Visualization Working Group at TU Wien

Visible Facimus Quod Ceteri Non Possunt

Hsiang-Yun Wu, Aleksandr Amirkhanov, Nicolas Grossmann, Tobias Klein,
David Kouřil, Haichao Miao, Laura R. Luidolt, Peter Mindek,
Renata G. Raidou, Ivan Viola, Manuela Waldner, and M. Eduard Gröller
TU Wien, Austria

Abstract

Building-up and running a university-based research group is a multi-faceted undertaking. The visualization working group at TU Wien (vis-group) has been internationally active over more than 25 years. The group has been acting in a competitive scientific setting where sometimes contradicting multiple objectives require trade-offs and optimizations. Research-wise the group has been performing basic and applied research in visualization and visual computing. Teaching-wise the group has been involved in undergraduate and graduate lecturing in (medical) visualization and computer graphics. To be scientifically competitive requires to constantly expose the group and its members to a strong international competition at the highest level. This necessitates to shield the members against the ensuing pressures and demands and provide (emotional) support and encouragement. Internally, the vis-group has developed a unique professional and social interaction culture: work and celebrate, hard and together. This has crystallized into a nested, recursive, and triangular organization model, which concretizes what it takes to make a research group successful. The key elements are the creative and competent vis-group members who collaboratively strive for (scientific) excellence in a socially enjoyable environment.

1. Overview and history

The visualization working group (vis-group) started out with an interest in fractal geometry applied to computer-generated natural phenomena (e.g., landscapes, clouds). Fractal objects are in many cases closely related to dynamical systems, which we began to visualize in about 1994. A small group of researchers and (PhD) students formed the vis-group at the then Institute of Computer Graphics at TU Wien, Austria. For the next few years the visualization of dynamical systems and flow data was the focus of our research.

Flow visualization has been a major topic in scientific visualization with volume rendering being another intensely investigated area. In the late nineties we started a series of applied research projects in medical visualization together with a company partner (Tiani Medgraph later acquired by AGFA). We researched medical visualization techniques (e.g., maximum intensity projection, curved-planar reformation), which then were integrated into a company-developed medical workstation. These activities led to a long-lasting cooperation with radiologists from the general hospital (AKH) in Vienna in the area of CT-angiography. In 2000 we were one of the scientific proponents of the VRVis research center [1], which is now Austria's leading research institution in the field of visual computing. With more than 70 employees, VRVis is engaged in innovative research in cooperation with industrial companies and universities. Over the years, the vis-group has been involved in many research projects at VRVis and a sizeable number of PhD students graduated based on these applied research activities.

Figure 1: Prenatal ultrasound diagnosis (https://www.youtube.com/watch?v=BD7quHKgEuk).

Our work in medical visualization brought us to several basic research projects and further cooperation projects with company partners like Philips Healthcare Eindhoven and General Electrics (Kretztechnik). With Philips we investigated colonoscopic and orthopaedic magnetic resonance data for analysis, diagnosis, and evaluation. Between 2009 and 2015 purely company funded projects with General Electrics dealt with natural fetascopic rendering, i.e., high-quality rendering of noise-affected 4D ultrasound data. We investigated the robust and efficient applicability of advanced lighting and material effects for real-time display. The results were successfully commercialized by the company partner in their prenatal ultrasound diagnosis station (Figure 1). Medical visualization led us to a basic investigation of volume processing and depiction. Volume rendering is characterized by a high sensitivity to small parameter variations and occlusion effects. We proposed several new, efficient, and high-quality methods in illustrative visualization [2, 3] where we have been one of the leading groups in advancing this area. Tutorials on illustrative visualizations were organized at conferences like Eurographics and IEEE Visualization.

The visualization results in the medical domain, brought us to other application areas where volumetric data are researched as well. This led to a longstanding cooperation, since 2004 until now, with the Research Group on Computed Tomography at the University of Applied Sciences Upper Austria, Wels. Three- and four-dimensional volumetric data are generated through X-ray industrial tomography for the non-destructive analysis of advanced materials like CFRP (carbon-fiber reinforced polymers) [4, 5].

Due to the dual constellation of basic research in our group at TU Wien and applied research at VRVis, we have been contacted in 2005 by the University of Bergen (UiB), Norway. In a somewhat similar set-up they wanted to establish a visualization group at UiB as well. We have been involved in building up the visualization group there by participating in the selection process of the corresponding positions and giving lectures.

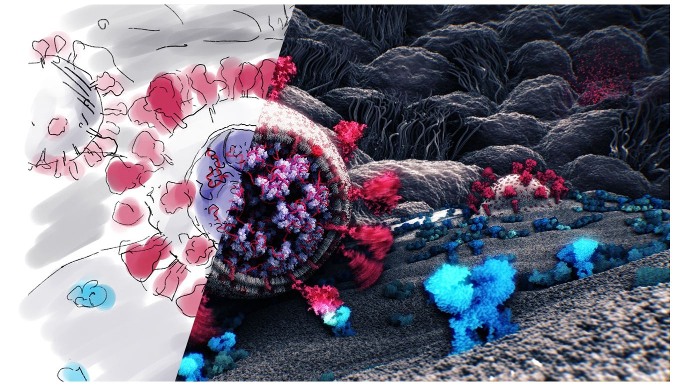

Figure 2: Computer Graphics Forum (CGF) cover contest winner [6].

More recently not only one data set, but a set or sequence of datasets is available in all areas of computational sciences, where the abundance of data makes the analysis and visualization especially challenging. The necessity of analyzing many datasets simultaneously, has resulted from several of our investigated application domains (non-destructive testing, medical analysis, visual analytics for decision support systems under uncertainty). We have abstracted the domain-specific context and proposed several visualization approaches in the area of comparative and cohort visualization [7]. The rapidly changing domain knowledge of biological nanostructures requires to include at least semi-automatic adjustment capabilities in the corresponding analysis tools (see Figure 2). Also, the involved phenomena are often characterized by several types of complexities (massive multi-instance, dense, multi-scale), which requires new visual computing contributions to cope with these intricacies [8, 9].

The current vis-group comprises four professorships (Figure 3) and researchers (Figure 4), under a strongly connected ecosystem with students and researchers. The vis-group has had an average size of about 10 researchers over the years. About 50 PhD students and 120 Master students graduated from the vis-group. A sizable number of vis-group students have already established successful research groups in the area of visual computing on their own. Five former PhD students have founded start-up companies. The vis-group has been very internationally oriented with PhD students from many different countries. We have tried and mostly succeeded to have a good balance in our research activities between basic research, translational research, and applied research.

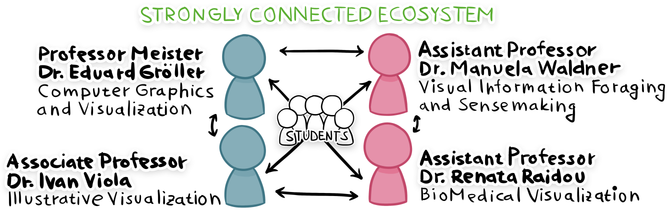

Figure 3: The current professorships at the vis-group.

Figure 4: The hybrid photo of the vis-group in 2020. Top row, from left to right, Dr. Haichao Miao, Prof. Ivan Viola, Prof. Renata Raidou, Prof. Manuela Waldner, M.Sc. David Kouřil. Bottom row, from left to right, Dr. Tobias Klein, M.Sc. Laura R. Luidolt, Dr. Peter Mindek, Prof. Meister Eduard Gröller, M.Sc. Aleksandr Amirkhanov, Dr. Hsiang-Yun Wu, M.Sc. Nicolas Grossmann.

2. Major Research Directions

Visualization has been a major part of the research activities of our Institute over the last 25 years. The vis-group performs basic and applied research projects in all areas of visualization (scientific visualization, information visualization, visual analytics) and visual computing. Current research focuses are summarized in the following:

2.1. *BioMedical Visualization*

The group has always had a very strong profile in biomedical visualization, with numerous influential publications throughout the last 20 years. In the last years, the focus has shifted from traditional applications towards the support of P4 (*personalized*, *predictive*, *preventive*, and *participatory*) medicine—especially, the field of cancer treatment.

With our visual analytics solutions for tissue characterization, clinical researchers explore and analyze non-invasively large feature spaces of imaging-derived tissue characteristics against clinical reference data (e.g., histopatology) to improve *personalized* patient diagnosis (e.g., for neuro-degenerative conditions) and to design more targeted treatments (e.g., for prostate, cervical, or breast cancer) [10].

Visual analytics can also be employed for *predictive* exploration and analysis—for example, in radiobiological modeling of tumor treatment, or in-patient rehabilitation [11]. This is done on the basis of large cohorts of patients. Together with researchers from the Danish Centre for Particle Therapy, the Medical School of UC San Diego, the University of Bergen, and VARIAN Medical Systems, we recently designed and implemented a novel predictive framework for radiotherapy [12]. For the first time in radiotherapy, a framework (Figure 5) is able to support the prediction and accurate quantification of per-treatment anatomical changes of a new incoming patient (with incomplete data), on the basis of a large cohort of past patients (with complete data).

In *preventive* visualization, we deal with understanding how the shape and size of organs affects the accuracy of automatic segmentation algorithms [13]. We are also interested in the impact of their (in)accuracies on the robustness of treatment strategies, such as adaptive radiotherapy [14]. This project started by dealing with only one organ (the bladder), and then was extended to cover the entire pelvis. The topic is tightly coupled with the predictive component, discussed above.

Finally, physicalization can be applied within the context of *participatory* anatomical edutainment to engage laymen or schoolchildren, through the use of inexpensive and accessible computer-generated physical models. Here, we focus on medical physicalization approaches that go beyond 3D printing—either with 2D printable and 3D foldable physicalizations. These change their visual properties (i.e., hues of the visible spectrum) under colored lenses or colored lights to reveal distinct anatomical structures through user interaction [15], or with assemblable oct-tree-based sculptures of volumetric medical datasets.

2.2. *Dental Aesthetics Visualization*

The group is collaborating with cool IT GmbH in Austria, Denttec KG in Italy, and Otto-von-Guericke University Magdeburg in Germany, on the visualization for dental aesthetics. Recently, we proposed a virtual mirror approach for a virtual dental treatment preview in augmented reality [16], to facilitate early feedback and to build the confidence and trust of patients in the outcome. This is intended to be used by patients, to preview their potentially selected dentures before fitting. An example is shown in Figure 6 (left) for differently sized dentures. Denture presets are visually evaluated and compared by switching them on-the-fly. In addition to the virtual mirror approach, we proposed a solution to support the workflow of dental technicians, by integrating aesthetics analysis into the functional

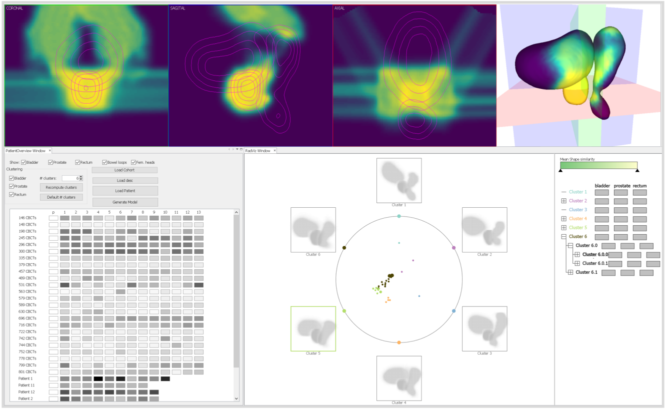

Figure 5: A predictive framework for the visual exploration and analysis of anatomical variability in radiotherapy decision support [12].

workflow of dental technicians [17]. This is shown in Figure 6 (right), and is intended to assist dental technicians in choosing the aesthetically most fitting preset from a library of dentures, in identifying the suitable denture size, and in adjusting the denture position.

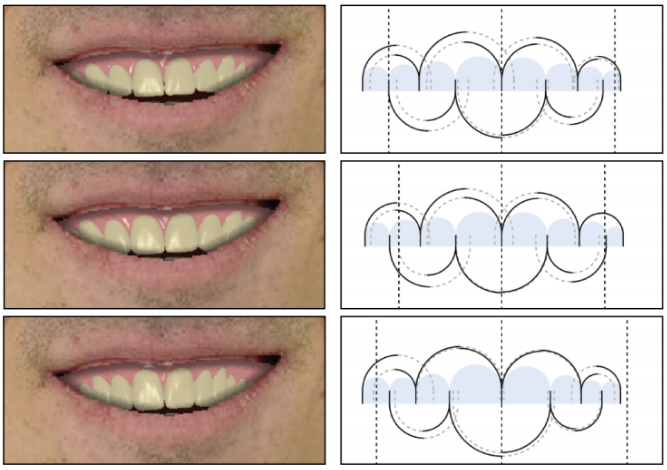

Figure 6: Research on dental aesthetics visualization [16, 17].

2.3. *Mathematical Visualization*

Our group has proposed in the past several approaches to support the exploration of dynamical systems. Our most recent work is *ManyLands* [18], a visual analytics tool for the exploration of 4D continuous-time dynamical systems. Such dynamical systems allow the mathematical description of numerous biological processes, using ordinary differential equations of varying complexity and dimensionality. A few examples include dynamical systems for the cell division cycle, or models that explain bipolar disorder mechanisms. *ManyLands* provides capabilities for the holistic and dissected exploration of these systems, supported by interaction and smooth animated navigation through phase space (Figure 7). Domain scientists can effectively interact and navigate between different visual representations of the system trajectories in a simple, yet novel, way. They can travel across *HyperLand* (a hyperspace representation) to *SpaceLand* (three-dimensional representations), *FlatLand* (two-dimensional representations), and *TimeLines* (one-dimensional representations). For localized analysis, we offer an additional dissected view of the system trajectories. This relies on abstracted, small-multiple pictograms, embedded within *TimeLines*. The abstractions serve as compasses for easy navigation across phase space and across segments of interest, as well as a selection mechanism for segments of interest.

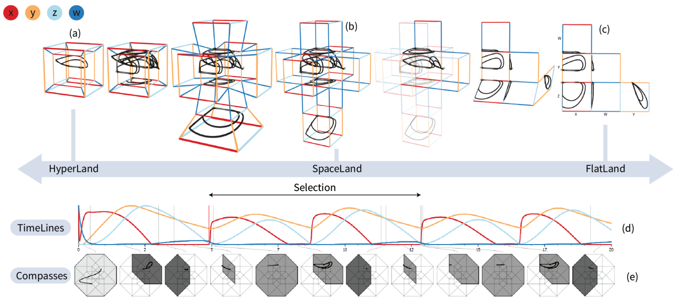

Figure 7: *ManyLands*: A visual analytics tool for the exploration of 4D continuous-time dynamical systems of biological processes [18].

2.4. Molecular Visualization

Molecular visualization is one of the principal directions in our research group. The research started with investigating display algorithms for very large datasets, with the goal of real-time rendering performance. These efforts have materialized into *cellVIEW* [19], a framework for real-time rendering of molecular data. Besides performance, we are also interested in illustrative visualization of molecular data. We proposed several methods enhancing the clarity of the visualizations [20]. Computational models of biological entities, such as viruses and cells, have significantly advanced research in integrative cell biology. In our research, we approach the construction of computational models from a visualization perspective [8, 21] (Figure 8(left)).

Over the years of contributing to molecular visualization, we have developed relationships with domain experts that were at the dawn of molecular graphics. It has also come to our attention just how important visualization is in efforts related to science outreach, i.e., communication of biology to non-expert audiences. To address this challenge, and to unify our software development efforts in molecular visualization, we created *Marion* [22]—a software prototyping framework focused on storytelling and science outreach. Since then we are using it across several branches of our research to implement new illustrative visualization methods with maintainability and reusability in mind.

The framework became the basis of a spin-off company Nanographics [6] that we started out of our research group. The company focuses of developing visualizations as well as novel visualization algorithms, focusing on science communication

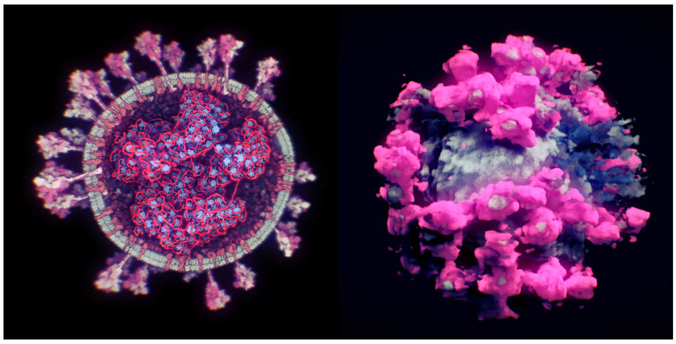

Figure 8: 3D visualization of a coronavirus particle.

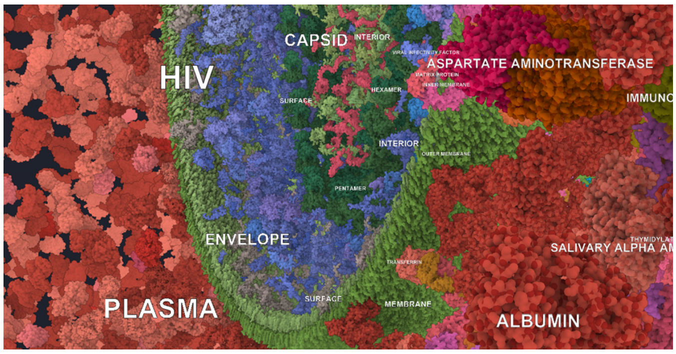

Figure 9: Textual labeling of a multi-scale, multi-instance, dense 3D biological model [9].

and outreach. Amongst our achievements is the first 3D visualization of a coronavirus particle directly from cryo-electron tomography data (Figure 8, right), without the use of subtomography averaging. We continue to develop novel solutions for various problems related to communicating the unique aspects of biological structures spanning several scales of magnitude. Elements of the visualization must be adapted to enable exploration of multi-scale data. That can include dynamically adjusting the coloring [23], shading, or even labeling [9] (Figure 9), while the user explores the three-dimensional model.

Multi-scale biological models have implications also for the way users can explore and navigate them. We investigated multi-scale navigation in the *HyperLabels* [24], *ScaleTrotter*, and *Molecumentary* [25] projects.

2.5. Network Visualization

The use of networks is ubiquitous since networks have been used to model relationships between entities in various applications. Graphs are mathematical notations of networks that allow us to handle relationship information in a systematic manner. Untangling relationship information, such as biological networks, social networks, knowledge graphs, and many other big data applications, is heavily in demand, not only in academia but also in industry. The graph visualization research in the vis-group aims to propose scalable solutions to relax the hairball effect of network representation. One effective method is the introduction of a schematic representation [26], which has been used in cartography, to ease route planning tasks through a simplified network geometry.

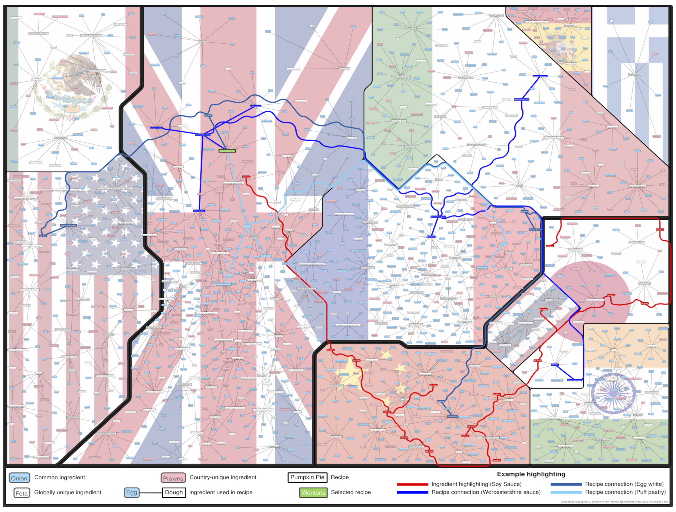

Figure 10: World Map of Recipes [27].

We have been inspired and introduced well-known map semiotics as visual metaphors to present the detailed connectivity of biological pathways [28]. This allows us to analogously synthesize pathway diagrams using functional categories as city blocks and edges as road networks in an urban area. We successfully accelerate the conventional manual drawing process of biologists from 20 months to two hours while simultaneously preserving the global and local context. An extended version that relaxes the rectangular boundaries to arbitrary polygonal shapes has been developed, and new criteria that balance the vertex distribution have been investigated [27]. Figure 10 won the Graph Drawing Contest 2019 1st Place Award and gives an example showing the relationship between food recipes and ingredients. With the network structure analysis, we successfully separate recipes by continents and proved that neighborhood countries tend to reuse similar ingredients. The applicability and feasibility of graph-based techniques have also been investigated. A taxonomy to categorize existing evaluation methodologies on graph visualization is introduced [29], in which we study the common settings of qualitative evaluations of graph visualizations. A smooth transition between graphs that are associated with geographical locations is developed [30]. We also investigate the visual quality and the discriminability of results synthesized using well-known graph drawing algorithms and the corresponding hand-crafted versions [31].

2.6. *Perception in Visualization*

The visual perception research in the vis-group focuses on two aspects: 1) Understanding and modeling user perception during visual analysis [33, 34] and 2) adapting the visual representation to effectively guide the user's attention and to improve the effectiveness of complex visualizations. Based on a new object-based saliency model, we introduced a novel multi-channel highlighting technique. It is able to generate an effective emphasis in complex visualizations with minimal context suppression by balancing the highlight effect across multiple visual channels [34]. While this technique creates visually prominent and pleasing highlight effects, the technique is not sufficient to effectively guide the user's attention on large displays, especially when showing a dynamic narrative visualization. We investigated the use of flicker as means to attract the users' attention, trying to find a trade-off between effectiveness of the highlight cue and its perceived annoyance [35]. We exploit the critical flicker frequency threshold to create highly effective, yet minimally disturbing visual attention guidance in crowded images without the need for eye trackers [36].

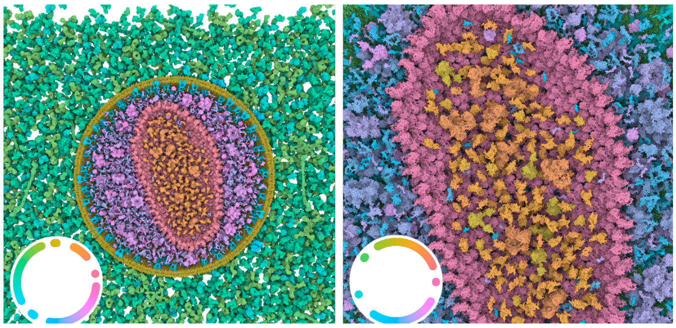

Figure 11: Cuttlefish [32] dynamically adapts categorical color maps to support discrimination of hierarchical structures in zooming interfaces.

While attention guidance is crucial for narrative visualizations, we also investigated how to utilize the limits of human visual perception to support exploratory analysis. One example are dynamic categorical color maps to maximize the number of hierarchically organized categories to be visualized in multi-scale visualizations [23, 32], as shown in Figure 11. Together with researchers from the Masaryk University in Brno, Czech Republic, we designed and evaluated a novel spatio-temporal focus+context technique, where user-selected elements and events of interest are visualized in full spatial (elements) and temporal (events) detail, while the context remains abstracted. Conversely, we explored the dynamic suppression of animation speed in the focus, while maintaining high velocities in the context to visually convey the complexity of the displayed scenery [37].

Apart from these works directly related to modeling and guiding visual attention, the vis-group is regularly conducting empirical studies investigating various perceptual aspects of visualization. Examples are studies assessing the effectiveness of visual channels encoding quantitative information in word clouds, the effectiveness of radial charts for visualizing daily patterns or the light perception of virtual scenes [38].

2.7. *Visual Modelitics of DNA Nanostructures*

Visual Modelitics describes the combination of intelligent, automated visualization methods for the interactive modeling of large, complex, dense and multiscale environments. Today we not only visualize molecular structures, but also have the tools to create real-world objects in the nanoscale. DNA

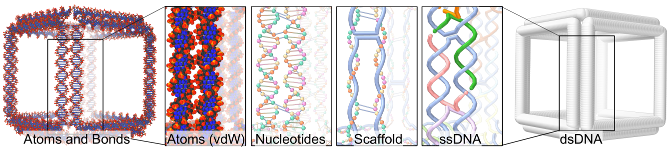

Figure 12: Multiple scales, from detailed to course, represent the same data (nanocube)

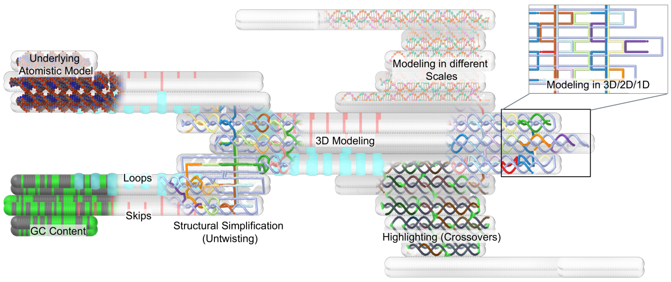

Figure 13: Various features of the visualization methods for a nanorobot.

nanotechnology describes the programming of DNA strands to self-assemble into arbitrary nanostructures [39]. A DNA nanostructure is a biomolecular objects consisting of features on several scales ranging from hundreds of thousands of atoms to hundreds of DNA strands and the overall shape. A key research direction in our group is to deal with the features across multiple scales through appropriate abstraction techniques. In Figure 12, Miao et al. [40] propose several cross-scale representations organized in a multiscale arrangement to support scale-adaptive modeling tasks. The user can switch the representation with a slider to seamlessly adjust the scale level. In this way, animated transitions are used to establish correspondences between features at different scales. Modeling operations such as Join, Break and Delete are the most basic DNA operations that can be applied to all scales. Instead of selecting groups of all atoms belonging to a nucleotide, only one sphere on a higher scale can be selected. In addition, the expert is provided with simplified views, coloring schemes, and visual guidance to further ease the modeling process (see Figure 13). The proposed Visual Modelitics approaches are implemented in Adenita [41], a software for the interactive modeling of DNA nanostructures, which has recently been published and released for experts in the field.

2.8. *Visual Sensemaking*

The vis-group explores how to improve visual information foraging and sensemaking interfaces to make knowledge work more efficient with three focus questions. The first focus lies on the role of *spatial organization in sensemaking interfaces*, where we investigate how users utilize space to organize their thoughts in different scenarios (e.g., Waldner et al. [44]). The second focus lies on the tight integration of information foraging interfaces into the user's working environment. For example, we investigated how to improve exploratory search through visual query expansion [45] and how to bridge operation and browsing histories to provide cross-application provenance [46]. Our final focus lies on the visualization of hidden

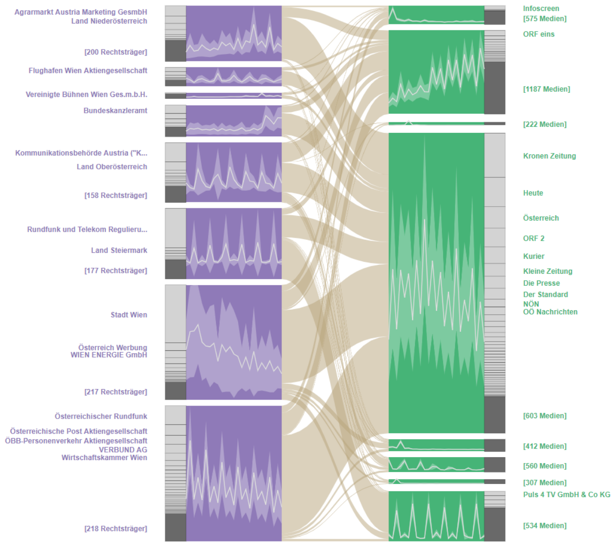

Figure 14: BiCFlows [42, 43] support the exploratory analysis of very large, time-dependent bipartite graphs, such as media-advertisment networks.

relations in large, complex information spaces. Examples are *BiCFlows*, a novel, large-scale visual encoding for large bipartite graphs based on biclustering [42] or agglomerative clustering of time series [43] (Figure 14).

2.9. *Planned Research*

Our current research activities can be also found on our website (https://www.cg.tuwien.ac.at/research/vis/). In the following we describe some of our planned research activities. (Data) visualization deals with computer-supported interactive visual representations of (abstract) data to amplify cognition. Visualization is a key technology in keeping the user in the loop in intricate decision-making processes. Though there is a strong trend towards automatic approaches (artificial intelligence (AI), machine learning, convolutional neural networks), the human expert has to remain in control for understanding and analyzing autonomous systems (e.g., explainable AI). Visualization will be an important method in this respect. Based on the given data and user with specific tasks, an appropriate visual encoding has to be designed and evaluated. As the perceptual and cognitive capabilities of the human analyst are not scaling with the increased data complexity, visualization as the interface in-between has to provide novel interactions and visuals. Complexity of the data cannot be addressed with complexity of the visualization. The guiding principle of many of our research works in the past has been to simplify interactions and visual representations as well.

Nowadays typically many and complex data items are given. This requires novel approaches in various related directions: visual analytics, comparative visualization, quantitative visualization, scalable visualization, linked/integrated views, immersive analytics, and physicalization. Important topics from these areas that are currently particularly interesting to us are multi-scale visualization and interaction, uncertainty visualization, and visual modelitics. visual modelitics is a novel approach to combine automated and intelligent modeling and synthesis techniques with interactive visual computing for an effective multi-user specification of large, complex, dense, multi-instance, multiscale, 3D, dynamic environments.

Further topics of interest to us are: medical visualization with cohort studies, biomolecular visualization, visualization in non-destructive testing, comparative visualization, contradiction visualization, joint visual representation of phenomena from data and computational sciences (i.e., visual data assimilation), visualization in the wild (i.e., under less controlled conditions as compared to now), going from data-driven to task-driven visualization, and output-sensitive interaction. The increasing digitalization and automation (AI, machine learning) of human activities through computational science and data science necessitates the design of novel visual computing approaches to make human-centered decision making tractable and trustfully amid the considerably increased data complexity. This provides many relevant and challenging topics for visual computing research in the future.

3. University education and vis-group

Our current teaching at TU Wien Informatics is primarily embedded in the Bachelor studies "Media Informatics and Visual Computing" with the two obligatory lectures "Computer Graphics" and "Visualization 1" and in the Master studies "Visual Computing" with the obligatory lecture "Visualization 2". The vis-group is further involved in the Master studies "Medical Informatics" and "Data Science". Recently we initiated a course on "Visual Data Science". Every semester the vis-group is supervising a sizeable number of students in various seminars, computer science projects, Bachelor and Master theses. We are mentoring students in the Bachelor with Honors program at our faculty. Internationally we have repeatedly participated and co-organized tutorials and panels at conferences like Eurographics and IEEE Visualization.

The advancing digitalization and knowledge society needs highly educated computer scientists. Ideally, these experts shall follow the c-triangle that is be creative, competent, and cooperative (i.e., motivated) in a balanced way (Figure 15 middle). The university education should accommodate and foster these characteristics. Teaching at a university should be research-guided already at an early stage. In our seminars we assign current research papers to the students to expose them soon on how scientific processes are done and also to motivate them through working on the most recent topics in our research area. In those courses where larger (scientific) projects have to be executed (Bachelor theses, computer sciences projects, Master theses), we mostly assign topics resulting from the present research work of the supervisors. This ensures a high commitment of all involved participants, and additionally motivates the student as (s)he is working on relevant and current research problems. The overarching strategy is to bring students as fast as possible into situations that are close to those that they will encounter in their future work environments.

An example on how to early engage students in real-world research activities, is the Central European Seminar on Computer Graphics (CESCG, https://cescg.org/), which has been initiated by our research unit about 30 years ago. It is a student seminar in a conference-like setting including student participants from several Central-European countries. We consider a close interaction between students and teachers important for a fruitful and motivating knowledge transfer. This is difficult at mass universities with a high number of students per teacher, especially in the first years of study. To at least alleviate this issue, our research unit has founded about 25 years ago the CG Club (https://www.cg.tuwien.ac.at/staff/CGClub/). Highly motivated students especially interested in computer graphics get the chance to experience the daily life and work at our research unit, see how research is done, and learn more deeply about the special interests of scientists working here.

PhD education has always been a special focus of our research and teaching activities [47]. PhD studies should follow the s-triangle, i.e., student, supervisor, sources (Figure 15 left bottom). A creative student shall work together with a supervisor on a relevant research topic of mutual interest, where the necessary (re)sources like funding are adequately available. During the PhD studies the supervisor should act as mentor where the PhD student increasingly acts autonomously to solve challenging scientific problems. External constraints like an over-regulated PhD curriculum are detrimental to self-motivation, a key component in a successful PhD project. We have a minimalistic view in this respect, where the s-triangle of student, supervisor, and sources should be brought together, but then largely left alone to do its work. The PhD candidate should early on get the freedom to make decisions in uncertain situations, but also to take responsibility for the consequences. Vis-group provides also the opportunity to constantly bounce off one's research ideas and learn about the research work of others and how they are presenting their ideas. Constant reflection and retrospection are integral parts of scientific advancements. PhD students are rapidly encouraged to become self-reliant researchers by involving them in supervision and reviewing activities early on.

4. Reflections on the vis-group set-up

Figure 15 illustrates our triangular, recursive, and group-centric research world view. In the central triangle, research (R) encompasses a group of scientists working in a specific area to produce scientific output. In our case the area is visualization where data, tasks, and user determine the appropriate visual representation (dut-triangle). An essential research output are PhDs as denoted by the s-triangle (student, supervisor, sources). A successful research group is a balanced combination of people, papers, and projects (p-triangle). A good scientific paper integrates imagination, impact, and implementation (i-triangle). A good scientist is characterized by creativity, competence, and cooperative attitude (c-triangle). Besides this nested triangular view on a successful research group, there are other triangles floating around in our activity space. Publishing happens in an

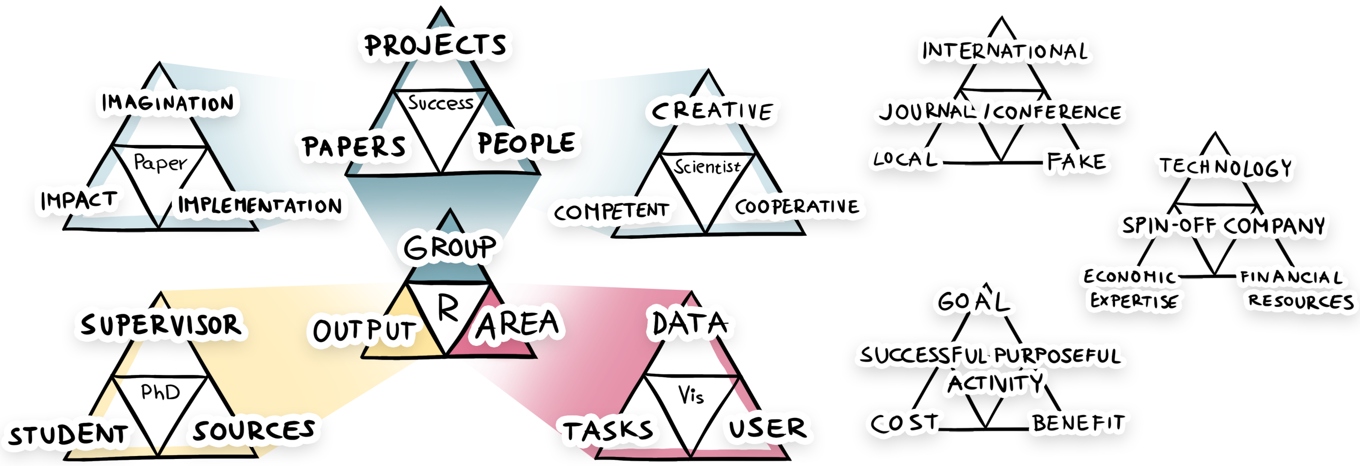

Figure 15: What Makes a Research Group Successful?

interconnected environment, where we strive to publish at the best international, but highly competitive conferences and journals. Local but serious events play nonetheless an important role in the nurturing and fostering of young research talent. At the same time detrimental and exploitative fake conferences and journals have to be avoided (ilf-triangle). Commercial utilisation of technological advances is exemplified by spin-off companies (tfe-triangle). On a whole scientific working is a targeted search process where the achievement of defined goals is optimized through a cost/benefit trade-off (gcb-triangle).

Our vis-group is following the p-triangle, i.e., we strive for a balanced set of people, papers, and projects (Figure 15). A close group-interaction is promoted in the vis-group with for example weekly scientific meetings and a yearly closed meeting where we discuss strategic research directions for the coming year. For a successful collaboration within a highly motivated and ambitious group, we consider also a tight social interaction as necessary and valuable ("work hard, celebrate hard"). The group is regularly engaging in social activities. One example are rejection parties, where after the notification deadline of the most important conferences in our field, we meet and appreciate the efforts gone into submissions even if they have been rejected (and we also celebrate the successes). A multi-year PhD project should be broken down into manageable sub-projects where the achieved scientific results are then documented by research publications following the i-triangle, i.e., they should be characterized by imagination=originality, impact=relevance, and implementation potential=technical soundness (Figure 15 top). Increasingly utilization of research results, e.g., as spin-offs, is becoming important especially for graduates from technical universities. This option and opportunity should be communicated more clearly to the PhD graduates. Spin-offs follow the tfe-triangle (technology, finance, economics) (Figure 15 right), where our students are rather strong on the technology side, but need more support in financial, and marketing and sales matters. It would be great if PhD graduates, after finishing their studies, get the possibility (from funding sources) to explore exploitation perspectives coming from their research work. Thoughts on our way of supervising successful PhD projects have been published as a journal paper [47]. Future teaching activities should take emerging trends into account: visual data science, visual computing in the computational sciences, visualization as approach for retrospectively understanding autonomous systems (explainable artificial intelligence and machine learning), internet of things, aso. In the ever-complex world with autonomous agents, it is important that the human (expert) remains closely involved. Visualization is an evolving and important technology in this respect.

The vis-group tries to provide valuable contributions for students, the university, and society at large. Finally, the strong internal cohesion of the vis-group is also reflected in our motto: *Visible Facimus Quod Ceteri Non Possunt*, i.e., *we make visible what others cannot*.

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