INRIA, Evaluation of Theme Interaction et visualisation

Project-team ALICE

October 2014

Project-team title: ALICE, Geometry and Light

Scientific leader: Bruno Lévy

Research center: Nancy Grand-Est

Common project-team with: LORIA lab.

1 Personnel

Personnel (October 2010)

	Misc.	INRIA	CNRS	University	**Total**
DR / Professors		1			**1**
CR / Assistant Professor		5		1	**6**
Permanent Engineer					
Temporary Engineer		1			**1**
PhD Students	4	5			**9**
Post-Doc.		2			
Total	**4**	**13**			**17**
External Collaborators				1	**1**
Visitors (> 1 month)				1	**1**

(1) "Senior Research Scientist (Directeur de Recherche)"
(2) "Junior Research Scientist (Chargé de Recherche)"
(3) "Civil servant (CNRS, INRIA, ...)"
(4) "Associated with a contract (Ingénieur Expert or Ingénieur Associé)"

Personnel (October 2014)

	Misc.	INRIA	CNRS	University	**Total**
DR / Professors		2		1	**3**
CR / Assistant Professor		5		2	**7**
Permanent Engineer					
Temporary Engineer		1			**1**
PhD Students	1	5			**6**
Post-Doc.		2			**2**
Masters		1			**1**
Total	**1**	**16**		**3**	**20**
External Collaborators				1	
Visitors (> 1 month)					

Changes in staff

	Misc.	INRIA	CNRS	University	total
DR / Professors		+1		+1	
CR / Assistant Professors				+1	

Comments:

- Jean-Claude Paul is an Inria Research Director, who joined Tsinghua University (China) in 2004. He directed the CAD team (cooperation between Inria and Tsinghua University). He came back in France in 2013 and is now hosted by ALICE;
- Xavier Antoine is a professor of applied mathematics. He is temporarily associated with ALICE ("delegation", for 1 years, Sept. 2013 - Sept. 2014), to develop some joined research projects (including project BECASIM, more on this below);
- Dobrina Boltcheva (Assistant Professor) was hired in Sept. 2011. She is specialized in computational geometry and computational topology.

Between 2004 and 2010 (previous evaluation period), the team has known a fast expansion, boosted by the European Research Council grant GOODSHAPE (1.1 M Euros) obtained by B. Lévy, and by 3 new Inria researchers (Sylvain Lefebvre, Rhaleb Zayer and Samuel Hornus) and 1 new associate professor (Dmitry Sokolov). The team reached a "critical mass" in 2010.

After this fast expansion, between 2010 and 2014 (this evaluation period), we hired in 2011 a new associate professor (Dobrina Boltcheva) and we worked on structuring the team. An important aspect in the past four years was to prepare the emergence of new leaders within the team. Rhaleb Zayer advised two Ph.D. theses (Alejandro Galindo and Kun Liu), funded by the 300K Euros grant that he obtained from the ANR (French NSF). Sylvain Lefebvre proposed to extend his "by-example" approach for designing textures to real 3D objects, and proposed a new research axis on 3d printing. He obtained an European Research Council grant SHAPEFORGE (1.3 M Euros) that allowed him to start funding Ph.D. students and advising them. He defended his habilitation thesis (HDR) in 2014 (French diploma that allows one to advise Ph.D. candidate). Jean-Claude Paul came back from China in 2013. We have now three faculties with habilitation thesis in the team. Another important aspect was to keep a good synergy between the two research axes (geometry processing and 3d printing). We developed a common strategy, with the general goal of developing computer graphics tools that can be ported "into reality". The common scientific culture and the cross-fertilization between the two research axes (geometry processing and 3d printing/by-example generation) is a key aspect of our strategy.

Current composition of the project-team (Oct. 2014):

Permanent Researchers

- Bruno Lévy, Inria Research Director (DR, HDR) (head of the team)
- Laurent Alonso, Inria Research Associate (CR)
- Samuel Hornus, Inria Research Associate (CR)
- Sylvain Lefebvre, Inria Research Associate (CR, HDR)
- Jean-Claude Paul, Inria Research Director (DR, HDR) - since Nov. 2013
- Nicolas Ray, Inria Research Associate (CR)
- Rhaleb Zayer, Inria Research Associate (CR)

- Dobrina Boltcheva, U. Lorraine, Associate Professor
- Dmitry Sokolov, U. Lorraine, Associate Professor
- Xavier Antoine, U. Lorraine, Professor (Sept. 2013 - Sept. 2014), temporary "delegation"

External Collaborator

- Guillaume Caumon, U. Lorraine, Professor (head of Gocad consortium)

Ph.D. Students

- Jérémie Dumas, Ph.D. candidate, ENS Lyon / ERC SHAPEFORGE
- Jean Hergel, Ph.D. candidate, ERC SHAPEFORGE
- Patricio Galindo, Ph.D. candidate, ANR PHYSIGRAPHICS
- Kun Liu, Ph.D. candidate, ANR PHYSIGRAPHICS
- David Lopez, Ph.D. candidate, ERC GOODSHAPE / Inria
- Arnaud Botella, Ph.D. candidate, GOCAD consortium

Masters, Post-Docs and Developers

- An Lu, Master Students, ERC SHAPEFORGE
- Jonas Martinez, Post-Doc., ERC SHAPEFORGE
- Lionel Unterreiner, Post-Doc., ANR BECASIM
- Frederic Claux, software developer, ERC SHAPEFORGE

Current position of former project-team members (2011-2014):

- Anas Lasram (Ph.D., defended Dec. 2012 ERC SHAPEFORGE):
  Now GPU architecture model developer, AMD, Sunnyvale / California

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  Dear Sylvain and Bruno,
  I am pleased to inform you that Anas Lasram is finishing his research
  internship in AMD this week and will join as full time employee starting
  October 2014 after  brief visit to his family.
  Now we are looking for another internship candidate from INRIA considering
  exceptional level of Anas Lasram who picked very complicated internal tools
  development and works with multiple teams inside AMD.

  Timour Paltashev, Senior Manager, AMD (Advanced Micro Devices)
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- Vincent Nivoliers (Ph.D., defended Nov. 2012, ENS AND ERC GOODSHAPE):
  Now researcher with CNRS, Lyon

- Nicolas Cherpeau (Ph.D., defended Apr. 2012, co-advised with GOCAD):
  Now post-doc in Stanford U., USA

- Romain Merland (Ph.D., defended Apr. 2013, co-advised with GOCAD):
  Now with PARADIGM Geophysical / Earth Decisions Sciences

- Jeanne Pellerin (Ph.D., defended March 2014, co-advised with GOCAD):
  Now post-doc with Hang Si (author of TETGEN), WIAS Berlin and with TOTAL

- Thomas Jost (Ph.D. candidate, not defended, ERC GOODSHAPE):
  Now with Findspire (Nancy), lead software engineer

- Yang Liu (Post-Doc. in 2009, ERC GOODSHAPE):
  Now researcher with Microsoft Research Asia (Beijing / China)

- Nicolas Bonneel (Post-Doc. in 2012, ERC GOODSHAPE):
  Now researcher with CNRS, Lyon

Last INRIA enlistments

No new Inria researcher in the evaluation period.

2 Work progress

2.1 Keywords

- Geometry processing, mesh generation, sampling, scientific computing
- Additive fabrication (3d printing), by-example generation, texture synthesis

2.2 Context and overall goal of the project

Original objectives, as indicated in the initial ALICE project proposal[1] (May 2006)

ALICE is an INRIA Project-team on Computer Graphics. The fundamental aspects of this domain concern the interaction of *light* with the *geometry* of the objects. The lighting problem consists in designing accurate and efficient *numerical simulation* methods for the light transport equation. The geometrical problem consists in developing new solutions to *transform and optimize geometric representations*. Our original approach to both issues is to restate the problems in terms of *numerical optimization*. We try to develop solutions that are *provably correct*, *scalable* and *numerically stable*.

To reach these goals, our approach consists in transforming the physical or geometric problem into a numerical optimization problem, studying the properties of the objective function and designing efficient minimization algorithms.

Besides Computer Graphics, our goal is to develop cooperations with researchers and people from the industry, who experiment applications of our general solutions to various domains, comprising CAD, industrial design, oil exploration, plasma physics...

Evolution of the research directions (2011-2014): Into Reality

In 2010, we started to develop techniques to model not only virtual objects, but also real ones. Our *Modeling and Rendering* research axis evolved, and we generalized our results on by-example texture synthesis to the production of real objects, using 3d printers. As compared to virtual object, this setting defines higher requirements for the *Geometry Processing* techniques that we develop, that need to be adapted to both numerical simulation and computer-aided fabrication. We study how to include *computational physics* into the loop, and simulation methods for various phenomena (e.g., fluid dynamics).

2.3 Objectives for the evaluation period

2.4 Objective 1 : Applied Mathematics and Numerical Simulation *(defined in Nov. 2010)*

Our work in numerical approximation is more and more connected with the applied mathematics community. We aim at developing new partnerships with this community, and start studying numerical simulation problems with a "geometry processing" perspective. We will experiment new numerical solution mechanisms based on our results on hex-dominant meshing[2] and dynamic function basis[3], for problems such as fluid simulation for oil and

[1] alice.loria.fr/alice_proposal.pdf

[2] L_P-Centroidal Voronoi Tesselation, B. Lévy and Y. Liu, ACM SIGGRAPH, 2010

[3] On Centroidal Voronoi Tesselation, Energy Smoothness and Fast Computation, ACM Transactions on Graphics, 2008

gas exploration, light simulation and acoustics.

2.4.1 Personnel

- **Permanent researchers** : Xavier Antoine, Laurent Alonso, Dobrina Boltcheva, Samuel Hornus, Bruno Lévy, Jean-Claude Paul, Nicolas Ray, Dmitry Sokolov, Rhaleb Zayer
- **Ph.D. candidates** : Arnaud Botella, Nicolas Cherpeau, Patricio Galindo, Kun Liu, David Lopez, Vincent Nivoliers, Jeanne Pellerin
- **Post Docs** : Lionel Unterreiner

2.4.2 Project-team positioning

In France, we share some interests in scientific problems with TITANE (Pierre Alliez's team). These topics include parameterization and sampling. We attack the problem from a different angle: Pierre Alliez (and his colleague in Caltech Mathieu Desbrun) use a discrete formalism (discrete differential geometry, discrete exterior calculus), based on discrete differential operators (matrices) acting on discrete functions (vectors).

We explore the continuous setting (Riemann, finite element modeling, continuous exterior calculus), with Hilbert spaces structured by an inner product, operators, functions, Finite Element Modeling. We have many discussion and exchanges with P. Alliez, M.Desbrun and other researchers working on the discrete point of view. We think that both points of view are complementary.

Worldwide, there are many teams interested in geometry processing (including Marc Alexa's group and Nina Amenta's group :-). We participate to the activities of the community on a regular basis (PC committees, reviewing, editing etc...). We cooperate with Wenping Wang (HK University) on Voronoi diagrams.

The specificity of our approach is to focus on the continuous setting. This allows to "talk the same language" as the applied mathematics community, and bring new mathematical tools to the geometry processing community and vice-versa. This strategy allowed us in the past to develop methods that had a lasting high impact in both domains[4].

We continue our trend of digging the numerical analysis foundations deeper and deeper, and now shift the center of gravity of this research axis more and more towards the mathematics community. Xavier Antoine, prof. in Mathematics, joined the team for 1 year (Sept. 2013 - Sept. 2014) and we started launching cooperative research projects (BECASIM, more on this below). We published articles in SIAM J. of Scientific Computing [11], [17] in J. of Computational Physics [28], [18], [20] and submitted an article to ESAIM Mathematical Modeling and Analysis [67]. We are more and more interested by research topics that are at the junction between computer sciences and mathematics.

2.4.3 Scientific achievements

- **Parameterization** constructs a coordinate system over a mesh, that makes it easy to change the representation (re-meshing, Splines, . . .). We developed a quadrangulation algorithm that starts from a pointset, published in Computer and Graphics J. [47] (a "meshless" version of our previous Periodic Global Parameterization method). For objects of arbitrary topology, it is interesting to see how to decompose the object

[4]Least Squares Conformal Maps, published in 2002, based on Riemann mapping, has over 850 citations, and is listed as one of the highest impact SIGGRAPH paper ever in *Metagraphics: Impact papers from SIGGRAPH/TOG, Nehab and Sander, SIGGRAPH ASIA 2013*, and our work on Periodic Global Parameterization published in 2006 has over 200 citations, according to Google Scholar

into simple charts, that can be easily parameterized. Such a decomposition can be deduced from a vector field (Morse complex), by cutting the surface along streamlines that connect the singularities of the vector field. However, when meshes are concerned, it is not completely clear how to trace a streamline over a mesh. This requires a well-behaved definition of streamlines and singularities. We proposed such a definition together with a robust algorithm that ensures that the streamlines do not cross and published it in ACM Transactions on Graphics [10]. We also worked on parametric representations (polynomial surfaces) directly. We developed techniques for designing shapes using polynomial surfaces that respect some boundary conditions [21] (CAD J.), and developed some methods for assembly retreival [22] (CAD J.).

- **Sampling and remeshing:** we continued to study the algorithms based on Centroidal Voronoi Tesselation for sampling and re-meshing surfaces and volumes. We developed algorithms to avoid obtuse triangles in the result [42] (CAGD J.), to compute the intersection between a Voronoi diagram and a tetrahedral mesh [35] (CAD J.) (a key component for applying the method to volumetric data) and an anisotropic generalization of the method [34] (ACM SIGGRAPH) based on a kernel formulation. We also studied how to introduce a varying density in Optimal Delaunay Triangulations [11] (SIAM J. on Scientific Computing). With our continuous point of view, the resulting algorithm has a consistent definition, and a faster speed of convergence;

- **Function approximation:** in his Ph.D. thesis, Vincent Nivoliers [3] studied function approximation with Voronoi diagrams. He published his results on image approximation and direct illumination in SGP [29]. We studied also how to generalize the Centroidal Voronoi Tesselation framework to objects that are more general than pointsets [41] (Eurographics). This allowed us to invent a method to minimize the approximation error realized by a function [16] (Engineering with Computers J.). We developed a volumetric version and published it in SGP [30].

- **Numerical simulation:** *flow simulation for oil exploration:* during the evaluation period, we co-advised three Ph.D. thesis with the Gocad Consortium, that develops modeling algorithms for oil and gas exploration [4], [6], [7]. We developed specialized meshing algorithms, well suited to represent geological layers at various resolutions [9], [51], [60]. In 2011, Nicolas Cherpeau received an award of merit in 2011 from the SEG (Society of Exploration Geophysicists) for his paper "Stochastic Simulation of Fault Networks" published in 2010 (co-authored with G. Caumon and B. Lévy). We experimented the so-obtained grids for flow simulations [63] that simulate how a well can extract oil from geological layers. *non-linear deformation mechanics:* we also developed finite element models for non-linear deformations of beams [38]. *optimal transport:* this is an active research topics in the mathematics community. Given two measures μ and ν, optimal transport defines a distance between μ and ν, as the minimum cost of "morphing" μ into ν. This distance (called the *Wasserstein distance*) structures the space of measures and offers new ways of solving some highly non-linear PDEs (Monge-Ampere, Fokker-Plank . . .). This requires a numerical way of computing the Wasserstein distance and its gradients. We studied different techniques, a "smoothed" discrete one (point to point distances smoothed by Gaussians) [43] (SIGGRAPH ASIA 2011), and a semi-discrete one [67] (submitted to ESAIM J. M2AN), that optimizes power diagrams. This is to our knowledge the first numerical implementation of optimal transport for volumetric densities (computes the

Wasserstein distance between a sum of Dirac masses and a piece-wise linear density supported on a tetrahedral mesh). *Bose-Einstein condensates:* Xavier Antoine (prof. in mathematics) joined the team on a "delegation" position (Sept. 2013 - Sept. 2014) to explore some common research topics. We are members of the BECASIM project, funded by the ANR ("French NSF"). In a certain sense, a Bose-Einstein condensate is a "Schroedinger cat" made of a few hundred atoms. By special physical means (low temperature and lasers), the probability waves of these atoms are intermixed, thus forming an alternative state of matter. The BECASIM project aims at developing numerical simulation methods for these complicated phenomena (that intermix fluid dynamics, electromagnetics and quantum physics). We developed different techniques, and studied different aspects of the problem, comprising domain decomposition [17] (SIAM J. on Scientific computing), local operators [18] (J. on comput. physics), numerical toolbox [19], boundary conditions [20] (J. on comput. physics), numerical solvers specialized for this type of problem [28] (J. on comput. physics).

2.4.4 Cooperations

- We have a long-term cooperation with the Gocad Consortium (Nancy school of Geology), with co-advised students. This resulted in some applications of our result to oil exploration, listed in the *numerical simulation* item above (Ph.D. theses of Arnaud Botella, Nicolas Cherpeau, Jeanne Pellerin, Romain Merland);
- We cooperate since 2008 with Wenping Wang's group (Hong-Kong University), on centroidal Voronoi tesselation. The results on *Sampling and Remeshing* listed above are the results of this cooperation, and the publications in: [11] Siam J. on Scientific Computing, [34] (SIGGRAPH 2013), [35] (CAD J.), [41] (EUROGRAPHICS 2012), [42] (CAGD J.)
- Cooperation with Pierre Poulin and Gilles-Philippe Paillé on volumetric distance minimization [30] (SGP 2009)
- Cooperation with Tsinghua University (Jean-Claude Paul was Professor there from 2004 to 2013).

2.4.5 External support

- ERC GOODSHAPE, 2008-2013, Starting Grant, 1.1 MEuros, on sampling and approximation
- ERC VORPALINE, 2013-2014 Proof of Concept Grant, 150 KEuros, to pre-industrialize the results stemming from GOODSHAPE
- ANR Physigraphics, 2010-2013 (PI), 300 KEuros, on acquisition-driven numerical simulation of deformation
- BluePrint, 2014-2017 (Lorraine regional council grant), 1/2 Ph.D. thesis
- ANR MORPHO, 2010-2015 (participant), on human modeling
- ANR BECASIM, 2013-2018 (participant), on physics (numerical simulation of Bose-Einstein condensates)

2.4.6 Self assessment for Geometry Processing (into reality or into abstraction ?)

The path taken by the team, i.e. designing 3d modeling tools that can be used to model real objects ("into reality"), requires more and more demanding technology and scientific background under the scene, so that our models have predictive behavior. This made us digging deeper and deeper into the related mathematical background ("into abstraction").

Strong points: Our evolution towards applied mathematics is well started. We integrate more and more mathematical aspects in our research, from numerical analysis, PDE modeling and numerical optimization. Xavier Antoine (professor in Mathematics, Nancy School of Mines) joined the team in 2013 (for a short-term "delegation" of 1 year), this allowed us to start new projects, including the BECASIM ANR project on computational physics (Bose-Einstein condensates). B. Lévy is invited in workshops on mathematics (ANR TOMMI on optimal transport, ANR Geometrya, optimal tranport days in Paris/Dauphine), Ph.D. and habilitation thesis commitees of mathematicians (S. Jabrane, Q. Merigot, reviewing for SIAM journals, invitation in International Meshing Roundtable).

Weak points: It is difficult to be involved in two different research communities (graphics and math.) simultaneously. The main difficulty comes from the difference of "pace/speed" between both communities : while in computer graphics, the rhythm is defined by the conferences, mathematics require much longer review cycles (e.g., SIAM journals). Our latest results (e.g., in optimal transport [67]) confirm this trend towards mathematics. This new orientation represents a risk for this research axis since our mathematical background was only recently acquired, but we think that our strategy, driven by "following the steepest excitation gradient" is high risk / high gain, and we think we can contribute a "fresh" point of view on some mathematical problems.

This risk can be also mitigated by ourr strategy of continuing to publish our computer-graphics related results in journals (ACM Trans. on Graphics, IEEE Trans. on Visualization and Computer Graphics, Computer Graphics Forum) that have intermediate review cycles. Our result about the topology of stream lines published in ACM Transactions on Graphics [10] is an example of this strategy, and some of our results still fit relatively well within the space/time constraints of the SIGGRAPH review cycle, e.g., [34] (but it is a bit long for a SIGGRAPH paper, 14 pages).

2.5 Objective 2 : Modeling and Rendering *(defined in Nov. 2010)*

Virtual environments are widely used in applications ranging from training simulators, navigation systems, movie special effects and video games. While they may depict existing or imaginary worlds, they pose the same challenges: How to create, display and interact with the massive amounts of details required to depict an immersive environment.

These problems – content creation, display and interaction – have historically been addressed separately. We plan to investigate new approaches for content generation seeking to address these problems together. Our goal is to design methods able to automatically generate large amounts of content from small examples, while still storing the results under a compact form in memory. Such approaches greatly reduce authoring time, and simultaneously reduce memory bandwidth and increase data locality enabling faster display. There is a large impact potential for the industry, as content creation cost has grown to be the largest expense in most video game and movie special effects productions.

Generating content from example requires a deep understanding of the data that is being manipulated. Graphical content is essentially made of images and geometric primitives. The images – or textures – are mapped onto the surfaces of objects in order to generate details when computing the light/surface interactions. Thus, they often store not only colors but also various surface properties such as transparency, the local orientation of surface micro-geometry, or localized light-transport information. Research on content generation directly benefits from advances in the understanding of the nature of graphical content: How to analyze and represent geometry, textures, and the interaction of light and materials. The theoretical background required for the analysis of the example content is largely shared with the fields of signal and geometry processing. The generative process often leads to complex optimization problems, which are also common in the field of geometry processing. These objective is thus a natural complement to the focus of the ALICE team on geometry processing.

New orientation (2011-2014) We decided to explore the possibility of applying our by-example texture synthesis methods to real objects, fabricated by 3D printers, and how to design good 3d object representations for fabrication. These ideas evolved into a complete research program, that we proposed to the ERC (SHAPEFORGE project) and that was accepted for funding.

2.5.1 Personnel

- **Permanent researchers** : Samuel Hornus, Sylvain Lefebvre, Bruno Lévy, Jean-Claude Paul
- **Ph.D. candidates** : Jérémie Dumas, Jean Hergel, Anass Lasram
- **Masters, Post-Docs and Developers** : An Lu, Jonas Martinez, Frederic Claux

2.5.2 Project-team positioning

Computer aided fabrication (3d printing) is a very popular thus highly competitive research theme, and most major Computer Graphics research teams in the world have explored this newly emerged application domain. Our specificity is driven by our taste for solutions that can be used by the widest possible audience. This has three consequence in terms of our research objectives:

1. the software that we develop should be easy to use, not only by specialists, but also by the (possibly inexperienced) general public. For instance, we study methods that allow reusing existing geometry, from acquired examples, or from pre-designed parts created by experts, to automatically generate shapes and fine-scale structures;

2. the methods that we develop should be applicable not only to high end (100KEuros and above) printers, but also to off-the-shelf more affordable technology (low-end 2KEuros printers). This leads very practical problems (for instance, how to avoid oozing when using dual color extrusion printers), that can be translated into interesting computational geometry problems (how to generate a “protecting wall” geometry that will avoid oozing);

3. in addition, we are interested in methods that can generate complex objects, with intricate details, that would be impossible to fabricate with traditional means. This challenges 3d modeling with methods that can handle these complex shapes and that allow the user to design them.

To summarize, our originality is to consider both 3d printing technology at a low level (“mechanics” of printing, how to steer the printer in the most efficient manner, and in some cases, GPU programming) and from a user perspective (how this technology can be made available and easy to use by the widest possible audience). Our "IceSL" software is a typical illustration of this strategy (more on this below).

2.5.3 Scientific achievements

- **Texture Synthesis:** We continue our work about noise generation using Gabor kernels as a primitive. We proposed some improvements of the initial algorithm [46](TVCG), and a version of the algorithm that reproduces the examples specified by the user [37](SIGGRAPH 2012). We developed some techniques to facilitate specifying procedural textures by generating well-parameterized slides [57](Eurographics 2012, short paper) and showing a meaningful preview of the influence of two parameters [40](Eurographics 2012). We also worked on parallel implementations of patch-based texture synthesis [55](High Perf. Graphics Conf), and on an algorithm that generates animations for complicated sets of 3d objects [32](SIGGRAPH 2013). We used synthesis algorithm to generate complicated and constrained objects, such as maps for game levels [14]. We also observed an interesting connection between the methods used in texture synthesis and the methods used in geosciences to generate equiprobable distributions that match some statistical properties [26](Computers and Geosciences J).

- **GPU algorithms:** We developed several efficient data structures for implementing parallel texture generation algorithms on the GPU. We introduced a new spatial hashing algorithm [44](SIGGRAPH ASIA 2011), that can be used as an efficient building block for several algorithms. We used it (and some variants) to implement a texture cache [39](SMI 2012), and a A-Buffer [13](GPU Pro) that can be easily integrated into any OpenGL application. It produces for each pixel a depth-sorted list of fragments, efficiently stored in a dynamic hash table. We observed that it was very easy to implement CSG operators using a small modification of the shader / per-fragment operations. As a consequence, this rendering method can be used as a complete modeling system (that operates on discretized "dexel" geometry, i.e. compressed voxel grids, directly). We created the **IceSL** software that implements this idea, and that can be used to steer 3D printers [52] (presented at the European Forum on Additive Fabrication). It was used to produce the results in most research papers of this axis during this evaluation period;

- **Computer Aided Fabrication (3d printing):** Using the **IceSL** software, we started investigating how to optimize the representations of 3D objects for printing. Given a mesh, we proposed a technique to optimize its center of gravity in such a way that it is balanced, formalized by an objective function. This objective function can be optimized with a combination of mesh deformation and carving its interior [33](SIGGRAPH 2013). We also studied how to ease the fabrication process with low-end extrusion printers. We improved the technique that prints a scaffold that supports the object under construction. Our technique, by taking into account the overall balance of the scaffold and the object, prevents them from collapsing during the fabrication, and allows to create some geometries with overhangs that would be impossible to construct otherwise [14](SIGGRAPH 2014). Such extrusion printers often have two heads, that can be fed with two different plastics for printing objects with two different colors. However such devices generate significant "oozing" on the object (when printing one color, the other head that is still hot "oozes" on the part under construction). To avoid this phenomenon, we designed a technique that constructs (disposable) "protective walls" (the other head oozes on the wall instead of the object), by optimizing the navigation of the print head [12] (Eurographics 2014). We combined these techniques with structure synthesis, to generate curvilinear structured patterns from examples [31](Eurographics 2013). Besides the usual constraints, this requires introducing a topological one, that ensures the continuity of the generated pattern (in order to avoid generating isolated parts that "float in thin air", that could not be printed);

- **Computer Graphics and Scientific visualization:** We also continued some more traditional applications in graphics, for modeling trees from photographs and relighting them [45](TVCG 2011), and for optimizing color transfer [23] and for detecting similar objects in image [25]. We also developed some applications in visualization of molecular surfaces for bio-molecular chemistry [48](J. computational chemistry), [49](briefings in bio-informatics).

2.5.4 Cooperations

- We cooperate with Li-Yi Wei (Hong-Long University) and published together an article about dynamic element textures [32]. Interestingly, this is the same lab. as Wenping Wang, who cooperates with the other research axis (geometry processing), and there are some possible cooperation topics interesting for both research axes. We proposed an Inria Associate team (more on this below);
- Alla Sheffer (UBC), cooperation on game design [14] (EUROGRAPHICS 2014);
- Olga Sorkine, cooperation on design of well-balanced printable 3d objects [33] (SIGGRAPH 2013);
- We continued the cooperation with George Drettakis and Ares Lagae on Gabor noise [37] (SIGGRAPH 2012) [46] (TVCG 2011);
- We cooperate with Carsten Dachsbacher (KIT) on data structures for the GPU [39] (SMI 2012);
- We cooperate with the Allegorithmics company on texture generation [40] [57] (Eurographics 2012).
- We cooperate with Christophe Geuzaine (U. Liege) on mesh generation and numerical simulation [18]. Vincent Nivoliers, a former Ph.D. candidate of the team, did a post-doc in C. Geuzaine's team.

2.5.5 External support

- ERC SHAPEFORGE Starting Grant, 2012-2017, 1.3 MEuros, on sampling and approximation

- ANR SIMILAR-CITIES, 2010-2013 on automatic content generation

- BluePrint 2014-2017 (Lorraine regional council grant), 1/2 Ph.D. thesis

2.5.6 Self assessment for "Modelling and Rendering"

Strong points With our strategy of attacking the problem under two original angles — by-example content creation for 3d printing, and data structures / algorithms well adapted to core 3d printing technology — we managed to advance the state of the art in several directions: balancing input shapes, improving print quality and reliability, generating printable geometries from examples. We were able to publish the results in the major conferences of our field, as well as to initiate collaborations with the additive manufacturing community

(Inria/IJL). We believe a strength of our work is to build a framework of original algorithms for modeling, processing and printing of complex geometries, that are all available within our research platform IceSL.

Weak points Our new research direction (3d printing) is becoming more and more competitive. Therefore we need to remain focus on our strong points — modeling of complex, intricate geometries that difficult to model with standard tools — and avoid to disperse into the many interesting and open problems surrounding this technology. Another risk is to focus too much on a particular technology (Fused Filament Fabrication) that might become obsolete. We are currently in the process of testing our methods on a wider range of additive manufacturing processes to mitigate this risk, and to determine what the right level of abstraction is.

Risk Analysis (Evolution) and Objectives (for both research axes)

For the last evaluation (Oct. 2010), we had identified the following risks. We now give comments *in italics* on the actions we took regarding these risks (as on Sept. 2014).

- **[2010]:** administratively, advising Ph.D. students requires to defend a HdR ("Habilitation Thesis"). In ALICE, only B. Lévy has the HdR, which is not reasonable for a team with 7 permanent researchers. However, N. Ray and S. Lefebvre are in the process of writing and defending it (this is a key objective for the next evaluation period)
  [2014]: With Sylvain Lefebvre who defended his HdR in 2014, we have now sufficient habilitation in the team. We keep the objective for Nicolas Ray for the next evaluation period;
- **[2010]:** the rapid growth of the team is a strength but could be also a weakness. There is a risk of loosing the initial focus of ALICE. However, we think that the interests and mathematical skills of the new researchers point towards the right direction.
  [2014]: The cross-fertilization continued between both research axes. The new orientation towards the physics of real objects can strengthen this common focus.;
- **[2010]:** attracting good Ph.D. students is difficult, since there is not such a thing as a "computer graphics" master in Nancy. ALICE is somewhat isolated in this theme in Nancy. The strong connections with the community allowed us to attract good post-doc students and applicants for permanent researcher positions, but this does not apply to the undergraduate level. *[2014]: Members of the team teach in different masters and schools, and this allowed to attract some students, but this remains the main difficulty.* ***It got even worse with the Ministry of Defense that has the right to reject any foreign student that we want to hire (4 out of 6 were rejected this year !!).***
- **[2010]:** three of our submissions to ACM SIGGRAPH were redirected to ACM Transactions on Graphics (and finally accepted). The main reason was a lack of clarity in the writing. We now have a better strategy and we schedule longer-term projects (> 1 year) for writing some of the articles. This strategy was successful this year (2010);
  [2014]: This remark still applies to our "Geometry Processing" axis that generates

articles that do not fit well within the paper length / reviewing time constraints of SIGGRAPH, our strategy is to target some contributions towards TOG, and keep select some contributions for SIGGRAPH submission (e.g., [34])

3 Knowledge dissemination

3.1 Publications

	2011	2012	2013	2014
PhD Thesis		3	1	1
H.D.R (*)				1
Journal	9	5	13	14
Conference proceedings (**)	5	5	1	2
Book chapter				1
Edited conf. proceedings			1	1
Patent	1		1	
Technical report			1	1

(*) HDR Habilitation à diriger des Recherches
(**) Conference with a program committee

1. ACM Transactions on Graphics: 8 articles
(including 5 SIGGRAPH and 2 SIGGRAPH Asia)
(+ 1 conditionally accepted SIGGRAPH ASIA 2014)
2. Computer Graphic Forum: 9 articles (including 5 Eurographics and 2 SGP)
3. IEEE Transactions on Visualization and Computer Graphics: 2 articles
4. SIAM Journal of Sci. Comput, Journal of Computational Physics: 6 articles
5. CAD J. and CAGD J.: 7 articles

3.2 Software

Vorpaline is an automatic surfacic and volumetric mesh generation software, distributed with a commercial license. Vorpaline is based on the main scientific results stemming from projects GoodShape and VORPALINE, funded by the European Research Council, about optimal quantization, centroidal Voronoi diagrams and fast/parallel computation of Voronoi diagrams in high-dimension space. The current version provides functionalities such as isotropic/adaptive/anisotropic surface re-meshing, tolerant surface re-meshing, mesh repair and mesh decimation, constrained surface meshing, quad-dominant surface meshing and hex-dominant volume meshing. It is extensively tested on industrial data with a continuous integration platform, and extensively documented. It is now proposed (since 2014) to the sponsors of the Gocad consortium, as an extension package of the Gocad software.

IceSL proposes to exploit recent advances in GPU and Computer Graphics to accelerate the slicing process of objects modelled via a CSG (Constructive Solid Geometry) language. Our main targets are open source low cost fused deposition modeling printers such as RepRaps (but also high-end printers).

Our approach first inputs a CSG description of a scene which can be composed of both meshes and analytic primitives. During display and slicing the CSG model is converted on the fly into an intermediate representation enabling fast processing on the GPU. Slices can be quickly extracted, and the tool path is prepared through image erosion. The interactive preview of the final geometry uses the exact same code path as the slicer, providing an immediate, accurate visual feedback.

IceSL is the recipient software for our ERC research project "ShapeForge", led by Sylvain Lefebvre.

Graphite is a research platform for computer graphics, 3D modeling and numerical geometry. It comprises all the main research results of our "geometry processing" group. Data structures for cellular complexes, parameterization, multi-resolution analysis and numerical optimization are the main features of the software. Graphite is publicly available since October 2003. It is hosted by Inria GForge since September 2008. Graphite was one of the common software platforms used in the frame of the European Network of Excellence AIMShape .

Graphite and its research-plugins are actively developed and extended. The latest version was released on January 2nd, 2014 and has been downloaded 732 times as of Sept. 5.

Graphite Life Explorer is a 3D modeler, developed as a plugin of Graphite, dedicated to molecular biology. It is developed in cooperation with the Fourmentin Guilbert foundation and has recently been renamed "GraphiteLifeExplorer". Biologists need simple spatial modeling tools to help in understanding the role of the relative position of objects in the functioning of the cell. In this context, we develop a tool for easy DNA modeling. The tool generates DNA along any user-given curve, open or closed, allows fine-tuning of atoms position and, most importantly, exports to PDB (the Protein Data Bank file format). A paper describing it was published in the broad audience journal PLOS One [27].

OpenNL is a standalone library for numerical optimization, especially well-suited to mesh processing. The API is inspired by the graphics API OpenGL, this makes the learning curve easy for computer graphics practitioners. It is used by several OpenSource and commercial softwares, including Blender and 3DCoat. There is also a version with templates distributed as a CGAL package.

GEOGRAM is a software library with geometrical algorithms. The focus is put on the ease of use, minimal memory consumption, minimal size of the code and extensively documented algorithms (whereas in existing libraries such as CGAL, the focus is put on the extensibility). GEOGRAM includes the PCK (Predicate Construction Kit), a system to automatically generate robust predicates from their equation. It provides a standalone exact number type, based on Shewchuk's expansion arithmetics. The library is portable under Linux, Windows, MacOS, Android, and any system that has IEEE floating point arithmetics. The arithmetic kernel may be used by other programming library and proposed as extension packages (e.g. for CGAL).

3.3 Valorization and technology transfert (Socio-economic impact and transfer)

Gocad Consortium: We have a long-term cooperation with the Gocad consortium (Nancy School of Geology), aiming at developing 3d modeling tools for oil exploration and geosciences. All the major oil companies and several universities are members of the consortium. During the evaluation period, the Ph.D. theses of Nicolas Cherpeau, Romain

Merland, Jeanne Pellerin (defended) and Arnaud Botella (on-going) were funded by the consortium. They are co-advised by B. Lévy and G. Caumon (prof. School of Geology, head of the consortium). Their results are presented at the annual meetings of the consortium, where participants from the oil companies and the universities can follow tutorials on how to use the new tools that were developed, and start using them in their companies. Romain Merland was hired by the Earth Decision Sciences / Paradigm company, member of the consortium, and Jeanne Pellerin does a post-doc funded by the TOTAL company, at the Weierstrass Institute (Berlin) with Hang Si (author of the TETGEN meshing software).

Vorpaline project: This pre-industrialization project was evaluated and selected by the ERC, as a promising way of pre-industrializing the results stemming from our previous project GOODSHAPE. We hired an experienced software architect, and we wrote a software prototype that implements innovative 3D meshing algorithms. We did technology testing with our industrial partners (Gocad consortium, Distene, Dassault Systems). More details are given in the online article in ERCIM news: http://ercim-news.ercim.eu/en91/ri/goodshape-towards-flexible-mesh-generation. The software prototype now passes our validation tests for the surfacic meshing capabilities. The most elaborate algorithms (hex-dominant meshing) require more work before being fully usable in the industry, we plan to finalize the development of these functionalities this year. We will then study possibilities of commercialization with the Gocad Consortium: the software is now proposed as an extension package of Gocad to the sponsors of the consortium. We also have a transfer project with the Distene Company. All the major CAD/CAE editors use Distene's meshing components (Dassault, Autodesk, Siemens, PTC, MSC, CST, and Sandia Labs), which gives a wide potential audience to our technology. Its main competitor is the American company Simmetrix. Distene has a long-term (since 1984) history of successful technology transfers with Inria (the research institute of the Principal Investigator). We have started technical testing by exchanging datasets with them (see next section below). Our technology can be seamlessly integrated into their mesh generation offer and complements it with new features.

3.4 Teaching

- Sylvain Lefebvre is involved in the following courses:
  - Cours Ecole Centrale (9h)
  - Cours Ecole de Géologie: introduction to parallelism (3h TP) and introduction to computer graphics (3h cours, 6h TP)
  - OpenCL, master M2, avec Dmitry Sokolov.
  - Course on Video Game programming at "Ecole des Mines de Nancy". Taught with Guillaume Bonfante.
- Samuel Hornus is involved in the following courses:
  - "Functional programming with OCaml" at ÉPITECH Nancy (private school training programmers, http://nancy.epitech.eu/). Lecture: 9h. Lab work: 18h. 3 student projects.
- Dmitry Sokolov is involved in the following courses:
  - Algorithmique avancée, 28h, M2 Math de l'UL, France

  - Géométrie et représentation dans l'espace, 35h, L2 Informatique de l'UL, France
  - Logiques et Modèles de calcul, 30h, M1 Informatique de l'UL, France
  - Infographie 76h, M1 Informatique de l'UL, France
  - Modèles de perception et raisonnement, 56h, M1 Informatique de l'UL, France
  - Parallélisme de données, 15h, M1 Informatique de l'UL, France

- Dobrina Boltcheva gives 200 hours teaching:
  - Licence ISN, IUT Saint-Dié-des-Vosges
  - 2A DUT INFO, IUT Saint-Dié-des-Vosges
  - 1A DUT INFO, IUT Saint-Dié-des-Vosges

- Xavier Antoine gave the following invited courses:
  - 6 hours course on numerical methods for Schrödinger equations, Workshop "Non-linear optical and atomic systems: deterministic and stochastic aspects" - January 2013, Lille, France.
  - 3 hours course at 7th Montréal Scientific Computing Days , CRM, Montréal, QC, Canada, May 2013.

- Bruno Lévy teaches:
  - "Numerical Geometry" (15 h) in the National School of Geology and in Nancy School of Mines.

3.5 General audience actions

Bruno Levy animates "initiation to computer programming", 1h each Friday evening (10 kids, 7 to 12 years old).

Members of the team participate each year to "science fair" events, scientific demos, conferences for the general audience.

Sept. to Dec. 2011, we gave a series of demos and presentations at the "Palais de la Decourverte" (museum of science in Paris).

3.6 Animation of the Scientific Community

Sylvain Lefebvre is associate editor for ACM Transactions on Graphics

Bruno Lévy is associate editor for IEEE Transactions on Visualization and Computer Graphics

Xavier Antoine is associate editor for ISRN Applied Mathematics

Bruno Lévy is associate editor for Graphical Models (Elsevier)

Bruno Lévy was program co-chair for Eurographics 2014

Bruno Lévy was program co-chair for Pacific Graphic 2013

Jean-Claude Paul and Bruno Lévy were conference co-chair of CAD Graphics 2013

Sylvain Lefebvre was STAR co-chair for Eurographics 2014

Xavier Antoine is âscientific delegate at ANR (French NSF) in charge of mathematics and interactions

Bruno Lévy was chair of the Inria Nancy Grand-Est junior positions hiring committee in 2013 and 2014

Bruno Lévy is vice head of the Charles Hermite federation (that regroups the laboratories in CS, mathematics and control theory in the Lorraine region).

Members of the team are invited to be program committee members for the major conferences (SIGGRAPH, Eurographics, SMI, SGP, SPM ...) on a regular basis

3.7 Misc.:

Bruno Lévy received the **Inria Young Researcher Award** in 2011 http://www.inria.fr/en/institute/inria-in-brief/inria-awards/2011-winners/young-researche

4 Funding

4.1 Funding external to Inria

(k euros)	2011	2012	2013	2014
National initiatives				
ANR Similar-cities	60K	60K	60K	
ANR MORPHO	20K	20K	20K	
ANR PHYSIGRAPHIX	60K	60K	60K	
ANR BECASIM				60K
European projects				
ERC GOODSHAPE	150K	150K	160K	
ERC VORPALINE				150K
ERC SHAPEFORGE		90K	120K	160K
Other external funding				
INRIA COLORS		15K		
Region Mesh&PDEs				25K
Region BluePrint				20K
Total	290K	395K	420K	415K

4.2 Inria competitive funding

(k euros)	2011	2012	2013	2014
Associated teams				
BluePrint (canceled)				30K

Comments: Our external fundings (ERC and ANR) provided us with sufficient resources to fund all our activities, including the salaries of Ph.D. candidates, post-docs and software developers, therefore we did not apply for additional Inria funding. We submitted a proposal for an associated team with Hong-Kong University. Due to interferences from the ministry of Defense, that imposes a heavy procedure that dramatically slows down things and that forbid us to hire some Post-Docs and Ph.D. candidate from foreign countries, we had to abandon this project and gave back the funding to the international department of Inria.

National initiatives

2010-2013: ANR Similar-cities (PI: Sylvain Lefebvre): The SIMILAR-CITIES project is a joint effort between INRIA, CSTB and Allegorithmic to enhance the visual appearance of virtual cities, using procedural methods. Our key insight is to replace the numerous textures used to faithfully render large virtual cities by procedural equivalents. These procedural textures are thousands of times smaller but can still be quickly generated whenever required by the rendering engine. Our every-day tools for this research are procedural texture generators, texture synthesis by example, texture streaming algorithms and image processing tools.

2010-2013: ANR Physigraphix (Rhaleb Zayer, "Chaire d'excellence"): This Physigraphix project aims at developing new numerical simulation of material deformation behavior. Usual Finite Element models are parameterized by physical quantities (e.g. Young modulus, elasticity coefficient ...), and these quantities are often difficult (or even impossible) to acquire from real objects. The idea is to use measurable displacements to parameterize the model from the behavior of the material, directly acquired from videos and depth images. This project funded two Ph.D. theses (Alejandro Galindo and Kun Liu).

2010-2015: ANR Morpho (PI: LJK/Inria Grenoble, Loria/Inria Nancy and Gipsa Lab Grenoble): this project aimed at designing new technologies for the measure and for the analysis of dynamic surface evolutions using visual data. The interest arises in several application domains where temporal surface deformations need to be captured and analyzed. It includes human body analyses but also extends to other deforming objects, sails for instance. Potential applications with human bodies are anyway numerous and important, from the identification of pathologies to the design of new prostheses. The project focus is therefore on human body shapes and their motions and on how to characterize them through new biometric models for analysis purposes.

2013-2018: ANR BECASIM: Becasim is a thematic "Numerical Models" ANR project granted by the French Agence Nationale de la Recherche for years 2013-2016. The acronym Becasim is related to Bose-Einstein Condensates: Advanced SIMulation Deterministic and Stochastic Computational Models, HPC Implementation, Simulation of Experiments. The members of the ANR Project Becasim belong to 10 different laboratories

- Institut Elie Cartan de Lorraine, UMR CNRS 7502
- Laboratoire Paul Painlevé, UMR CNRS 8524
- Laboratoire de Mathématiques Raphaël Salem, UMR CNRS 6085
- Laboratoire Jacques-Louis Lions, UMR CNRS 7598
- Centre de Mathématiques Appliquées, Ecole Polytechnique, UMR CNRS 7641
- Centre d'Enseignement et de Recherche en Mathématiques et Calcul Scientifique, Ecole des Ponts ParisTech
- LORIA, Inria-Nancy Grand-Est
- Inria-Lille Nord-Europe
- Institut de Mathématiques et de Modélisation de Montpellier, UMR CNRS 5149
- Institut de Mathématiques de Toulouse, UMR CNRS 5219

European projects

2012-2017: ERC SHAPEFORGE, 1.3 MEuros: Project Shapeforge aims at developing new methods for creating objects from examples, with 3D printers. The main challenge with this project is combining approaches that are very different in nature: algorithms from computer graphics which are used to build forms and textures using examples are combined with digital optimization methods which make sure that the real object complies with the function it is assigned. Thus, to produce a Louis XV bench, on the basis of a Louis XV chair, you need to not only capture the appearance of the example but also formalize the characteristics of a bench as well as its mechanical properties to ensure that it is solid enough. You then need to find, from among all the shapes that can be produced from a single example, the one that best complies with the various criteria.

2013-2014: ERC VORPALINE, 150 KEuros: The Vorpaline software takes a new approach to 3D mesh generation, based on the theory of numerical optimization. The optimal mesh generation algorithm developed in the frame of the European Research Council GOODSHAPE project globally and automatically optimizes the mesh elements with respect to geometric constraints (two patents) . The mathematical foundations of this algorithm, i.e. the minimization of a smooth energy function, result in practice in a faster algorithm, and - more importantly - in a higher flexibility. For instance, it will allow automatic generation of the aforementioned "hex-dominant" meshes. It is now proposed (since 2014) to the sponsors of the Gocad consortium, as an extension package of the Gocad software.

2008-2013: ERC GOODSHAPE, 1.1 MEuros: Project GOODSHAPE (Numerical Geometric Abstraction: from bits to equations), involves several fundamental aspects of 3D Modelling and computer graphics. GOODSHAPE is taking a new approach to the classic, essential problem of sampling, or the digital representation of objects in a computer. This new approach proposes to simultaneously consider the problem of approximating the solution of a partial differential equation and the optimal sampling problem. The proposed approach, based on the theory of numerical optimization, is likely to lead to new algorithms, more efficient than existing methods. Possible applications are envisioned in inverse engineering and oil exploration

Industrial contracts

Gocad Consortium: Ph.D. theses of Arnaud Botella, Nicolas Cherpeau, Jeanne Pellerin, Romain Merland (see Section 3.3 for more details).

Associated teams and other international projects

PrePrint3D: cooperation project between ALICE and Hong-Kong University (Wenping Wang and LiYi Wei). This project was supposed to be a follow up for existing cooperations between Bruno Lévy - Wenping Wang, and Sylvain Lefebvre - Li-Yi Wei. We proposed to join these two parallel cooperations into a single one, with a common research project on 3d printing. The associate team project was selected and accepted by the Inria. It was supposed to start in Feb. 2014. **Due to interferences of the Ministry of Defense that imposes to give its authorization before starting, and that did not answer before June 2014, introducing more than 4 months delays, and that forbid us to recruit 4 people, we had**

to give up this project and gave the money back to the Inria international cooperation department.

Other funding

Meshing and PDEs, Regional Council of Lorraine, 25 KEuros for initiating the cooperation between Xavier Antoine (Prof. in Math., Nancy who joined ALICE for a short-term 1 year period) and Bruno Lévy;

COLORS Modeling and Rendering with Distance Functions, 15 KEuros in 2011 for initiating the cooperation between Sylvain Lefebvre and Carsten Dachsbacher / Karlsruhe Institute of Technology (KIT), funded by the Centre Inria Nancy Grand-Est.

5 Objectives for the next four years

5.1 Geometry Processing

We plan to contribute bridging the gap between the methods used in Geometry Processing and in Numerical Analysis of Partial Differential Equations. Our general goal is to find new ways of inventing algorithms that can be translated into efficient Geometry Processing computer programs (Geometric Programming), while keeping a continuous path from the mathematical formalization to the program. For the next four years, we propose to study the problem under three angles:

- **Geometry:** What is the role played by *distances* and *anisotropy* ? Which *abstractions* can capture them in a way that can be translated into efficient geometric algorithms ?
- **Functions:** How can we manipulate functions leaving on the objects, and define *differential operators* acting on them that are both *consistent* and *convergent* ?
- **Combinatorics:** How can we deduce the right combinatorics from the geometry ? How can we easily transform *geometric predicates* into computer programs and *certify* them, in both generic and limit cases ? Can we invent *programming tools* that will help designing such algorithms ?

Risk Analysis: We now review each aspect and the associated risk :

- **Geometry :** computing anisotropic Voronoi diagrams in 3d has been an open problem for more than a decade. Designing efficient algorithms for optimal transport in dimension ≥ 2 is notoriously difficult. We plan to tackle these issues with an original point of view, that was never tried before. It avoids some of the main previously encountered obstructions, but introduces new theoretical and practical difficulties : how will the distribution of points impact the complexity of the method ? how will it be possible to implement it efficiently ? The risk for this part of the project is high;
- **Functions :** We aim at deriving new discretizations of function spaces, adapted to design well-behaved numerical solution mechanisms. We are especially interested in some non-linear PDEs, for which no numerical solution mechanism exists in 3d (Monge Ampere, Fokker Planck . . .). If we are proved right, our geometric point of

view will lead to highly efficient means of computing the Wasserstein distance and its gradient in 3d, leading to efficient solvers for a whole class of PDEs. The way is paved with many difficulties, both theoretical and practical, due to the highly non-linear nature of these PDEs, and the presence of singularities (similar to the shock on the medial axis that the eikonal equation has). This is the part of the project that has the maximum risk;

- **Combinatorics :** this part of the project, required by the other ones, is more technical. Except the part on formal specification that is more prospective/exploratory, it has a low to average risk.

To mitigate the risk, we mention that the project-team has now reached a sufficient "critical mass". We gained experience during our previous projects (GOODSHAPE, PHYSIGRAPHIX, VORPALINE), and we think that we are ready to tackle these difficult issues. This project has several computer science / mathematics cross-disciplinary aspects. We interact more and more with mathematicians. Inria and its scientific network is an ideal ecosystem for establishing cooperations, with specialists in numerical analysis (R. Abgrall), computer arithmetics (P. Zimmermann, main author of MPFR), measure theory (Q. Merigot, B. Thibert), geometric programming (M.Teillaud, one of the architects of CGAL, who is moving to Nancy), formal program verification (S. Boldo), ... with whom we have scientific discussions on a regular basis.

5.2 Modeling, Rendering and 3d Printing

Our research axis on modeling and rendering evolved into a research project on computer aided fabrication and 3d printing. This requires a full understanding of the creation pipeline, from the modeling of the object to the fabrication on the 3D printer. This also means developing innovative CAD softwares for additive manufacturing, as we started to do with our IceSL software.

The goal is to start from a description of an object in terms of solid operations (union, difference, intersection, offsetting) and directly generates the instructions driving the printer. We think that this strategy is especially well-suited for combining parts from existing designs, as well as dealing with shapes with complex, intricate geometries. A longer-term goal is to erase the boundaries between modeling and the printing process, and develop novel approaches considering both issues simultaneously.

We hope to bring novel ways to model complex shapes, developing algorithms that handle the difficult task of finding a compromise between the intention of the designer, the technical requirements of the fabrication process, and the function of the final, real object.

Risk Analysis: There is an increasing level of competition in the Computer Graphics community on 3d printing, which is a "fashionable" topic. There is also a risk to disperse into the many interesting problems surrounding additive manufacturing.

We intend to remain focused on what makes our point of view original: modeling from examples of complex geometries and geometry processing for fabrication through image/voxel based representations. This approach resulted in interesting contributions, and we think it will continue in the future. We also plan on working more closely with researchers in the field of additive manufacturing (processes/materials) to further explore the interaction between modeling and fabrication. Another difficulty is the wide spectrum of techniques that we need to master, including modeling software, path planning, computational geometry and numerical simulation. Here again, the Inria ecosystem and its international network of collaborations is ideal for setting up the cooperations needed for the project.

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