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Topology-based versus Feature-based Flow Analysis – Challenges and an Application

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Abstract

This paper is the result of research and contemplation on the actual usefulness of topology-based methods in real-world applications. We recapitulate commonly used arguments in favor of topology-based approaches first to realign our expectations with respect to the utilization of topology extraction in the context of concrete applications. To illustrate some of our considerations, we take a closer look at one specific example, i.e., the visual analysis of flow through a cooling jacket and we report our respective experiences. After discussing the topology-based analysis of the cooling jacket case, we contrast topology-based flow visualization with an alternative approach, i.e., the interactive feature extraction for feature-based visualization. Without generalizing just from the one concrete example scenario, we still are able to conclude with some broader experiences which we have made in the past and which seem to align well with the opinion of others in our field.

Keywords: flow visualization, topology-based flow analysis, feature-based flow analysis, interactive feature specification

1.1 Introduction

Due to the rapidly increasing use of computational flow simulation and due to the concurrently increasing size and complexity of flow simulation results, there is a great demand for tools which help with the visual exploration, analysis, and presentation of flow simulation results. A vast number of technological approaches have been proposed during the last decades [9, 10, 12, 13].

Approaches range from the direct (one-to-one) visual representation of flow data, e.g., through the use of color coding or hedgehog plots, through geometric and

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texture-based approaches, to the large class of solutions which utilize a significant amount of computational analysis before the actual visual representation.

In this last class of flow visualization techniques, topology-based approaches are very popular. Before visualization, the topological skeleton of the flow is extracted. Critical points are identified and classified as well as critical structures of higher order (e.g., cycles, invariant tori, etc.). Their critical structures are related to each other, separatrices are computed. The extraction of the topological skeleton of flow data can be interpreted as the segmentation of the flow into regions of coherent long-term behavior – all points within a flow region which is bounded by critical structures and the associated separatrices share a common long-term behavior (at least qualitatively).

Once the topological skeleton of a flow is extracted, it can be used for visualization. In many cases [10], “only” the topological skeleton is visualized (instead of the original data). This results in a number of advantages which motivate the use of topology-based visualization techniques:

1. The extraction of a topological skeleton equals flow abstraction. Instead of the original data, *information about the flow data* is visualized. Accordingly, such a topology-based flow visualization provides information,
   - which is not explicitly contained in the original data, but abstracted from it, i.e., it is something additional to the original data,
   - which is very informative in case the long-term evolution of the flow under investigation is of significant interest, and
   - which is extremely condensed as compared to the original data (a few geometric structures convey a lot about the entire flow).

   As a result, *deeper insight* is possible through the use of topology-based flow visualization.
2. Due to the condensation as a result from the abstraction process technical advantages are yielded. Rendering a concise topological skeleton instead of millions of simulation cells allows for interactive and real-time rendering. It also reduces memory requirements significantly, i.e., the resource requirements for visualization (not necessarily for the extraction process) are drastically reduced, usually by several orders of magnitude.

These advantages motivate the use of topology-based methods for flow analysis in practical applications. If insights are possible which otherwise are impossible or especially hard to derive, qualitative benefits may result in a practical application. If interactive visualization becomes possible, even on customer computers, quantitative benefits are possible.

However, we still cannot report a wide-spread establishment of topology-based methods in real-world applications. This could be due to the fact that still the respective methods are considered to be relatively young (many from the last decade only). But, of course, also other reasons seem to be possible for the fact that topology-based methods have not (yet) conquered the offices of practitioners. In the following, we aim at a better understanding of this situation by considering a concrete example and by recapitulating additional previously gathered experiences.

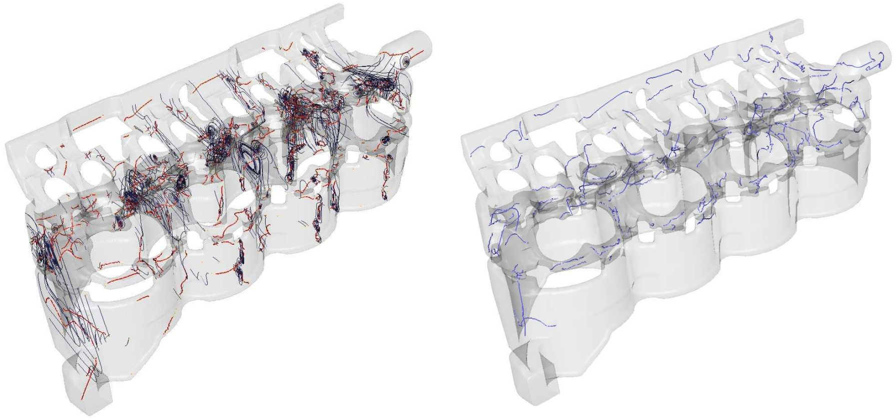

Fig. 1.1. (left) Cutting plane topology revealing flow structures perpendicular to the dominant longitudinal flow. Within the cutting planes, streamlines are depicted in blue; longitudinal vortex cores (connected critical points) are then shown in red. (right) Vortex core line extraction using the method from Sujudi and Haimes [16].

1.2 Analyzing a Cooling Jacket – an example from industry

To investigate the interesting question of why topology-based approaches are no yet wide-spread, we first consider a concrete example from our cooperation with AVL List GmbH in Graz, Austria, i.e., the flow through a cooling jacket as employed for the cooling of car engines [8].

Figure 1.1 (left) shows a visualization result which is based on the extraction of topological features on a set of cutting planes through the 3D cooling jacket flow [17]. Connected critical points (in red) indicate vortical flow structures and additional streamlines (within the cutting planes, depicted in blue) add in more information about the local flow structures[2]. The cutting planes are placed equidistantly along one direction chosen by the user. With some *a priori* knowledge, this approach indeed can provide useful insights into flow structures.

The application to the cooling jacket is straightforward in our case, since interesting flow structures are expected to be orthogonal to the longitudinal constituent. Positioning the cutting planes orthogonal to the longitudinal axis reveals a number of interesting features, most notably several vortices in the head. They show up as sources and sinks on the cutting planes. The vortex cores are then indicated by the connection of the critical points across the cutting planes. This type of visualization (composed of many line-type features in 3D) does not always yield good spatial perceptibility. The use of tube-like primitives (as one standard solution to this problem) is prohibitive in our case due to the large number of lines both from a rendering performance point of view and because of visual clutter. We have therefore employed

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[2] For original, high resolution images, please visit
`http://www.VRVis.at/scivis/laramee/topology/`

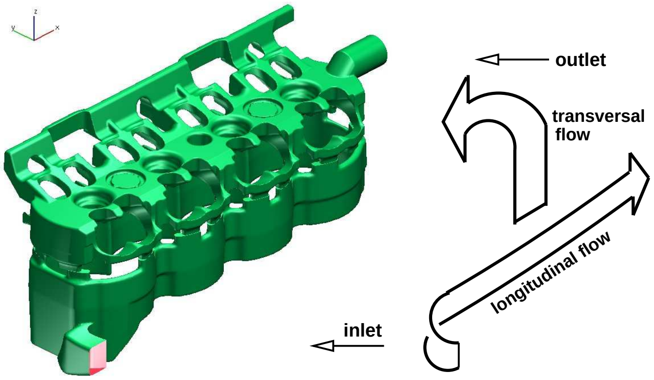

Fig. 1.2. The major components of the flow through the cooling jacket include a longitudinal component, lengthwise along the geometry, and a transversal component in the upward-and-over direction. The inlet and outlet of the cooling jacket are also indicated.

a simple scheme to illuminate the lines based on tangents, similar to the illuminated streamlines technique [15].

Nevertheless, this visualization still suffers from a lot of visual clutter and increased structural complexity so that gaining new and deep insight into the shown flow remains a challenge, even for experienced practitioners.

When comparing this topology-based visualization with a feature-based visualization, e.g., the vortex core line extraction according to Sujudi and Haimes [16] (see figure 1.1 (right)), we can see that the feature-based approach generates less clutter (in this particular example), but still suffers from similar perceptual problems. However, we also know from other applications, that topology-based methods, when applied to real-world CFD simulation data, often generate a lot of geometrical structure which seems to be more difficult to control then results from feature-based approaches.

One way to address this complexity issue is to apply a topological simplification algorithm after the extraction stage. This reduces the number of critical points. Simplification algorithms of this kind often are fairly complicated to implement. Additionally, the advantage of reducing the geometric complexity of the visualization result comes at the price of an increased interpretation load on the user side – often it is not truly intuitive to understand what the simplification algorithm did (what structures have been removed and why).

1.3 An Engineer's Point of View

The above mentioned challenges (complexity of implementation, challenging interpretation) motivate an alternative approach to flow analysis, i.e., a more semantics-based, interactive, feature-extraction approach, guided by the engineer. It's been our experience that engineers analyzing CFD simulation data do not necessarily think in terms of critical points within the flow or in terms of a topological skeleton, but rather in terms of an ideal or optimal pattern of flow they are trying to achieve.

As an example, Figure 1.2 (right) attempts to depict the ideal pattern of flow through the cooling jacket geometry. A diagram similar to this one was shown to us by a mechanical engineer when we were learning what flow the CFD engineers were trying to create. There are two major components to the flow: longitudinal and transversal. Longitudinal flow is oriented lengthwise along the cooling jacket geometry whereas transversal flow is oriented in the upward-and-over direction. Essentially, the ideal pattern of flow is the most efficient path from inlet to outlet. By following the ideal path, the cooling jacket is most effective in its job of transferring heat away from the engine block. Some questions that the engineers designing the cooling jacket are interested in answering are:

1. Are there any areas where the flow is moving in the wrong direction?
2. Where, in the cooling jacket, are the areas of stagnant flow?

The function of a cooling jacket is to transfer heat away from the engine as efficiently as possible. Engineers are interested in learning where and how the flow deviates from the ideal. Deviance from the ideal leads to less effective heat transfer.

1.4 Interactive, Feature-Based Flow Visualization

We have applied both an automatic topology extraction algorithm as well as an interactive, feature-based approach in order to investigate and analyze the behavior of the flow through a cooling jacket. The interactive, feature-based flow analysis system we have used is called SimVis [2, 5, 6]. SimVis establishes an interactive visual analysis loop with the following essential properties:

- The user visualizes the multi-variate attribute space of a CFD dataset in such a way that it can be intuitively explored and accessed directly by brushing (brushing means that interesting flow features are directly marked up in the views).
- A sophisticated interaction framework is provided that allows the user to identify interesting flow features intuitively and easily, even if the features can only be characterized in a complex specification with multiple flow attributes [3]. This includes an iterative refinement process. Specifications can be rapidly prototyped with immediate feedback.
- Linking attribute visualization to spatio-temporal visualization yields feature-based focus+context visualization of the CFD dataset in an intuitive manner.
- A feature specification system is provided that (in contrast to most other related approaches) reflects the often quite smooth distribution of flow attributes across the domain, a property resulting from most CFD flow simulations. This is achieved via degree of interest functionality instead of using sharp selections [4].

SimVis uses multiple linked views, utilizing visualization techniques of different kind (scatterplots, histograms, 3D visualization, etc.). Generally, the user specifies which subsets of the flow to focus on, e.g., by brushing in a scatterplot. The marked

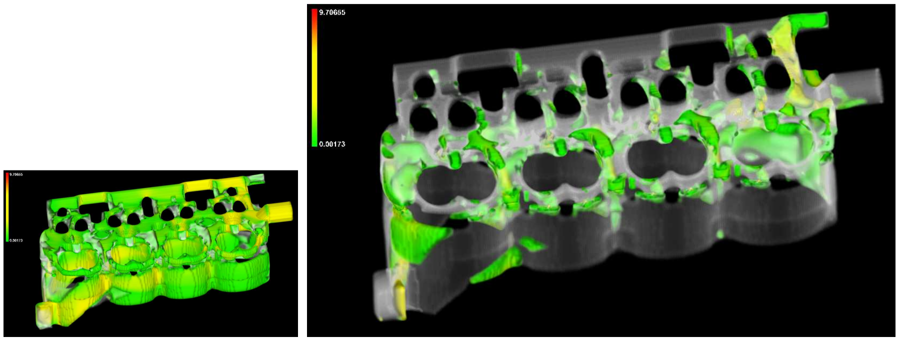

Fig. 1.3. (left) The visualization of all regions of forward-longitudinal flow. Color-mapping reflects velocity magnitude. (right) The result of selecting all regions of reverse-longitudinal flow, the inverse of the left selection.

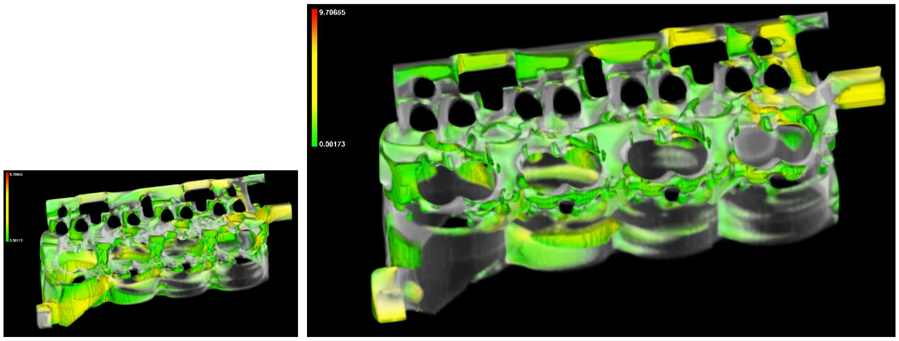

Fig. 1.4. (left) The visualization of all regions of forward-transversal flow. Color-mapping indicates velocity magnitude. (right) The result of selecting all regions of reverse-transversal flow, again the inverse of the left selection.

data subsets are then rendered as the visually emphasized focus in a focus+context visualization style. In the following, we describe the use of SimVis in order to answer the questions outlined above by the engineer.

Extracting Forward and Reverse-Longitudinal Flow

Figure 1.3 (left) depicts the result of selecting all positive x-velocity values via smooth brushing. The positive x-velocity component is aligned with the longitudinal flow direction. Thus all regions containing a positive x-velocity component are flowing, at least partially, forward with the goal of traversing the shortest path from inlet to outlet. Figure 1.3 (right) shows the result of selecting all negative x-velocity values. The right image is more interesting to the engineer. It shows precisely those regions in the geometry where the flow is moving in the opposite direction from that which is desired. Here, the forward-longitudinal flow fills 76.2% of the volume ($\pm 1\%$) whereas reverse-longitudinal flow occupies 18.4% ($\pm 1\%$). This is not a bad

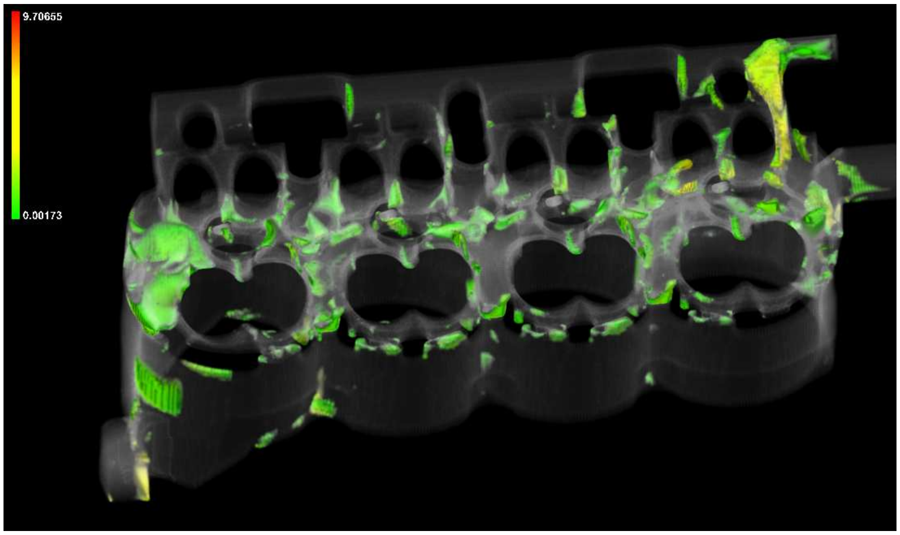

Fig. 1.5. The result of selecting all regions of reverse-longitudinal flow *and* regions of reverse-transversal flow.

forward-to-reverse flow ratio, but still significantly different from the ideal. It is interesting, for example, to see a region of reverse-longitudinal flow immediately near the inlet, representing a major recirculation zone.

Extracting Forward and Reverse-Transversal Flow

Figure 1.4 visualizes both forward and reverse regions of transversal flow. Essentially, engineers are mostly interested in seeing where in the geometry the ideal pattern of flow is not being realized, e.g., in the right figure. Figure 1.4 (right) reveals many regions of flow that are traveling downward, or rather against the ideal current of flow. In fact, the amount of forward-transversal flow is only 54.6% $(\pm 1\%)$ while the amount of reverse-transversal flow is 37.7% $(\pm 1\%)$. The amount of reverse-transversal flow is considerably higher than what we expected. A major region of reverse-transversal flow, for example, can be seen in the second cylinder block (from the left). We see regions of reverse-transversal flow again at the inlet.

We can further refine the region of interest by including only velocity values with negative x- *and* negative z-components. Figure 1.5 depicts the regions where flow moves backward and down instead of the shortest path – up and forward from inlet to outlet. From this result, we can deduce that flow through the cylinder head is a complex patchwork of flow, especially along the center of the head.

Extracting Regions of Stagnant Flow

Figure 1.6 illustrates regions with a velocity value, $|\mathbf{v}|$, of less than 0.1 m/s. We know that regions of stagnant flow, like those in Figure 1.6, are less effective in transporting

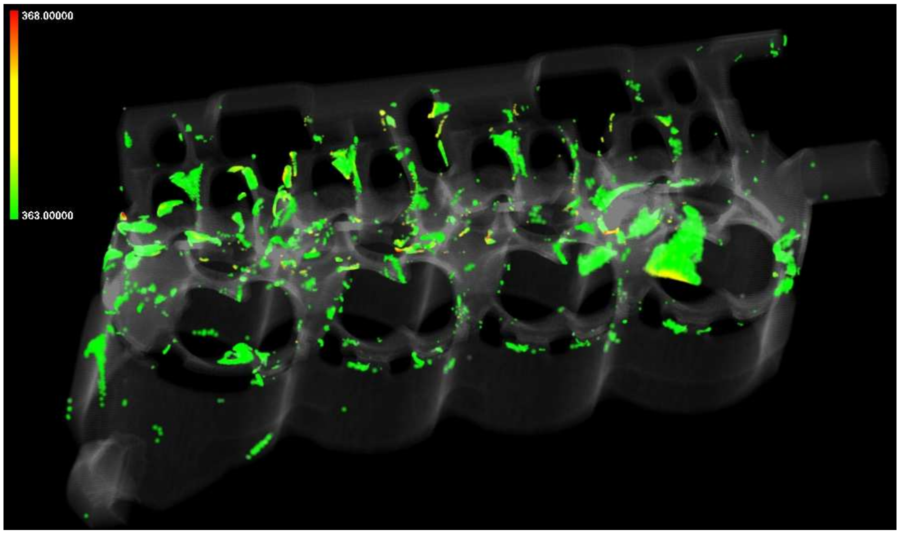

Fig. 1.6. A feature-based, focus+context visualization showing regions of near-stagnant flow, specified interactively.

heat away from the engine. The color-coding in Figure 1.6 indicates temperature. The optimal fluid temperature, $363°K$, is mapped to green and higher temperatures are mapped to red. This visualization result indicates that there are very few, small regions where low velocity and high temperature coincide – an advantageous design characteristic for an engine part designed to transport heat away.

Figure 1.7 further refines the feature specification by also restricting the focus to high temperature values. The new feature is defined as:

$$(|\mathbf{v}| < 0.1m/s) \cap (364°K < t)$$

The result in Figure 1.7 is a less cluttered image, showing undesirable regions, where slow flow and hot flow are apparent. These regions are less effective in transporting heat away. Fortunately, these regions seem to be rather small, thus, from a heat-transfer point of view, the simulation results point toward a good design. Areas of very high velocity, leading to cavitation, can be identified in a similar way.

Considering the above described analysis, we state, that obviously also other options for the investigation of the properties of this particular application scenario exist. Alternatively, an engineer also could pick a simulated measure of heat-flux and analyze the data with respect to this data attribute. The Nusselt number [19] or the heat transfer coefficient [1] could be used if available from the simulation.

1.5 Semantics-Based Segmentation of Flow

What we have done in Section 1.4 is essentially a segmentation of the flow based on semantics. Such semantics-based segmentation is standard practice in many other

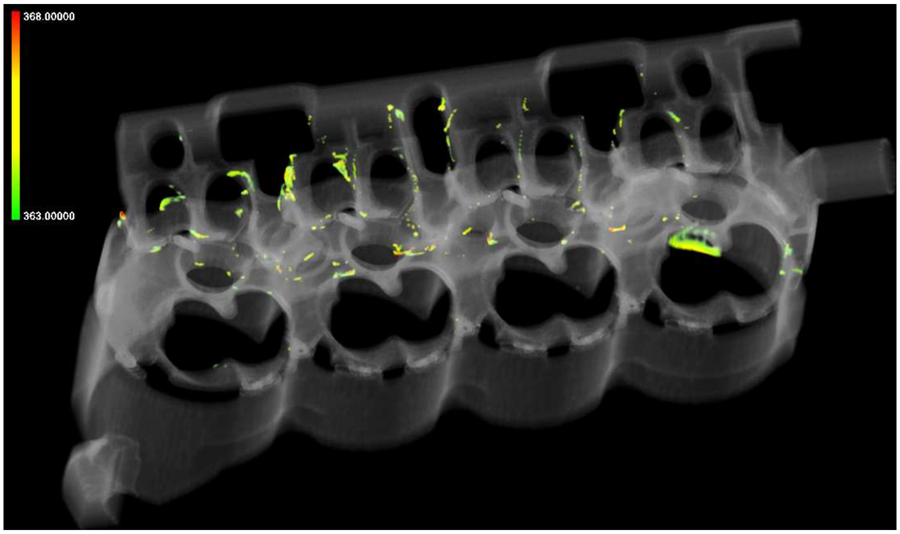

Fig. 1.7. Areas of temperature $t > 364°K$ and velocity $|\mathbf{v}| < 0.1m/s$ are interactively-specified by the user and rendered in focus.

fields, e.g., in medical visualization. A notion of objects or regions (or the like) is generated on top of the raw data which is more meaningful to application experts.

In the above discussed example, the flow domain has been segmented according to different components of the flow direction. In this particular context, each of the Cartesian velocity direction has a specific meaning. The semantics are based on the questions posed by the engineer in Section 1.3. One speciality here, however, as compared to other standard domain segmentation approaches, is that smooth region boundaries are considered (smooth brushing [4]). Another speciality here is that we have employed multi-variate segmentation in our analysis, i.e., selections with respect to multiple attributes.

When we compare this approach with the classical topology-based approaches, we claim that interpretation of the results is easier and clearer to the user (at least in many cases). Improved comprehension of the visualization seems to result from (a) a step-by-step extraction process with steps easy to understand and (b) an approach which per se associates well with the way the users think about their data (in terms of the attributes rather than in complex terms of flow topology).

1.6 Topology-Based Flow Visualization in Industry

Unlike direct flow visualization such as color-coding of velocities, or geometric techniques like the use of streamlines or isosurfaces, topology-based flow visualization methods not really have made their way into common commercial flow visualization software. Why not? In a manner inspired by Globus and Raible [7], we try to list some possible answers to this question. We note that a similar theme is addressed by Van Wijk [18] about the value of scientific visualization in a broader sense.

1. The advantage of extracting meaningful, high-level abstractions from flow data (such as topological features) at the same time seems to be a disadvantage, also: Higher levels of abstraction are more difficult to understand and can cause problems with their interpretation. More cognitive work is required at the user side.
2. Topology-based methods usually are not easy to implement. The extraction of topological features can be challenging in unstructured grids, in higher dimensions, from noisy datasets, and also with respect to robust numerics. From a computational point of view, for example, it is very challenging to properly compute the separatrix structure of a 3D vector field [11]. When Galilean-invariant solutions are required [14], many existing techniques fail. Also, the dependence of extraction results on the turbulence models employed in the simulation makes interpretation difficult in some cases.
3. Development and use of topology-based methods are expensive; costs include:
   - An initial development cost, including one or more engineers, possibly also the acquisition of new hardware.
   - An initial cost per user – topology-based analysis techniques usually are not intuitive to use; also, in a highly specialized environment, tools sometimes lack optimal GUIs and their usage requires special training.
   - Costs per session/use, including the time it takes the user to generate the required visualization from a given algorithm or method each time of use.
   - The cost of cognition, i.e., the time the user needs to understand and explore the visualization result to gain insight into the underlying data.

   Taking into account that many application questions also are solvable with more simple approaches, costs also might be responsible, why topology-based methods are not so often used in practive.
4. This tightly relates to the question whether a topology-based solution is a ”must have” or a ”nice to have” – it is much harder for the latter to establish itself on the market; in this case the cost-question (see above) plays a much more important role than in the ”must have” case.
5. As already mentioned, it is often also possible to solve the same problem with other, more simple methods. Given a suitable seeding strategy, streamlines may be used to visualize critical points in a planar domain, for example. An explicit extraction computation is not always required.
6. Lack of communication between communities also might be responsible. These days, there is quite a gap between the visualization research community and prospective users (they usually do not visit the visualization conferences, for example). In fact, other communities such as the engineering analysis community are not even aware that a visualization community *exists*. Closely related is the lack of inter-community knowledge transfer and a lack of educational literature.
7. Lack of customer demands: Software development in industry usually is driven by customer demands, i.e., customers who demand new features of the software.

Surely, some of these problems can be solved. The last problem on the list, for example, might be addressed when more motivation for inter-disciplinary communication is generated. The problem of difficult implementation may be solved with more time invested in research and development. Often algorithms, which present an easier and more elegant solution to a problem that originally required a very complex solution, are published at later points in time in a larger community. Clearly, visualization solutions with less complexity are needed as well as more communication between fields of expertise.

The above list summarizes some of the challenges that topological methods must face before being incorporated on a more wide-spread basis. Does this mean we should stop topology-based visualization research? No. The original motivations for this line of work are more prevalent than ever. Data sets grow at faster rates than hardware and this trend promises to continue. Data, especially CFD simulation data, is becoming ever more complex. The demand for tools that can help the user sift through this complexity will only increase. The research field of topological analysis is still relatively young, thus much work remains to be done.

Acknowledgments

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