first non-trivial lower bound for the expected length of the shortest path between $(0, 0)$ and $(1, 0)$ in the Delaunay triangulation associated with X when the intensity of X_n goes to infinity. Simulations indicate that the correct value is about 1.04. We also prove that the expected length of the so-called upper path converges to $\frac{35}{3\pi^2}$, giving an upper bound for the expected length of the smallest path.

In collaboration with Nicolas Chenavier (Université du Littoral Côte d'Opale).

7.3.2. *Delaunay triangulation of a Poisson Point Process on a Surface*

The complexity of the Delaunay triangulation of n points distributed on a surface ranges from linear to quadratic. We proved that when the points are evenly distributed on a smooth compact generic surface the expected size of the Delaunay triangulation is can be controlled. If the point set is a good sample of a smooth compact generic surface [22] the complexity is controlled. Namely, good sample means that a sphere of size ϵ centered on the surface contains between 1 and η points. Under this hypothesis, the complexity of the Delaunay triangulation is $O\left(\frac{\eta^2}{\epsilon^2} \log \frac{1}{\epsilon}\right)$. We proved that when the points are evenly distributed on a smooth compact generic surface they form a good sample with high probability for relevant values of ϵ and η . We can deduce [15] that the expected size of the Delaunay triangulation of n random points of a surface is $O(n \log^2 n)$.

7.3.3. On Order Types of Random Point Sets

Let P be a set of n random points chosen uniformly in the unit square. In our paper [19], we examine the typical resolution of the order type of P . First, we showed that with high probability, P can be rounded to the grid of step $\frac{1}{n^{3+\epsilon}}$ without changing its order type. Second, we studied algorithms for determining the order type of a point set in terms of the the number of coordinate bits they require to know. We gave an algorithm that requires on average $4n \log_2 n + O(n)$ bits to determine the order type of P , and showed that any algorithm requires at least $4n \log_2 n - O(n \log \log n)$ bits. Both results extend to more general models of random point sets.

In collaboration with Philippe Duchon (LABRI) and Marc Glisse (project team DATASHAPE).

7.4. Classical Computational Geometry and Graph Drawing

Participants: Vincent Despré, Olivier Devillers, Sylvain Lazard.

7.4.1. Delaunay Triangulations of Points on Circles

Delaunay triangulations of a point set in the Euclidean plane are ubiquitous in a number of computational sciences, including computational geometry. Delaunay triangulations are not well defined as soon as 4 or more points are concyclic but since it is not a generic situation, this difficulty is usually handled by using a (symbolic or explicit) perturbation. As an alternative, we proposed to define a canonical triangulation for a set of concyclic points by using a max-min angle characterization of Delaunay triangulations. This point of view leads to a well defined and unique triangulation as long as there are no symmetric quadruples of points. This unique triangulation can be computed in quasi-linear time by a very simple algorithm [18].

In collaboration with Hugo Parlier and Jean-Marc Schlenker (University of Luxembourg).

7.4.2. Improved Routing on the Delaunay Triangulation

A geometric graph $G = (P, E)$ is a set of points in the plane and edges between pairs of points, where the weight of each edge is equal to the Euclidean distance between the corresponding points. In k -local routing we find a path through G from a source vertex s to a destination vertex t , using only knowledge of the present location, the locations of s and t , and the k -neighbourhood of the current vertex. We presented [11] an algorithm for 1-local routing on the Delaunay triangulation, and show that it finds a path between a source vertex s and a target vertex t that is not longer than $3.56|st|$, improving the previous bound of 5.9.

In collaboration with Nicolas Bonichon (Labri), Prosenjit Bose, Jean-Lou De Carufel, Michiel Smid and Daryl Hill (Carleton University)

7.4.3. Limits of Order Types

We completed an extended version of a work published at SoCG 2015, in which we apply ideas from the theory of limits of dense combinatorial structures to study order types, which are combinatorial encodings of finite point sets. Using flag algebras we obtain new numerical results on the Erdős problem of finding the minimal density of 5-or 6-tuples in convex position in an arbitrary point set, and also an inequality expressing the difficulty of sampling order types uniformly. Next we establish results on the analytic representation of limits of order types by planar measures. Our main result is a rigidity theorem: we show that if sampling two measures induce the same probability distribution on order types, then these measures are projectively equivalent provided the support of at least one of them has non-empty interior. We also show that some condition on the Hausdorff dimension of the support is necessary to obtain projective rigidity and we construct limits of order types that cannot be represented by a planar measure. Returning to combinatorial geometry we relate the regularity of this analytic representation to the aforementioned problem of Erdős on the density of k -tuples in convex position, for large k [20].

In collaboration with Alfredo Hubard (Laboratoire d'Informatique Gaspard-Monge) Rémi De Joannis de Verclos (Radboud university, Nijmegen) Jean-Sébastien Sereni (CNRS) Jan Volec (Department of Mathematics and Computer Science, Emory University)

7.4.4. Snap rounding polyhedral subdivisions

Let \mathcal{P} be a set of n polygons in \mathbb{R}^3 , each of constant complexity and with pairwise disjoint interiors. We propose a rounding algorithm that maps \mathcal{P} to a simplicial complex \mathcal{Q} whose vertices have integer coordinates. Every face of \mathcal{P} is mapped to a set of faces (or edges or vertices) of \mathcal{Q} and the mapping from \mathcal{P} to \mathcal{Q} can be built through a continuous motion of the faces such that (i) the L_∞ Hausdorff distance between a face and its image during the motion is at most $3/2$ and (ii) if two points become equal during the motion they remain equal through the rest of the motion. In the worse case, the size of \mathcal{Q} is $O(n^{15})$, but we conjecture a good complexity of $O(n\sqrt{n})$ in practice on non-pathological data [12].

In collaboration with William J. Lenhart (Williams College, USA).

7.4.5. On the Edge-length Ratio of Outerplanar Graphs

We show that any outerplanar graph admits a planar straight-line drawing such that the length ratio of the longest to the shortest edges is strictly less than 2. This result is tight in the sense that for any $\epsilon > 0$ there are outerplanar graphs that cannot be drawn with an edge-length ratio smaller than $2 - \epsilon$. We also show that this ratio cannot be bounded if the embeddings of the outerplanar graphs are given [9].

In collaboration with William J. Lenhart (Williams College, USA) and Giuseppe Liotta (Università di Perugia, Italy).

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

- Company: WATERLOO MAPLE INC
Duration: 2 years
Participants: GAMBLE and OURAGAN Inria teams
Abstract: A two-years licence and cooperation agreement was signed on April 1st, 2018 between WATERLOO MAPLE INC., Ontario, Canada (represented by Laurent Bernardin, its Executive Vice President Products and Solutions) and Inria. On the Inria side, this contract involves the teams GAMBLE and OURAGAN (Paris), and it is coordinated by Fabrice Rouillier (OURAGAN).
F. Rouillier and GAMBLE are the developers of the ISOTOP software for the computation of topology of curves. One objective of the contract is to transfer a version of ISOTOP to WATERLOO MAPLE INC.
- Company: GEOMETRYFACTORY
Duration: permanent
Participants: Inria and GEOMETRYFACTORY
Abstract: CGAL packages developed in GAMBLE are commercialized by GEOMETRYFACTORY.

9. Partnerships and Cooperations

9.1. Regional Initiatives

We organized, with colleagues of the mathematics department (Institut Elie Cartan Nancy) a regular working group about geometry and probability.

9.2. National Initiatives

9.2.1. ANR SingCAST

Project title: Singular Curves and Surfaces Topology

Duration: March 2014 – August 2018

Coordinators: Guillaume Moroz 60%, and Marc Pouget 40%

Abstract: The objective of the young-researcher ANR grant SingCAST was to intertwine further symbolic/numeric approaches to compute efficiently solution sets of polynomial systems with topological and geometrical guarantees in singular cases. We focused on two applications: the visualization of algebraic curves and surfaces and the mechanical design of robots. We developed dedicated symbolic-numerical methods that take advantage of the structure of the associated polynomial systems that cannot be handled by purely symbolic or numerical methods.

The project had a total budget of 100k€. Project website: <https://project.inria.fr/singcast/>.

9.2.2. ANR SoS

Project title: Structures on Surfaces

Duration: 4 years

Starting Date: April 1st, 2018

Coordinator: Monique Teillaud

Participants:

- Gamble project-team, Inria.
- LIGM (Laboratoire d'Informatique Gaspard Monge), Université Paris-Est Marne-la-Vallée. Local Coordinator: Éric Colin de Verdière.
- RMATH (Mathematics Research Unit), University of Luxembourg. National Coordinator: Hugo Parlier

SoS is co-funded by ANR (ANR-17-CE40-0033) and FNR (INTER/ANR/16/11554412/SoS) as a PRCI (Projet de Recherche Collaborative Internationale).

The central theme of this project is the study of geometric and combinatorial structures related to surfaces and their moduli. Even though they work on common themes, there is a real gap between communities working in geometric topology and computational geometry and SoS aims to create a long lasting bridge between them. Beyond a common interest, techniques from both ends are relevant and the potential gain in perspective from long-term collaborations is truly thrilling.

In particular, SoS aims to extend the scope of computational geometry, a field at the interface between mathematics and computer science that develops algorithms for geometric problems, to a variety of unexplored contexts. During the last two decades, research in computational geometry has gained wide impact through CGAL, the Computational Geometry Algorithms Library. In parallel, the needs for non-Euclidean geometries are arising, e.g., in geometric modeling, neuromathematics, or physics. Our goal is to develop computational geometry for some of these non-Euclidean spaces and make these developments readily available for users in academy and industry.

To reach this aim, SoS will follow an interdisciplinary approach, gathering researchers whose expertise cover a large range of mathematics, algorithms and software. A mathematical study of the objects considered will be performed, together with the design of algorithms when applicable. Algorithms will be analyzed both in theory and in practice after prototype implementations, which will be improved whenever it makes sense to target longer-term integration into CGAL.

Our main objects of study will be Delaunay triangulations and circle patterns on surfaces, polyhedral geometry, and systems of disjoint curves and graphs on surfaces.

Project website: <https://members.loria.fr/Monique.Teillaud/collab/SoS/>.

9.2.3. ANR Aspag

Project title: Analyse et Simulation Probabilistes d'Algorithmes Géométriques

Duration: 4 years

Starting date: January 1st, 2018

Coordinator: Olivier Devillers

Participants:

- Gamble project-team, Inria.
- Labri (Laboratoire Bordelais de Recherche en Informatique), Université de Bordeaux. Local Coordinator: Philippe Duchon.
- Laboratoire de Mathématiques Raphaël Salem, Université de Rouen. Local Coordinator: Pierre Calka.
- LAMA (Laboratoire d'Analyse et de Mathématiques Appliquées), Université Paris-Est Marne-la-Vallée. Local Coordinator: Matthieu Fradelizi

Abstract: ASPAG projet is funded by ANR undered number ANR-17-CE40-0017 .

The analysis and processing of geometric data has become routine in a variety of human activities ranging from computer-aided design in manufacturing to the tracking of animal trajectories in ecology or geographic information systems in GPS navigation devices. Geometric algorithms and probabilistic geometric models are crucial to the treatment of all this geometric data, yet the current available knowledge is in various ways much too limited: many models are far from matching real data, and the analyses are not always relevant in practical contexts. One of the reasons for this state of affairs is that the breadth of expertise required is spread among different scientific communities (computational geometry, analysis of algorithms and stochastic geometry) that historically had very little interaction. The Aspaga project brings together experts of these communities to address the problem of geometric data. We will more specifically work on the following three interdependent directions.

(1) Dependent point sets: One of the main issues of most models is the core assumption that the data points are independent and follow the same underlying distribution. Although this may be relevant in some contexts, the independence assumption is too strong for many applications.

(2) Simulation of geometric structures: The phenomena studied in (1) involve intricate random geometric structures subject to new models or constraints. A natural first step would be to build up our understanding and identify plausible conjectures through simulation. Perhaps surprisingly, the tools for an effective simulation of such complex geometric systems still need to be developed.

(3) Understanding geometric algorithms: the analysis of algorithm is an essential step in assessing the strengths and weaknesses of algorithmic principles, and is crucial to guide the choices made when designing a complex data processing pipeline. Any analysis must strike a balance between realism and tractability; the current analyses of many geometric algorithms are notoriously unrealistic. Aside from the purely scientific objectives, one of the main goals of Aspaga is to bring the communities closer in the long term. As a consequence, the funding of the project is crucial to ensure that the members of the consortium will be able to interact on a very regular basis, a necessary condition for significant progress on the above challenges.

Project website: <https://members.loria.fr/Olivier.Devillers/aspaga/>.

9.2.4. PHC Embeds II

Embeds is a bilateral, two-year project funded by the PHC Barrande program. It is joint between various french locations (Paris Est, Grenoble and, since september 2018, Nancy) and Charles University (Prague). The PI are Xavier Goaoc and Martin Tancer. It started in 2015 for two years, and was renewed in 2017 for two more years (5kE/year on the french side to support travels).

Starting Date: January 1st, 2017.

Duration: 2 years.

9.2.5. Institut Universitaire de France

Xavier Goaoc was appointed *junior member* of the Institut Universitaire de France, a grant supporting a reduction in teaching duties and funding.

Starting Date: October 1st, 2014.

Duration: 5 years.

9.3. International Initiatives

9.3.1. Inria Associate Teams Not Involved in an Inria International Labs

9.3.1.1. TRIP

Title: Triangulation and Random Incremental Paths

International Partner: Carleton University (Canada) - Prosenjit Bose

Start year: 2018

See also: <https://members.loria.fr/Olivier.Devillers/trip/>

The two teams are specialists of Delaunay triangulation with a focus on computation algorithms on the French side and routing on the Canadian side. We plan to attack several problems where the two teams are complementary: - Stretch factor of the Delaunay triangulation in 3D. - Probabilistic analysis of Theta-graphs and Yao-graphs. - Smoothed analysis of a walk in Delaunay triangulation. - Walking in/on surfaces. - Routing in non-Euclidean spaces.

9.3.1.2. Astonishing

Title: ASSociate Team ON Non-ISH euclidean Geometry

International Partner: University of Groningen (Netherlands) - Institute of Systems Science - Gert Vegter

Start year: 2017

See also: <https://members.loria.fr/Monique.Teillaud/collab/Astonishing/>

Some research directions in computational geometry have hardly been explored. The spaces in which most algorithms have been designed are the Euclidean spaces \mathbb{R}^d . To extend further the scope of applicability of computational geometry, other spaces must be considered, as shown by the concrete needs expressed by our contacts in various fields as well as in the literature. Delaunay triangulations in non-Euclidean spaces are required, e.g., in geometric modeling, neuromathematics, or physics. Topological problems for curves and graphs on surfaces arise in various applications in computer graphics and road map design. Providing robust implementations of these results is a key towards their reusability in more applied fields. We aim at studying various structures and algorithms in other spaces than \mathbb{R}^d , from a computational geometry viewpoint. Proposing algorithms operating in such spaces requires a prior deep study of the mathematical properties of the objects considered, which raises new fundamental and difficult questions that we want to tackle.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

Gert Vegter spent three weeks in GAMBLE in the framework of the Astonishing associate team.

Jean-Lou De Carufel and Prosenjit Bose spent one week in GAMBLE in the framework of the TRIP associate team.

Martin Tancer, Vojta Kalusza and Pavel Paták, from Charles University (Prague), spent one week each in GAMBLE. They were supported by the PHC program EMBEDS II.

9.4.2. Visits to International Teams

Olivier Devillers spent two weeks at the Computational Geometry Lab of Carleton University <http://cglab.ca/about.html> in the framework of the TRIP associate team.

Charles Duménil spent one month at the Computational Geometry Lab of Carleton University <http://cglab.ca/about.html> in the framework of the TRIP associate team.

Monique Teillaud and Jordan Jordanov spent one month at Johann Bernoulli Institute for Mathematics and Computer Science of the University of Groningen in the framework of the Astonishing associate team.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. Member of the Organizing Committees

Sylvain Lazard organized with S. Whitesides (Victoria University) the **17th Workshop on Computational Geometry** at the Bellairs Research Institute of McGill University in Feb. (1 week workshop on invitation).

Olivier Devillers and Xavier Goaoc co-organized the Aspag Prospective workshop, April 8-12 2018 in Arcachon.

10.1.1.2. Steering Committees

Monique Teillaud is chairing the Steering Committee of the Symposium on Computational Geometry (SoCG).

10.1.2. Scientific Events Selection

10.1.2.1. Member of the Conference Program Committees

Monique Teillaud was a member of the program committee of the European Workshop on Computational Geometry.

10.1.2.2. Reviewer

All members of the team are regular reviewers for the conferences of our field, namely the *Symposium on Computational Geometry* (SoCG) and the *International Symposium on Symbolic and Algebraic Computation* (ISSAC) and also SODA, CCCG, EuroCG.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

Monique Teillaud is a managing editor of JoCG, *Journal of Computational Geometry* and a member of the editorial board of IJCGA, *International Journal of Computational Geometry and Applications*.

Marc Pouget and Monique Teillaud are members of the CGAL editorial board.

10.1.3.2. Reviewer - Reviewing Activities

All members of the team are regular reviewers for the journals of our field, namely *Discrete and Computational Geometry* (DCG), *Computational Geometry. Theory and Applications* (CGTA), *Journal of Computational Geometry* (JoCG), *International Journal on Computational Geometry and Applications* (IJCGA), *Journal on Symbolic Computations* (JSC), *SIAM Journal on Computing* (SICOMP), *Mathematics in Computer Science* (MCS), etc.

10.1.4. Leadership within the Scientific Community

10.1.4.1. Learned societies

Monique Teillaud was a member of the Scientific Board of the *Société Informatique de France* (SIF) until July.

10.1.5. Research Administration

10.1.5.1. Hiring committees

Sylvain Lazard was the laboratory delegate in a prof (PR) hiring committee at Lorraine Univ. (IUT Charlemagne & Loria).

Monique Teillaud chaired the hiring committee for young researchers (CRCN) of Inria Bordeaux - Sud Ouest.

10.1.5.2. National committees

L. Dupont is the secretary of *Commission Pédagogique Nationale Carrières Sociales / Information-Communication / Métiers du Multimédia et de l'Internet*.

M. Teillaud is a member of the working group for the BIL, *Base d'Information des Logiciels* of Inria.

10.1.5.3. Local Committees and Responsibilities

O. Devillers: Elected member to *Pole AM2I* the council that gathers labs in mathematics, computer science, and control theory at *Université de Lorraine*.

L. Dupont: Head of the Bachelor diploma *Licence Professionnelle Animation des Communautés et Réseaux Socionumériques*, Université de Lorraine. Responsible of Fablab of IUT Charlemagne, Université de Lorraine (since 2018, November). Member of *Comité Information Edition Scientifique* of LORIA.

S. Lazard: Head of the PhD and Post-doc hiring committee for Inria Nancy-Grand Est (since 2009). Member of the *Bureau de la mention informatique* of the *École Doctorale IAEM* (since 2009). Head of the *Mission Jeunes Chercheurs* for Inria national. Head of the Department Algo at LORIA (since 2014). Member of the *Conseil Scientifique* of LORIA (since 2014).

G. Moroz: Member of the *Comité des utilisateurs des moyens informatiques*. Member of the CDT, *Commission de développement technologique*, of Inria Nancy - Grand Est.

M. Pouget is elected at the *Comité de centre*, and is secretary of the board of *AGOS-Nancy*.

M. Teillaud joined the *Conseil de Laboratoire* of LORIA in May. She was a member of the BCP, *Bureau du Comité des Projets* of Inria Nancy - Grand Est until end November.

X. Goaoc is a member of the council of the *Fédération Charles Hermite* since sep. 2018.

10.1.5.4. Websites

M. Teillaud is maintaining the Computational Geometry Web Pages <http://www.computational-geometry.org/>, hosted by Inria Nancy - Grand Est. This site offers general interest information for the computational geometry community, in particular the Web proceedings of the Video Review of Computational Geometry, part of the Annual/international Symposium on Computational Geometry.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Licence: Charles Duménil, *Algorithmique et programmation avancée*, 32h, M2, Université de Lorraine, France.

Licence: Laurent Dupont, *Algorithmique*, 15h, L1, Université de Lorraine, France.

Licence: Laurent Dupont, *Web development*, 100h, L2, Université de Lorraine, France.

Licence: Laurent Dupont, *Traitement Numérique du Signal*, 20h, L2, Université de Lorraine, France.

Licence: Laurent Dupont *Web development and Social networks* 100h L3, Université de Lorraine, France.

Licence: Iordan Iordanov, *Algorithmique et Programmation*, 64h, L1, Université de Lorraine, France.

Licence: Iordan Iordanov, *Systèmes de gestion de bases de données*, 20h, L2, Université de Lorraine, France.

Licence: Iordan Iordanov, *Algorithmique et développement web*, 28h, L2, Université de Lorraine, France.

Licence: Iordan Iordanov, *Programmation objet et événementielle*, 16h, L3, Université de Lorraine, France.

Licence: Sylvain Lazard, *Algorithms and Complexity*, 25h, L3, Université de Lorraine, France.

Master: Marc Pouget, *Introduction to computational geometry*, 10.5h, M2, École Nationale Supérieure de Géologie, France.

Licence: Galatée Hemery, *Programmation*, 64h, L3, École des Mines de Nancy, France.

Master: Vincent Despré, *Algorithmique*, 72h, M1, Polytech Nancy, France.

Master: Vincent Despré, *Systèmes distribués*, 20h, M1, Polytech Nancy, France.

Master: Olivier Devillers, *Modèles d'environnements, planification de trajectoires*, 18h, M2 AVR, Université de Lorraine. <https://members.loria.fr/Olivier.Devillers/master/>

Master: Olivier Devillers and Marc Pouget, *Computational Geometry*, 24h (academic year 2018-19), M2 Informatique, ENS Lyon <https://members.loria.fr/Olivier.Devillers/Master2-ENS-Lyon/>.

Master : Xavier Goaoc, *Algorithms and data structures*, 31.5 HETD (academic year 2018-19), M1, École des Mines de Nancy, France

Master : Xavier Goaoc, *Computer architecture*, 31.5 HETD, M1 (academic year 2018-19), École des Mines de Nancy, France

10.2.2. Supervision

PhD in progress: Sény Diatta, Complexité du calcul de la topologie d'une courbe dans l'espace et d'une surface, started in Nov. 2014, supervised by Daouda Niang Diatta, Marie-Françoise Roy and Guillaume Moroz.

PhD in progress: Charles Duménil, Probabilistic analysis of geometric structures, started in Oct. 2016, supervised by Olivier Devillers.

PhD in progress: Iordan Iordanov, Triangulations of Hyperbolic Manifolds, started in Jan. 2016, supervised by Monique Teillaud.

PhD in progress: George Krait, Topology of singular curves and surfaces, applications to visualization and robotics, started in Nov. 2017, supervised by Sylvain Lazard, Guillaume Moroz and Marc Pouget.

PhD in progress: Galatée Hemery, Algorithmic and geometric aspects of inclusion-exclusion, started in Sep. 2018, supervised by Xavier Goaoc and Éric Colin de Verdière (UPEM).

PhD in progress: Fernand Kuiebove Pefireko, Simulation of random geometric structures, started in Oct. 2018, supervised by Olivier Devillers.

10.2.3. Juries

O. Devillers was the president of the PhD committee of Tuong-Bach Nguyen (Université de Grenoble).

S. Lazard was a reviewer for the HDR of Yukiko Kenmochi (Université de Marnes-la-Vallée).

G. Moroz was a member of the PhD committee of Guillaume Rance (Université Paris-Sud).

10.3. Popularization

10.3.1. Education

G. Moroz is member of the Mathematics Olympiades committee of the Nancy-Metz academy.

10.3.2. Interventions

L. Dupont participated in several events of popularization of computer science:

Math en Jeans, March 30th, popularization of computer science for high-school students.

ISN day, March 22th, adult continuing education of computer science for high-school teachers.

FabLab14, July 13th, popularization of computer science, general audience.

Ada Lovelace Day 2018, october 9 : popularization of computer science for female high-school students.

11. Bibliography

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