Evaluation of Inria theme Interaction and Visualization

Project-team ALICE

04/10/2018

Project-team title: ALICE: Geometry and Light

Scientific leader: Bruno Levy

Research centers: Centre Inria Nancy Grand-Est

Common project-team with: LORIA and CNRS

1 Personnel

Current composition of the project-team:

Research scientists and faculty members:

- Laurent Alonso, Inria Research Associate
- Dobrina Boltcheva, associate professor, U. Lorraine
- Samuel Hornus, Inria Research Associate
- Sylvain Lefebvre, Inria Research Director
- Bruno Lévy, Inria Research Director
- Jonas Martines Bayona, Inria Research Associate
- Nicolas Ray, Inria Research Associate
- Dmitry Sokolov, associate professor, U. Lorraine
- Cédric Zanni, associate professor, U. Lorraine

Engineers:

- Wan-Chiu Li (starting Sept. 2018)
- Yamil Salim Perchi
- Noemie Vennin

Post-docs:

- Haichuan Song, Inria Starting Research Position
- Name

Ph.D. students:

- Pierre Anquez (co-advised with Guillaume Caumon, school of Geology)
- Justine Basselin (starting Sept. 2018)
- Agathe Herrou (starting Sept. 2018, co-advised with Nicolas Bonneel, Lyon)
- Jimmy Etienne
- Julien Renaudeau (co-advised with Guillaume Caumon, school of Geology)

Administrative assistant:

- Celine Simon

Personnel at the start of the evaluation period (15/10/2014)

	INRIA	CNRS	University	Other	**Total**
DR (1) / Professors	2		1		**3**
CR (2) / Assistant professors	6		2		**8**
ARP and SRP (3)					
Permanent engineers (4)					
Temporary engineers (5)	2				**2**
Post-docs	2				**2**
PhD Students	6		3		**8**
Total	**17**		**6**		**23**

(1) "Senior Research Scientist (Directeur de Recherche)"
(2) "Junior Research Scientist (Chargé de Recherche)"
(3) "Inria Advanced Research Position" and "Inria Starting Research Position"
(4) "Civil servant (CNRS, INRIA, ...)"
(5) "Associated with a contract (Ingénieur Expert, Ingénieur ADT, . . .)"

Personnel at the time of the evaluation (04/10/2018)

	INRIA	CNRS	University	Other	**Total**
DR / Professors	2				**2**
CR / Assistant professors	3		3		**6**
ARP and SRP					
Permanent engineers					
Temporary engineers	3				**3**
Post-docs	1				
PhD Students	1		2	2	**5**
Total	**10**		**5**	**2**	**17**

Changes in the scientific staff

DR / Professors / ARP CR / Assistant Professors / SRP	INRIA	CNRS	University	Other	**Total**
Arrivals	1		1		**2**
Departures	2		1		**3**

Comments:

- **Arrival:** Jonas Martines, first hired as a post-doc (SRP funded by Sylvain Lefebvre's ERC grant), was then hired as a permanent researcher (CR research associate);
- **Arrival:** Cédric Zanni was hired as a Associate Professor;
- **Departure:** Rhaleb Zayer (CR research associate) left the team in 2016 for family reasons (his wife obtained a permanent position in Germany);
- **Departure:** Jean-Claude Paul (DR senior researcher) retired in 2016;
- **Departure:** Xavier Antoine (math. professor, U. Lorraine) joined the team in 2014 in the frame of a common ANR ("french NSF") research projet on computational physics. After the end of the project he returned to the math. lab. (IECL).

Current position of former project-team members

- Arnaud Botella, Ph.D. student 2013-2016, currently R&D TOTAL (Pau, France)
- Frédéric Claux, Engineer 2014-2015, currently Associate Professor (Limoges, France)
- Jérémie Dumas, Ph.D. student 2014-2017, currently post-doc in New-York U with Prof. Daniele Panozzo;
- Alejandro Galindo, Ph.D. student 2012-2015, currently head of R&D Iris Automation (San-Francisco, USA)
- Kun Liu, Ph.D. student 2012-2015, currently Data Scientist at IHS Markit (London, UK)
- Maxence Reberol, Ph.D. student 2015-2018, currently post-doc in Louvain U with Prof. J.-F. Remacle (ERC Advanced Grant in mesh generation);
- Lionel Unterreiner, Post-Doc 2015-2016, currently Post-Doc Mimesis Inria team (Strasbourg, France)

Latest INRIA enlistments

- Jonas Martines (CR1) - hired as CR2 (research assistant) in 2016
  - **Micro-C.V.:** Ph.D. U. Catalunya (2013), then Post-Doc and SRP in Alice
  - **Specialites:** discrete Voronoi diagrams, computer-aided fabrication
  - **Highlight:** Young ANR ("french NSF") investigator grant in 2017 (14% selection)

Other comments:

To encourage Inria researchers rethinking their research strategy in function of the quickly-evolving context, Inria teams have a lifespan limited to 12 years. ALICE is reaching the end of its lifecycle (ALICE was created in 2006). It is an excellent opportunity to redefine both our main research orientations and organization of the team.

The initial focus of ALICE was on developing mathematical tools and algorithms for 3D image synthesis, with a special focus on geometry. During the last 12 years, two research topics naturally emerged in the team (first geometry processing around B. Lévy, the founder of the team, and more recently computer-aided fabrication around S. Lefebvre). Both axes were significantly boosted by 4 ERC grants in total (2 for each), helping them reaching a critical mass. This year we have started the Inria creation process for two new teams, one named MFX with S. Lefebvre as the head, on computer-aided fabrication, and one named GRAPHYS with B. Lévy as the head, on geometry processing with a new focus on computational physics. More details on this are given next page and further-on.

2 Research goals and results

2.1 Keywords

Geometry Processing, Mesh Optimization, Computer-Aided Fabrication, GPU Algorithms, Geometric Modeling.

2.2 History and overall goals of the project

ALICE is a project-team in Computer Graphics, focused on *Geometry Processing* and *Computer-Aided Fabrication*. This paragraph summarizes the evolution of the team during the past 12 years to give an idea of the common origin of these two (seemingly unrelated !) topics. Following our own idea and based on the recommendation of the previous evaluation, we have initiated the creation of two independent teams, one of each topic.

When we created ALICE in 2006, our initial point of view was to consider that the interaction of *light* with the *geometry* of the objects plays a central role in computer graphics[1]. Initially motivated by the numerical simulation of light, we identified a need for methods that *transform and optimize geometric representations*[2]. Our original approach to both issues was to restate the problems in terms of *numerical optimization*. Our goal was (and is still) to develop solutions that are *provably correct*, *numerically stable* and *scalable*.

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 in other domains (mathematics and computational physics). With this goal in mind, we studied the general problem of sampling arbitrary geometric objects, to make them usable in the context of numerical simulations. B. Lévy obtained an ERC Starting Grant on that topic in 2008, and an ERC Proof of Concept grant in 2013 to industrialize the results.

We also develop contacts with people from the industry, who test applications of our general solutions to various domains, comprising CAD, industrial design, oil exploration, astrophysics... Our solutions are distributed in both open-source software (Graphite, Geogram) and industrial software (Vorpaline, IceSL).

In 2009, Sylvain Lefebvre joined the team. At that time he was developing *texture synthesis* methods with efficient algorithms specialized for the GPU. There was a perfect match with the initial geometry processing axis that was concerned with *automatic texture mapping* and *mesh parameterization*: our team then became able to generate both the UVs (mesh parameterization) and the RGBs (texture synthesis). Soon, we realized that GPU synthesis algorithms could 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. Sylvain Lefebvre obtained an ERC Consolidator grant on that topic, and then an ERC Proof of Concept grant to industrialize the results.

Boosted by the ERC basic research grand + industrialization grant pair, soon each research axis reached a critical mass. This year, at the end of the ALICE project[3], we initiated the creation of two new INRIA projects: MFX around S. Lefebvre on computer-aided fabrication, and GRAPHYS around B. Lévy, still on geometry processing, but with a stronger focus on computational physics and applied mathematics.

The creation of two independent research teams does not mean the end of the cooperation between the researchers of both axes ! This year we submitted together a research article that just got accepted by SIGGRAPH ASIA [31].

[1] It is still the case in 2018 with the advent of GPU ray-tracing fostered by NVidia and his new RTX boards.

[2] The Finite Element "radiosity" method popular at that time was very sensitive to the slightest defect.

[3] INRIA projects have a lifespan limited to 12 years.

2.3 Research axis 1: Geometry processing and numerical simulation

Personnel

Permanent researchers: L. Alonso, D. Boltcheva, B. Lévy, N. Ray, D. Sokolov
Engineer: W.-C. Li
Ph.D. students: P. Anquez, J. Basselin, A. Herrou, J. Renaudeau

Scientific Context and Goals:

Numerical simulation is a key aspect in both industry and science: by replacing costly physical experiments (e.g. wind tunnel in fluid dynamics) with computer simulation, it dramatically reduces the overall cost of product development. In science, virtual experiments can be used to better understand various phenomena, especially when it is impossible to conduct direct experiments, as in astrophysics (more on this below).

The prominent methods in numerical simulation (finite elements, finite differences, ...) depend on discretizations of the geometry (meshes), that are notoriously difficult to generate: a quick search on the NSF grant web page[4] with "mesh generation AND finite element" keywords returns more than 30 currently active grants for a total of $8 million. NASA indicates mesh generation as one of the major challenges for 2020 [SKA$^+$14], and estimates that it costs 80% of time and effort in numerical simulation. This is due to the need for constructing supports that match both the geometry and the physics of the system to be modeled.

It is very unsatisfactory that meshing, i.e. just "preparing the data" for the simulation, eats-up the major part of the time and effort. Our goal is to make the situation evolve, by (1) studying the influence of shapes and discretizations, and inventing new algorithms to automatically generate meshes that can be directly used by today's simulators and (2) studying new discretizations of the physics, that dynamically evolve in time.

Project-team positioning

Positioning within the "meshing" international research ecosystem: We list below the international teams working on different type of meshes, and how we relate with them.

- *Full-hexahedral octree meshing:* L. Maréchal (Inria GAMMA3) developed the Hexotic software;
- *Hex-dominant and full-hex:* We attack this goal, based on direction fields and global parameterization. Other teams attack it with advancing front and recombination (J.-F. Remacle, U. Louvain), we have many exchanges with him (our former Ph.D. student J. Pellerin is doing a post-doc there). A. Sheffer (U. British Columbia) and D. Panozzo (U. New-York) also work on this problem, with alternative methods. We have exchanges with them on a regular basis. **On that topic, our team is one of the best positioned worldwide to come out with the very first usable fully automatic solution**;
- *Tetrahedral meshing:* many teams work on this problem, including Inria GAMMA3, Inria GEOMETRICA, Hang Si (Berlin), J.-F. Remacle (U. Louvain), Cécile Dobrinsky (Inria Bordeaux).
- *Fully unstructured, dynamic discretization:* We consider discretizations recomputed at each timestep. We have a cooperation with Q. Mérigot, Y. Brenier, J.-D. Benamou (Inria MOKAPLAN) on that topic (ANR MAGA, PRE EXPLORAGRAM), using these meshes for optimal transport computations, with applications in astrophysics (R. Mohayaee and J.-M. Al-

[4] https://www.nsf.gov/awardsearch

imi, Institut Astrophysique de Paris). We have a long-term cooperation with Wenping Wang (Hong-Kong U.) on Voronoi diagrams. P. Alliez (Inria TITANE) shares with us an interest in OT and power diagrams. V. Springel (U. Heidelberg) develops a similar discretization for astrophysics. We have cooperations with S. Bordas and contacts with A.-L. Buffa (IMATI), who develop isogeometric analysis and polyhedral schemes. We are creating a cooperation with Pascal Frey (UPMC) who develops dynamic discretizations based on the level set method. **Our specificity is an expertise in developing (very) efficient numerical methods for non-standard problems** (e.g., optimal transport).

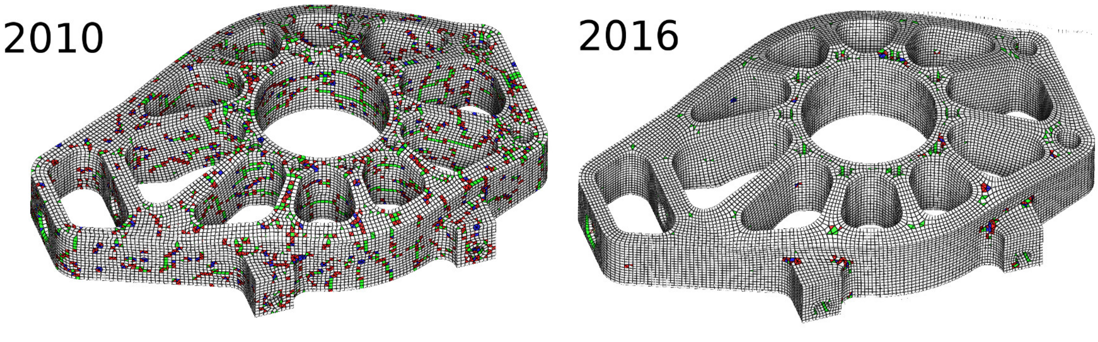
- *Physics:* we discuss with Philippe Helluy (TONUS, Inria Strasbourg) on meshing, Legendre duality and thermodynamics.

Positioning within Inria: Within the Inria theme "Numerical schemes and simulation", besides GAMMA3 and MOKAPLAN, we share interests with CARDAMON (grid adaptation, moving fronts) and IPSO (conservation laws).

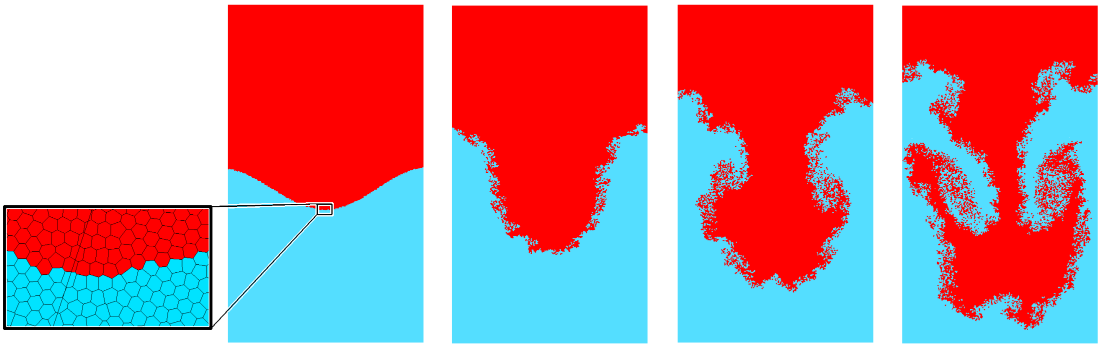
Main scientific achievements

From "Hex-dominant" to "Full-Hex": meshes for today's numerical simulation . . . Hexahedral meshes are composed of "deformed cubes" (hexahedra). They are appreciated for simulating certain physical phenomena (deformation mechanics, fluid dynamics . . .), because they can significantly reduce computation times and improve precision. This is because (1) they contain a smaller number of elements (5 or 6 tetrahedra for 1 hexahedron), (2) the tri-linear function basis associated with them can capture finer variations and (3) they avoid "locking" phenomena encountered with tetrahedra. Unfortunately, creating a hexahedral mesh requires considerable manual intervention of the user (days, weeks, even months for the most complicated geometries).

The figure shows our progress realized between 2010 [LL10] and 2016 [35] (see also [32, 7, 6]). The objective is to maximize the portion of the volume meshed with hexahedra (72 % of the volume for our 2010 method, 95 % of the volume in 2018), the rest is occupied by tetrahedra (colored). This results position us as one of the teams the most likely to come out with a "full-hex" automatic mesher in the forthcoming years. This requires to solve very difficult problems, in particular around the **singularities**, that is the poles, or the zones where the mesh is different from a regular grid. We will develop new **parameterization** methods, new **relaxation** methods and exploit **combinatorics**. This will **close one of the most important problems in meshing**. The result will be directly usable by existing numerical simulation softwares, and **directly transferable to the industry**, through our software VORPALINE.



Paving the road towards tomorrow's numerical simulation: the first "stones" (or cells !) Besides methods that can be directly applied to existing numerical methods, we are developing methods that use more non-conventional discretizations, such has time-evolving polyhedral meshes (Voronoi tessellations and power diagrams).



Such meshes offer more degrees of freedom than more conventional fixed meshes, and may lead to easier-to-use numerical simulators, needing no manual intervention to mesh the domain.

On the other hand, a simulation that uses such a dynamic mesh is going to compute one mesh per timestep, so at first sight our approach is not reasonable ! However, building on our Computer Graphics / computational geometry scientific culture, by relaxing some constraints, we can design algorithms and data structures that are much lighter than the classical ones used in scientific computing. With in head the goal of developing these new simulators, we developed efficient algorithms to compute and optimize Voronoi diagrams [12], made them available in our GEOGRAM software library, and developed a new algorithm highly efficient on the GPU [31]. Now, to simulate physics with such meshes, for instance to do fluid simulations (see figure), one needs to enforce conservation laws, the most natural one being volume conservation. The figure shows our numerical experiments with a fluid decomposed into cells. Controlling the volume of the cells requires an additional degree of freedom (moving from Voronoi to power diagrams), and we developed new numerical methods to solve the corresponding optimization problem, known as *semi-discrete optimal transport* [17, 37]. We developed the first efficient algorithm that works in 3D [20], available in GEOGRAM. The publication in a math. journal in 2015 already attracted more than 45 citations. Under the hood, the geometric part of the algorithm needs efficient and robust geometric predicates, for which we developed a methodology [21] (also available in GEOGRAM). We also developed anisotropic generalizations, using a higher-dimensional space [38].

Collaborations and External support

- Cooperation with G. Caumon (Nancy-School of Geology) through co-advised Ph.D. theses on 3D modeling for geosciences.
- Cooperation with R. Mohayaee (Institut Astrophysique de Paris), J.-M. Alimi (Observatoire de Paris) and the members of the MAGA network on astrophysics.
- ANR BECASIM (2013 – 2016) (as participant)
- Inria associate team PREPRINT 3D (2014 – 2017) (PI: S. Lefebvre and B. Lévy) with W. Wang and L.-Y. Wei (Hong-Long University).
- EXPLORAGRAM (2017) Inria exploratory grant (PI: B. Lévy)
- ANR ROOT (2016–2020) (as participant)
- MESHSPACE (2018) Inria Technological Transfer Action (W.-C. Li)

Self assessment

Strengths An expertise in geometry and numerical algorithms. A mathematical culture that makes us “talk the same language” as mathematicians and eases cooperations with them;
Weaknesses/risk make sure we do not “lose” anybody and keep the solidarity in the team with the new math./physics orientation. (note: the succees of our GPU-Voronoi project [31] is reassuring).

2.4 Research axis 2: Computer-Aided Fabrication

Personnel

Permanent researchers: S. Hornus, S. Lefebvre, J. Martines Bayona, C. Zanni
Engineers: Y.-S. Perchi, N. Vennin
Ph.D. students: J. Etienne

Scientific Context and Goals:

Digital fabrication already had a profound impact on most industries, by allowing complex products to be modeled in Computer Assisted Design (CAD) software, and then sent to Computer Aided Manufacturing (CAM). Typically, designing of a new product requires a long chain of expertise with highly skilled engineers and technicians at all stages: design, CAD modeling, fabrication and assembly chains. The advent of additive manufacturing (AM) – 3D printing – lets us envision a different scenario :

- parts with very complex geometries can be fabricated in a single production run, and the fabrication cost has no direct relation with the part complexity;
- the cost per–unit for fabricating an object is always the same and significantly lower than that of producing a small series of objects with traditional means;
- the machine setup is largely independent from the object being fabricated, and thus these technologies can be made available through generic 3D printing companies and online print services, or even through machines that can be used at *home* by hobbyists.

As a consequence it becomes possible for a *practitioner* to design and fabricate parts with short development-fabrication cycles, even if he/she is no 3D modeling/CAD/CAM expert.

Another key advantage of AM is to enable the fabrication of extremely complex geometries, having scales from a few microns to a meter. This moves AM well beyond traditional means of production and enables concepts such as *metamaterials*. However, no existing 3D modeling technology is usable to model shapes at this scale: large parts filled with micro-structures, porosities and intricate multi-scale details quickly lead to huge data-sets and numerical issues.

We propose to focus on the computational aspects of shape modeling and processing for digital fabrication, with a particular emphasis on dealing with shape complexity, enabling customization and assembly of existing designs, and providing a stronger integration between modeling and specificities of the target processes.

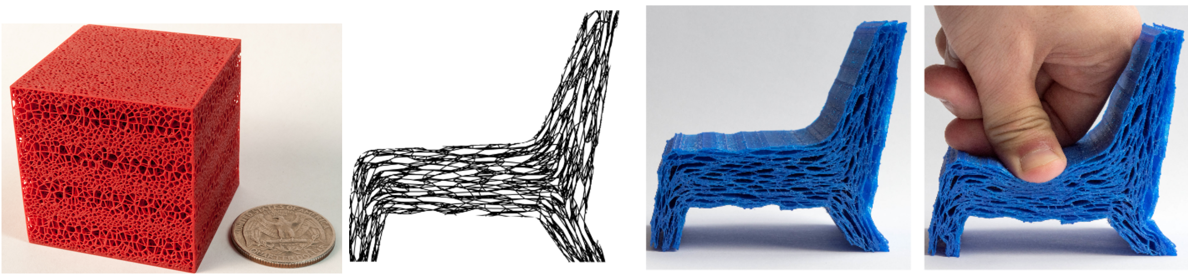
Project-team positioning

Our main academic competitors (and potential collaborators) are the Computational Fabrication Group at MIT, the Computer Graphics and Digital Fabrication group at IST Austria, the NYU Media Research Lab, the Visual Computing Laboratory of ISTI/CNR, the Advanced Manufacturing department of TU Delft, and the Department of Industrial and Systems Engineering at University of South California.

The originality of our approach stems from our focus on shape synthesis for digital manufacturing, which we backup with a unique blend of expertise. We are established experts in texture synthesis [WLKT09, Lef14], and have already developed original research towards using such methods for structure synthesis – in particular regarding *stochastic* and *by–example* structures (see below). Our expertise in interactive modeling, visualization and computing on GPUs [GLHL11, ZBL$^+$12, SL14] will help us reach our goals regarding interactive customization and efficient synthesis. Finally, in the past years, we developed hands-on expertise in additive manufacturing. We have not only *used* the technology but also considered *how to optimize the* *fabrication processes themselves* [DHL14, HL14]. Overall, this gives us a unique, global perspective on the challenges to be answered, from early interactive modeling stages and fast visualization to the intricacies of the machining instructions, and the hardware itself.

Within Inria, IMAGINE develops intuitive gesture interfaces driving procedural generation of virtual worlds, and GRAPHDECO develops methods to design virtual prototypes from imprecise inputs (sketches, pictures). There are opportunities for collaboration on modeling user interfaces for additive manufacturing, based on our synthesis and customization techniques. Similarly, we could collaborate with POTIOC regarding engaging user interfaces for modeling by non-experts. MAVERICK focuses on rendering from heterogeneous inputs (meshes, videos, simulations), both to produce realistic and expressive renderings. There are parallels between rendering and slicing (sampling, filtering) that we could jointly explore. Finally, we have ongoing discussions with teams in robotics regarding the use of our methods, in particular with team LARSEN (EPC Inria, Université de Lorraine and CNRS).

Main scientific achievements

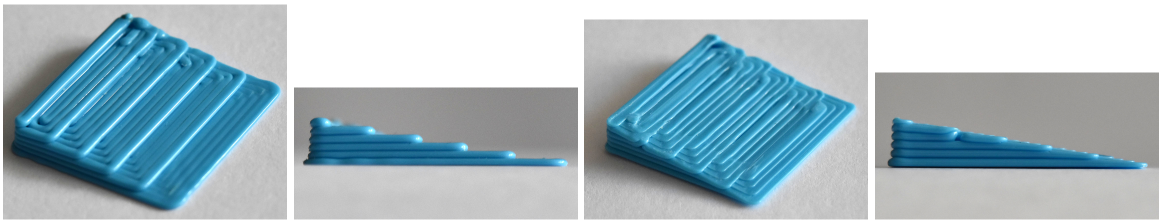


Synthesis of structured materials Based on our expertise in texture synthesis (by-example synthesis and stochastic textures), we developed new methods for structure and appearance optimization [25] and by-example synthesis of patterns [19].

To design finely structured material, the main problem is overcoming the high memory cost associated with the classical representation. Our idea is to use instead a procedural representation, generated on the fly, as usually done in computer graphics. We developed such a technique to model materials of varying density using a procedurally-defined Voronoi diagram [22] (left image). We continued to develop this idea, seeking for more control from the user (letting him specify not only density, but also anisotropy and angle). We further generalized the algorithm to Voronoi diagrams with varying anisotropy, interesting for creating materials with prescribed deformation behavior [24] (right image). Such structures can be created with stereolithography (SLA) or laser sinthering (SLS) processes. Finally, to extend the range of usable 3D printers, we developed a representation based on polyhedral diagrams [23], that can satisfy a user-specified varying density, anisotropy and angle, while satisfying all the geometric requirements of fused filament printers.

We have also proposed several algorithms to generate larger-scale structures, such as filigrees [11], or objects decomposed into tile decors [10].

During the evaluation period, one of the Ph.D thesis defended in the team (Jeremie Dumas) obtained the Regional best Ph.D thesis award for his thesis [2].



Fine control of the 3D printer Our specificity is to explore the complete chain, from the 3D modeling down to the 3D printer hardware. One of the problems with additive manufacturing is the jagged aspect of the generated objects, especially when using fused filament printer. To limit this effect, we have developed a new algorithm to optimize both the starting point of the slicing process and the thickness of each slice in a way that limits the artifacts [8]. Based on the similarity with aliasing artifacts in classical computer graphics, we have also developed a specialized anti-aliasing algorithm [36] (see Figure). We also study algorithms for other type of printers, that have more degree of freedoms (multi-axis rotations) [13], and that can avoid the need of generating supports with a well-optimized orientation of the 3D object.

Collaborations and External support

- ERC consolidator grant SHAPEFORGE (2012 – 2017) (PI: S. Lefebvre)
- ERC proof-of-concept grant ICEXL (2016 – 2018) (PI: S. Lefebvre)
- Inria associate team PREPRINT 3D (2014 – 2017) (PI: S. Lefebvre and B. Lévy) with W. Wang and L.-Y. Wei (Hong-Long University).
- CPER (2014 – 2020) (regional grant)
- PIC (2015–2017) (regional grant)
- ANR Implicit (2018–2022) (young investigator grant, PI: C. Zanni)
- ANR MUFFIN (2017-2021) (young investigator grant, PI: J. Martines)
- Collaborations with Marc Alexa (TU Berlin) regarding slicing algorithms for additive manufacturing.
- Collaborations with Niloy Mitra (University College London) on minimal wastage design of furniture.

Self assessment

Strengths The team covers the expertise required by the whole modeling/fabrication chain, even cooperation with specialists of materials;
Weaknesses/risk computer-aided fabrication becomes extremely competitive, which may make it harder and harder to produce novel research ideas. . . or on the contrary the is also the risk that it becomes a "niche" topic.

2.5 Evolution of research directions during the evaluation period

After the last evaluation period, our objectives were to (1) explore the possibility of redirecting our "geometry processing" research axis towards applied mathematics by publishing in applied math. journals, (2) strengthen our "computational fabrication" axis to make it ready to establish an independent group and (3) favor the emergence of new leaders within the team and help them evolving.

We were able to make progress for the three objectives, by establishing cooperation networks with mathematicians (ANR MAGA), by publishing 4 articles in applied math. journals during the evaluation period (2 in SIAM J. on Scientific computing, 1 in M2AN and 1 in J. of Computational and Applied Math), by hiring one new permanent researcher for the "computational fabrication" axis, and by initiating the creation of the two new teams. Within the team, Jonas Martines confirmed his excellent leadership abilities by obtaining a young researcher grant from the ANR in 2017, and Cedric Zanni just obtained one (August 2018). Both are ready to take the lead of new research directions in the team.

New research directions emerged from discussions within the ANR MAGA, from our Inria EXPLORAGRAM exploratory project that allowed us to hire a mathematician post-doc (Erica Schwindt), and starting experimenting with her new methods for computational optimal transport, and by encountering astrophysicists (Roya Mohayaee, Institut d'Astrophysique de Paris and Jean-Michel Alimi, Observatoire de Paris). With them we have a research project for a large-scale computation applied to astrophysics (more on this further-on).

3 Knowledge dissemination

3.1 Publications

	2015	2016	2017	2018
PhD Theses	2	1	2	1
H.D.R. (*)		1		
Journals	11	4	8	8
Conference proceedings (**)	2	1	1	3
Book chapters		1		2
Edited conf. proceedings			1	1
Patents	2			
General audience papers			1	

(*) HDR Habilitation à diriger des Recherches
(**) Conferences with a program committee. Note that conferences proceedings in graphics (Siggraph, Eurographics, SGP, ...) are special issues of journals (and are listed as such here). In this category we have listed courses and short papers.

Publications of articles coauthored by members of the project-team in the major conferences and journas accepted during the evaluation period:

1. ACM Transactions on Graphics: 12 (including 6 SIGGRAPH and 4 SIGGRAPH ASIA)
2. Applied math. journals (SIAM J. on computing, ESIAM M2AN, J. of comp. and applied math.): 4
3. CGF,TVCG,Visual Computer, CAD, Computer and Graphics: 10

3.2 Software

GRAPHITE *Experimental 3D modeler and geometry processing software* Web site: http://alice.loria.fr/software/graphite/doc/html/. Self-assessment:

- Audience: A-4 (large audience, used by people outside the team). (more than 43000 downloads on gforge.inria.fr)
- Software originality: SO-4 (original software implementing a fair number of original ideas).
- Software maturity: SM-4 (major software project, strong software engineering).
- Evolution and maintenance: EM-4 (well-defined and implemented plans for future maintenance and evolution).
- Software distribution and licensing: SDL-4 (public source or binary distribution on the Web). (GPL license)

GEOGRAM *General-purpose 3D geometric algorithms software library* Web site: http://alice.loria.fr/software/graphite/doc/html/.

- Audience: A-4 (large audience, used by people outside the team). (more than 56000 downloads on gforge.inria.fr since 2014 (**more than 13000 downloads per year**), used in several Open-Source and commercial products, including Houdini, Ovito, Trimble)
- Software originality: SO-4 (original software implementing a fair number of original ideas).
- Software maturity: SM-4 (major software project, strong software engineering).
- Evolution and maintenance: EM-4 (well-defined and implemented plans for future maintenance and evolution).

- Software distribution and licensing: SDL-4 (public source or binary distribution on the Web). (FreeBSD license)

VORPALINE *3D mesh generation software* Web site: http://alice.loria.fr/software/graphite/doc/html/.

- Audience: A-3 (ambitious software, usable by people outside the team). (used by our industrial contacts).
- Software originality: SO-4 (original software implementing a fair number of original ideas).
- Software maturity: SM-5 (high-assurance software, certified by an evaluation agency or formally verified). (we do systematic non-regression testing, memory tests and coverage analysis using Jenkins continuous integration platform)
- Evolution and maintenance: EM-4 (well-defined and implemented plans for future maintenance and evolution).
- Software distribution and licensing: SDL-3 (distributed to industrial partners in a contractual setting).

IceSL *Modeler and slicer for fabrication* Web site: http://alice.loria.fr/software/graphite/doc/html/.

- Audience: A-4 (large audience, used by people outside the team). (more than 17000 downloads on gforge.inria.fr)
- Software originality: SO-4 (original software implementing a fair number of original ideas).
- Software maturity: SM-4 (major software project, strong software engineering).
- Evolution and maintenance: EM-4 (well-defined and implemented plans for future maintenance and evolution).
- Software distribution and licensing: SDL-4 (public source or binary distribution on the Web). (binaries on the web, sources for industrial contracts)

3.3 Technology transfer and socio-economic impact

- Vorpaline (ERC Proof of concept) and MeshSpace (Inria Technological Transfer Action). The Proof of Concept allowed us to hire an experimented software architect (Thierry Valentin), who transformed our "artisanal researcher's development process" into a solid, quality-checked development process (systematic documentation, activation of maximum level of warning, non-regression tests, continuous integration platform, overnight memory tests). Two licenses were commercialised (to TOTAL and to Dassault Systems). Other commercialisations are currently studied (names not given for confidentiality issues). The next step is the creation of a start-up company, with W.-C. Li, who obntained an Inria ATT grant for that. This action is just beginning, but the first contracts that we were able to sign are very encouraging.
- IceXL (ERC Proof of concept) resulted in a 3D modeling with original functionalities for computer fabrication. A contract with an industrial partner has been signed (name not given for confidentiality issues). Similar status as the other action (the first contacts are very encouraging, but it is still too soon to say whether it is a successful technological transfer).

3.4 Teaching

- Undergrad: Samuel Hornus, Applied math. for CS. 64h eq. TD, niveau L3. à Télécom Nancy, France.
- Undergrad: Cédric Zanni, Informatique 2, 40h, L3, École des Mines de Nancy, France.
- Undergrad: Cédric Zanni, Informatique 1, 20h, L3, École des Mines de Nancy, France.
- Master: Nicolas Ray, Initiation to research, 10 heures, M1, université de Lorraine, France.

- Master: Sylvain Lefebvre, Computer Games Programming, 30h, Ecole des Mines de Nancy, France.
- Master: Sylvain Lefebvre, Introduction to parallelism and graphics, 9h , ENSG Nancy, France.
- Master: Sylvain Lefebvre, Introduction to additive manufacturing, 9h, ENSEM Nancy, France.
- Master: Cédric Zanni, Database essentials, 24h, M1, École des Mines de Nancy, France.
- Master: Cédric Zanni, Animation and computer grames, 27h, M1, École des Mines de Nancy, France.
- Master: Cédric Zanni, Software Engineering, 18h, M1, École des Mines de Nancy, France.
- Master: Cédric Zanni, Operating System, 17h, M1, École des Mines de Nancy, France.
- Master: Cédric Zanni, Introduction to C/C++, 34h, M1, École des Mines de Nancy, France.
- Master: Cédric Zanni, UML, 4h, M1, École des Mines de Nancy, France.
- Master: B. Lévy teaches Numerical Methods in École nationale supérieure de géologie de Nancy, France (12h).
- Master: B. Lévy teaches Algorithmic Gems in École des Mines de Nancy, France (8h).
- Master: B. Lévy teaches Computer Graphics in Telecom Nancy (20h)
- Master: B. Lévy teaches Programming Performance in Telecom Nancy (20h)

3.5 General audience actions

B. Lévy on TV (local news) https://www.youtube.com/watch?v=WNkk84_eK70&t=1s

3.6 Visibility

B. Lévy is associate editor of ACM Transactions on Graphics, Graphical Models and the Visual Computer
B. Lévy was program co-chair of Computer Graphics Intl 2018
B. Lévy was conference co-chair of workshop on Self Organizing Maps 2017
B. Lévy was conference co-chair of GMP 2016
B. Lévy was associate editor of TVCG (2010-2015)
B. Lévy was program committee memner of SIGRAPH in 2015
S. Lefevbre is associate editor of ACM Transactions on Graphics
S. Lefevbre was program co-chair of SMI 2017
S. Lefevbre was program committe member of SIGGRAPH in 2015 and 2016

4 Funding

National initiatives

ANR BECASIM (2013 – 2016) on the numerical simulation of Bose-Einstein condensates. Participants: X. Antoine, B. Lévy, L. Unterreiner;

EXPLORAGRAM (2017) Inria grant for exploring a new research direction on optimal transport. PI: B. Lévy. cooperation with Inria Mokaplan (Paris)

ANR MAGA (2016–2020) on the Monge Ampere equation and computational geometry. We are member of this cooperation network with mathematicians, physicists and computer scientists. PI: Quentin Merigot (Inria MOKAPLAN).

ANR ROOT (2016–2020) on Optimal Transport for Computer Graphics. PI: Nicolas Bonneel (CNRS Lyon). We will co-advise a Ph.D. thesis (Agathe Herrou).

ANR Implicit (2018–2022) on implicit modeling. PI: Cédric Zanni.

ANR MUFFIN (2017-2021) on structures for computer-aided fabrication (young investigator grant, PI: J. Martines)

CPER (2014 – 2020) on the interaction between software and material (ALICE + research labs. in Nancy: IJL, LRGP, ERPI)

PIC (2015–2017) on composite innovative polymers (ALICE + research lab IJL and company Cini in Nancy).

European projects

ERC consolidator grant SHAPEFORGE (2012 – 2017) on computer-aided fabrication. PI: Sylvain Lefebvre.

ERC proof-of-concept grant ICEXL (2016 – 2018) developing the industrial potential of our results in computer-aided fabrication. We developed a network of interested companies and started interacting with them[5].

Industrial contracts

Give a short description (5 lines) for each contract including the name of the company, the object of the collaboration, and the total amount of the grant. TBR.

Inria Project Labs, Exploratory Research Actions and Technological Development Actions

EXPLORAGRAM (2017) Inria PRE (grant for exploring a new research direction) on optimal transport. PI: B. Lévy. cooperation with Inria Mokaplan (Paris)

MESHSPACE (2018–2019) Inria ATT (grant for technological transfer), startup creation around the technologies stemming from B. Lévy's previous ERC grants (GOODSHAPE (2008-2013) and GEOGRAM(2014)).

Associated teams and other international projects

Give a short description (5 lines) for each associated team/project, including the type of project, its name and the list of partners. TBR.

PREPRINT 3D (2014 – 2017) two parallel cooperations with Hong-Kong university: W. Wang $\leftrightarrow$ B. Lévy (on geometry processing) and L.-Y. Wei $\leftrightarrow$ S. Lefebvre (on content generation), common to both research axes;

[5] company names not listed here due to confidentiality issues

5 Follow up to the previous evaluation

- **Recommandation: Create a new project group on 3d printing, potentially with S. Lefebvre as scientific lead**
  action taken: done
- **Recommendation: Focus the remaining group on more fundamental aspects of geometry, discretization, and numerics**
  action taken: done
- **Recommendation for the new group: strengthen focus on dissemination by making software available and encourage collaboration with academic partners in closely related subjects as well as relevant industrial partners**
  action taken: done
- **Recommendation for the remaining group: lessen the focus on tech transfer and provide freedom for more fundamental/theoretical work**
  action taken: We developed in priority the fundamental aspects, but we also kept an eye open for interesting industrial transfer opportunities (and we think that real-world problem are a good source of inspiration for more fundamental work)
- **Measure of success: numerical solutions for problems so far considered impossible to solve**
  results: our algorithm for semi-discrete optimal transport can process 16 million points on a laptop PC. In the 2000s, processing more than 200k points was considered out of reach, due to the $O(n^3)$ algorithm used so far. Our algorithm opens the door to new applications (for instance in computational astrophysics), but astrophysicists are greedy (they want 512 **billions** points (!));
- **Measure of success: geometric tools available for all making problem solving on geometry accessible for more researchers**
  results: to reach this goal, we separated our geometry-processing software into general-audience algorithms (GEOGRAM), that we made fully open (BSD license), and kept a kernel of specialized algorithms as closed-source (VORPALINE) for industrial transfer. For 3D printing, we made the binaries of our software (ICESL) accessible on the internet (and keep the sources closed, for our industrial partners);
- **contribution to 'gold standard' tools and formats in 3d printing**
  results: our results are not yet a "standard", but our IceSL software starts to have a significant user-base.

6 Objectives for the next four years

- Fully automatic hexahedral meshing: this is one of the main open problems in mesh generation. The problem is very difficult to solve, but we made significant progress towards this direction. We plan to further study the topology of the singular zones to remove the last percents of non-hexahedral elements. In the worst case, it we do not manage to generate a fully hexahedral mesh, we will develop special finite elements to handle singularities;
- Early Universe Reconstruction: we have started a cooperation with astrophysicists. The optimal transport that we solve exactly corresponds to a numerical problem in astrophysics: reconstructing the past history of the universe from a "3D map" of the current situation. Our current algorithm can handle 16 million points on a standard PC. The goal is to be able to handle 512 billion points. This requires to use a cluster (there is only a couple of clusters in France that are large enough to store the data, but our colleagues astrophysisicts know how to have access to them). The difficulty is to compute a large number of Laguerre diagrams in a distributed manner. We have started to work on this topic with Quentin Merigot. In a more general perspective, we keep the goal of developping "numerical solutions for problems so far considered impossible to solve" suggested in the previous evaluation (we like this one very much !);
- Numerical simulation with dynamic meshes: we plan to develop new fluid simulation algorithms that use dynamic meshes and that automatically adapt the shape of the fluid. Our approach is based on the least action principle, that formulates the law of physics in the form of a minimization problem. This minimization problem can be solved by some specialized algorithm, and fits very well with our dynamic meshes. We think this has the potential of better respecting the conservation laws, and better capturing the interfaces than with more traditional methods;
- Computer-Aided Fabrication: We propose to focus on the computational aspects of shape modeling and processing for digital fabrication, with a particular emphasis on dealing with shape complexity, enabling customization and assembly of existing designs, and providing a stronger integration between modeling and specificities of the target processes.
  - develop **novel shape synthesis and completion algorithms** that can help users *interactively* synthesize shapes having feature sizes from centimeters to microns, while following functional, structural, geometric and fabrication requirements;
  - develop algorithms that help *practitioners* create new designs by **customizing and assembling** existing ones, in particular **combining shape synthesis with traditional modeling**;
  - propose methodologies to help *expert* designers **describe shapes** and designs that can be **later customized and adapted** to different use contexts;
  - develop novel algorithms to **adapt and prepare complex designs** for fabrication onto a given technology, including the possibility to modify the design while preserving its functionality;
  - **integrate novel capabilities** enabled by advances in additive manufacturing processes and materials **in the modeling and processing chains**, in particular regarding functional materials (conductive, deforming) as well as embedding of electronics, sensors and actuators;
  - develop **novel shape representations, data–structures, visualization and interaction techniques** to support the integration of our approaches into a same, unified software framework that covers the full chain from modeling to machining instructions.

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