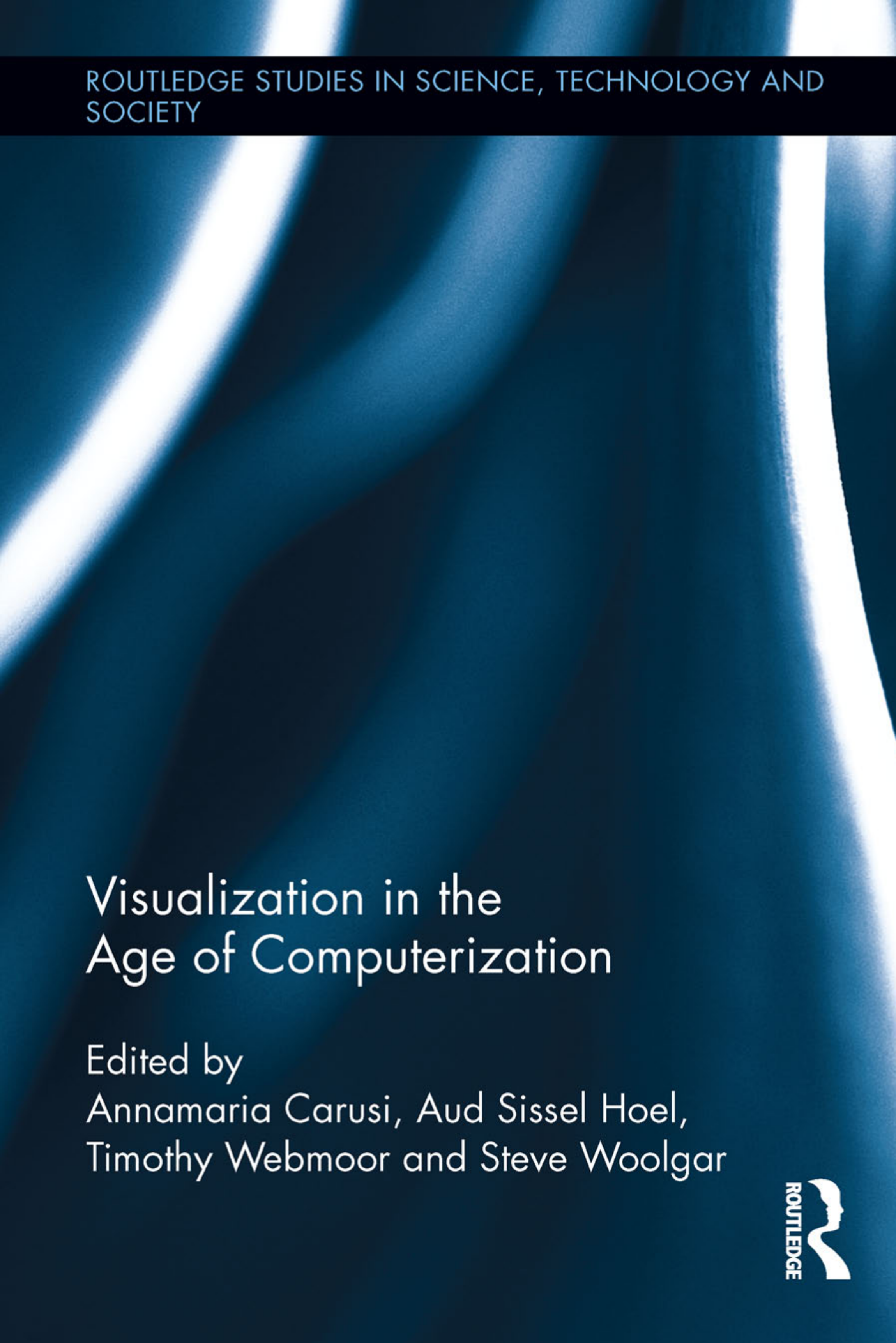

ROUTLEDGE STUDIES IN SCIENCE, TECHNOLOGY AND SOCIETY

Visualization in the Age of Computerization

Edited by
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4 Redistributing Representational Work

Tracing a Material Multidisciplinary Link

David Ribes

INTRODUCTION

Traditionally, we understand multidisciplinary links to be the work of human relationships across domains of heterogeneous expertise—for example, bringing together biologists and physicists in order to understand genetics (Kay 2000), or a collaboration between computer scientists and geologists as a means of framing a new understanding of geoinformatics (Ribes and Bowker 2009). This human focus directs our attention to questions of communication, shared language or diverging understandings (Galison 1999; Jeffrey 2003). From this perspective, technology plays a supportive role in human collaborations—facilitating communication across domains, time and/or space (Olson, Zimmerman et al. 2008). Yet multidisciplinarity does not rely solely on a human-to-human links: Frequently, technology plays a leading role in collaboration across disciplines. In this chapter, I focus on how technology becomes the multidisciplinary link, sustaining relations across domains of scientific expertise that are not centered on human-to-human ties (Ribes, Jackson et al. 2012).

While produced through multidisciplinary collaboration, certain representational technologies can become relatively autonomous of the initial human-to-human relationships responsible for their creation. Through visual output, multidisciplinarity can also be structured through representation tools—technologies that continue to carry a history of their development over time. By tracing the production of visualization systems, such as those used in the sciences and medicine, we as analysts must also travel across multiple disciplinary boundaries. This chapter is one such journey: the exploration of a distinct multidisciplinary link, in the end tied together not by the human-to-human collaboration of heterogeneous experts but by the development, and thereafter use, of technology.

Multidisciplinary relationships sustained through technology restructure how we should think about knowledge production. In visualization studies we have come to consider representational technique as tied to scientific knowing. For example, in his classic study of visual representation in geology, Martin Rudwick claimed that we should take the "development of the visual language of geology not only for the way that it gradually enabled the concepts of a new science to be more adequately expressed, but also as a reflection of the growth of a self-conscious community of geological scientists" (Rudwick 1976, 151). Visualizations, from this perspective, are a shorthand for epistemic commitments. But with the redistribution of representational work—by "outsourcing" of the methods of representation to a group external to the domain—we are witnessing the reconfiguration of scientific relations of knowledge production (Latour 1986; Hutchins 1995; Suchman 2007). Programmers and their software output now mediate between the practices of data generation and their analysis as visual images.

This chapter is structured as follows. I first introduce today's visualization researchers and the double trajectory of their research output: These scholars are both publishing research findings and producing visualization software. Using a case of visualization research that seeks to "capture" existing artistic techniques to inform the design of novel visualization tools, I trace the work of "Marie" as it follows two distinct trajectories: 1) published findings as academic research and 2) the production of data visualization software used in the sciences. In the first trajectory—publication—Marie reflects critically upon her research design, as is common with experimental research. That is, in her papers Marie identifies flaws or weaknesses in her empirical research and experimental approach. However, in the second trajectory her research is built into visualization tools that circulate across disciplinary boundaries. Scientists using these visualization tools in their research have little, if any, knowledge of the experimental problems that Marie encountered in the tool's development. It is the gap between the first and second trajectories that interests me: The methodological problems outlined within her published research are difficult to identify in her visualization software. In the second half of this chapter I follow Marie's code itself as she translated it across multiple sites of application. While the algorithms described in this chapter were initially intended for visualizing cancer treatment regimes, their "social life" did not end with a single application. Marie works with many disciplines, and her visualization tools travel with her. Findings from visualization research and code from visualization software were reassembled for use as data visualization software in new settings. With each such translation across disciplines, the origins of the production of software tools become increasingly difficult to discern.

While we usually consider scientists to be the arbiters of their own representational techniques, in Marie's case I find a distinct rupture between tool development and its use. Visualization tools not only sustain the multidisciplinary relationship between visualization scholars and scientists but also hide, or render invisible, the problems faced in their development from those who use these tools.

VISUALIZATION RESEARCHERS

In 1963, Ivan Sutherland produced what is often cited as the first computer graphical user interface (GUI) as part of his dissertation, entitled "Sketchpad: A Man-Machine Graphical Communications System." Sketchpad, a system for computerizing the practice of drawing and design, was displayed on a monitor utilizing a physical interface of a light pen, switches and knobs. Sutherland innovated techniques such as memory structures in order to store objects; the rubber banding of lines; the ability to zoom in and out on the computer display; and even the ability to make automatically rendered lines, corners and joints. These techniques—now familiar to any user of low-end drawing or painting programs—also remain the staples of all forms of computer-aided design (CAD).

Today, fifty years after Sutherland's innovation, his "new science" is in full swing. An entire subdiscipline of computer science (CS) and information technology (IT) has emerged dedicated to the production of digital visualization tools. These programmers, or at least their software products, now mediate between the activities of generating data and producing knowledge; this software operates in the interstices between data collection and the dissemination of scientific knowledge. In other words, visualization researchers create the tools for translating specific information into meaningful images for those in the sciences and engineering. Visualization researchers—or more specifically, the tools they build—stand between "raw data" (Ribes and Jackson 2013) and their meaningful interpretation.

Whether the design practices explored in this chapter are considered a science of computing or a sort of engineering, creators of visualization tools are not programmers alone, but also empirical researchers. Visualization experts are trained in many fields (e.g., engineering, mathematics, computer science, information science, etc.) and draw from a wide variety of heterogeneous disciplinary traditions, as evidenced by their idiosyncratic backgrounds. In the US, thousands of such researchers congregate annually at conferences on interface design (e.g., CHI) or computer graphics (e.g., SIGGRAPH), demonstrating their findings, doing proof-of-concept demonstrations or demonstrating commercial visualization tools. They may participate in fields such as human-computer interaction (HCI) or publish in specialized visualization journals. Their success in these fields is often tied to publication *and* to producing novel tools for visualization.

Visualization researchers may very well have a professional interest in the psychology of perception, the biology of the eye and brain or even techniques of illustration. For them, each of these activities or interests can inform how humans see and render imagery. In this sense, visualization researchers should be understood as sitting at the intersection of two diverging trajectories: 1) empirical research contributing to theoretical understandings of perception,

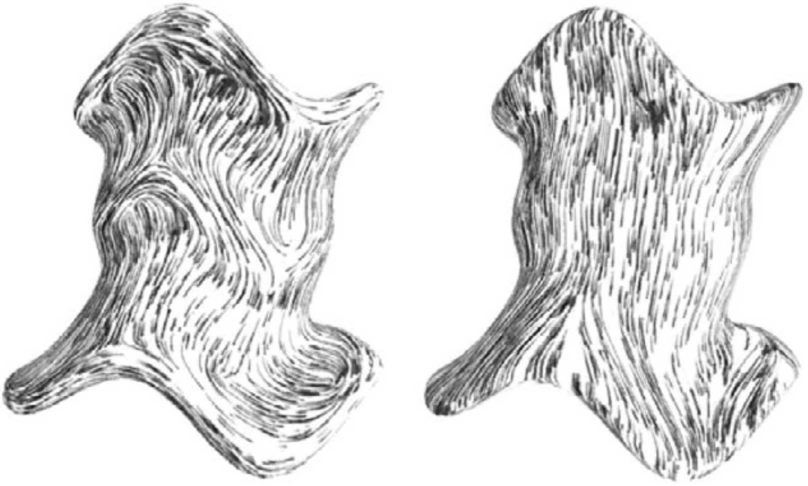

Figure 4.1 Two examples of Marie's work in the application of texture-mapping to a single surface. Which is more *effective*? © 2003 IEEE. Reprinted with permission from *IEEE Transactions on Visualization and Computer Graphics.*

visualization, image interpretation and human-computer interaction and 2) efforts to produce novel visualization software.

The software products of this second trajectory may come to be a tool for researchers in another scientific domain as they conduct data analysis. It is this transition that interests me. In this chapter I trace those visual rendering techniques that were once the *object of visualization research* and thereafter became the *tools for data representation in sciences and medicine*.

This chapter highlights one computer scientist, "Marie," who conducts research for the purpose of creating visualization tools. I do not claim that Marie "stands-in" as a representative for her field as a whole; instead, I chose her specifically for the range of methodological approaches she applies to visualization research, and to illustrate the unique connections she builds between techniques of visual rendering and contemporary scientific practice.

Marie's inspiration is the sophisticated use of technique in the arts. Her research focuses on applying insights from visual perception, art and illustration to the design of more effective techniques for data visualization (See Figure 4.1). She is in contact with disciplines as diverse as psychology, biology, art history, statistics and, of course, her own domain of computer science; her methodologies reflect this particular blend of multidisciplinarity. As Marie explains, her interests are grounded in *formalizing the knowledge and practice of arts and design and then incorporating this knowledge within information systems*. These inspirations come to be "captured" within the systems she designs.

The computer sciences do not often teach empirical methodologies, and in the case of Marie, it is largely her concordant training in experimental psychology that informs her empirical research. One of her main foci has been the study of texture's effect on the perception of shape and the use of texture-synthesis for shape representation, or, more specifically: the study of texture perception and classification for texture-synthesis in multivariate data visualization. In other words, how do you represent data as surfaces in order to maximize perception of topology?

Marie is both a scientist and an applied researcher: Through shared funding or contract work, she collaborates with biological and medical researchers to develop tools that support their work. In the first half of this chapter, I follow the development of one tool initially intended to represent the time lines of radiation exposure in cancer treatment. However, as we will see in the second half of this paper ("Mobile Code"), Marie also uses these same findings and software creations to produce tools for very different purposes: specifically, software that can represent the structure of veins and nanoparticle flows. Her tools travel with her as she works across disciplinary boundaries and domain applications, as well as across federal research grants and private collaborations.

Rather than positing "influence," "cultural diffusion" or loose borrowing, I follow the chain of productive work from analog to digital media, through research practice, and then programming. It is this productive work that links such diverse domains as design, HCI, visualization, laboratory practice and scientific publication. In the software products of visualization work, multidisciplinary links are maintained through the work of automated material relations.

CAPTURING THE ARTS AND DESIGN

This section outlines how artistic and illustrative techniques come to be scientific research objects, showcasing how Marie subjects them to experimental conditions. Marie reveres artists' ability to effectively render surface. She takes artists, as well as art and art history, as an enormous repository of informal knowledge to be systematized: "Observation of the practices of artists and illustrators provides a rich source of inspiration for the design of more complex and possibly more intuitively appealing methods for translating data into pictures" (publication).

As a computer scientist, Marie tasks herself with placing artists' informal, tacit or embodied knowledge within information systems. Drawn from an oral conference presentation, in the following excerpt she neatly encapsulates the goal of automating visualization:

> I went to St. Paul's Library and I was looking at these textbooks on fabric design and quilting and looking at these incredible pictures where

> they'd taken fabrics of different colours and textures and they had woven them into these beautiful artworks. And they were all different *and they all worked*. And I was trying to think, why is it that some things work and some things don't work? And I was trying to think can we measure this mathematically, so that people like me, who have a little bit of intuition but maybe not a lot of intuition, can maybe get a hand in trying to figure out something that works, how to choose something that works? But the problem is right now I'm having trouble figuring out what kind of statistics to use, and what the correlation is. (Conference presentation, emphasis in original)

To sum up, she took inspiration from the adept use of visual techniques used in art—something she viewed as an artist's sheer effectiveness in conveying a message. Subsequently, she sought to harness these skills to serve not only her own nonartistic practices but also those of her collaborators in the sciences.

However, capturing the arts is a complex endeavor. In this process art, art history and artists themselves become objects of the scientific gaze. Art and design techniques were the scientific objects on which Marie intervened. Art was made an analyzable object by subjecting it to the various techniques available to empirical research. Marie worked to make artistry (textures) researchable by embedding them within a distinct *experimental system*—an assembly of the research object, scientific discourse, instrumentation and practice (Rheinberger 2000). Experimental systems allow scientists to intervene with, to shape and to represent scientific objects. They embed scientific objects into a broader field of material scientific culture and practice, of instrumentation and inscription devices.

Marie used the methods of perceptual psychology for her studies. She brought art into an experimental context: "Research in perceptual psychology provides a rich source for insight into the fundamental principles underlying the creation of images that can be effectively interpreted by the human visual system" (publication). Inspired by texture use in medieval art, Marie selected a variety of sample patterns—these became "stimuli" in the language of perceptual psychology—and mapped them onto computer-generated surfaces. She took physical samples of medieval tapestries and digitized them using a high-fidelity scanner, and then created simple algorithms that allowed the strategic placement of these patterns on topological surfaces:

> The stimuli that we used in our experiments were cropped images of the front-facing portions of textured level surfaces rendered in perspective projection using a hybrid renderer . . . that uses raycasting . . . together with a Marching Cubes algorithm . . . for surface localization. (Publication)

The particular topological surfaces she chose to represent were "three dimensional dose distributions calculated for a radiation therapy treatment plan" (publication)—these are a medical representation for determining a time line of radiation exposure levels as part of cancer treatment. The particular set of experiments she described here was conducted in conjunction with funding to develop this application. The surfaces were selected because rendering software would "typically be" this sort of visualization:

> We chose to use the radiation data as our test bed, rather than a more restricted type of analytically-defined surface, because this data is typical of the kind of data whose shape features we seek to be able to more effectively portray through the use of surface texture. (Publication)

Marie generally works on data that, when visually represented, form a plane rather than a discrete object, or, as she puts it, where "shape-edge is not an available cue" (publication). Any object seen up close does not have edges; to perceive its shape, other cues must serve to render form, such as texture. See, for example, Figure 4.2, which includes a shaped surface with no edges. Thus, while Marie's application is specific (radiation exposure time lines), she was interested in a more general outcome (representing data without shape-edge cues). This focus was Marie's basis for generalizing her rendering tools across specific applications, a topic I return to later in the paper ("Mobile Code").

To test the effectiveness of texture in facilitating the perception of a shape without edge-cues, Marie and her research team first recruited a population of thirty "properly controlled" subjects. In two-hour-long trials for each of the thirty participants, subjects were asked to observe six computer-generated topological surfaces, each coated with digital "probes" that could be adjusted by "pulling on its handle until the circular base appear[s] to lie in the tangent plane to the surface at its central point and the perpendicular extension appear[s] to point in the surface normal direction" (publication; see Figure 4.2). Each surface was texture-mapped using various rendering algorithms drawn from real-life samples, such as wall hangings, paintings, sketches or even woven cloths.

The experiment yielded quantitative statistical results measuring the accuracy of the subject's ability to perceive topology. To understand and, most importantly, pinpoint the most effective textures, Marie compared the data, finding trends and generalizations across both the subjects and the various texture-maps (see Figure 4.2).

The results of Marie's experiment supported her "hypothesis that texture pattern anisotropy impedes surface shape perception in the case that the direction of the anisotropy does not locally follow the direction of greatest normal curvature" (publication). Or, put somewhat more straightforwardly, Marie found that human subjects could distinguish shape best when lined patterns are used, and specifically, if those lines went against the grain of curvature.

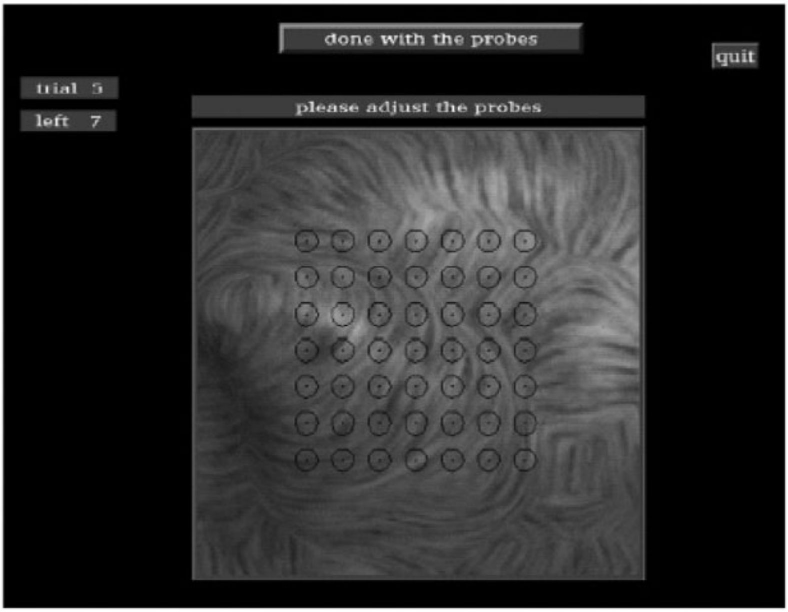

Figure 4.2 A texture-map used in one of Marie's experimental systems. Forty-nine "probes" appear on the map, as depicted by the dots within the circles. The user can adjust these to line up his or her perception of the topology. The surfaces themselves acted as 3-D renderings of radiation therapy exposure treatments. Reprinted with permission from *SPIE Proceedings*.

One may ask, "How could art be captured? Its qualities are sublime." But from the designer's perspective, this is a somewhat Romantic formulation. In fact, Marie acknowledges that it is not the ineffable qualities of "art" that are necessarily captured in automated systems, but rather the representational techniques that make them up:

> Visualization differs from art in that its ultimate goal is not to please the eye or to stir the senses but, far more mundanely, to communicate information—to portray a set of data in a pictorial form that facilitates its understanding. (Publication)

Scientific visualization does not seek *only* to "represent reality"; this is but one of its many concerns (c.f. Lynch and Edgerton 1988). "You need to be able to see something new, or even something easier, and sometimes that even means seeing something *wrong*—because domain experts don't just see my visual they also see everything else they know." Marie's visualizations seek to allow certain *kinds* of seeing that inform, while at the same time sustain, an orthogonal concern for reality. It is the interpretation of data (i.e., human perception of topology) that she seeks to facilitate: "The ultimate success of a visualization can be objectively measured in terms of the extent to which it proves useful in practice. But to take the narrow view that aesthetics don't matter is to overlook the complexity of visual understanding" (publication). Rather than capturing artistic technique, what interests these researchers is building a close tie between human perceptual systems and data (Tufte 1986).

Two Streams of Output: Publishing and Application

Marie, in addition to being interested in capturing art and design practices, is also application oriented. The study of the arts—textures and their relation to human perception—eventually comes to inform the construction of visualization tools for science and engineering research. Marie's research feeds into academic publication *and* the production of software for science, medicine and engineering, thus producing two distinct streams of output. Beyond those interventions to make artistry accessible to the scientific gaze described earlier, findings must be embedded within the software suites that are intended to render data as image—what the computational worlds call *applications*. It requires a very specific articulation, or what programmers call *coding*, to render the findings of research into machine language. Thereafter Marie's research was "applied," and her output is executable as a software algorithm.

Marie was capturing artistic technique *and* closely tuning a product to an existing stream of scientific practice. The study discussed earlier informed the design of a tool to visualize radiation exposure time lines for cancer patients. Marie worked closely with her various collaborators to ensure the particular visualization tool would be useful—that is, that it functioned with their current operating platforms, or that the interface achieved a balance between configurable and accessible.

Transitions between capture and coding have often been complicated for Marie. A scientific object, here art and design practice, may resist particular techniques of capture and representation. Marie encountered difficulties in producing "clean results" from her perceptual experiments. However, such problems were still several steps removed from application; they were still concerned with human perception:

> The root of our difficulties was that too many of the points on our surfaces were too near to being parallel with the image plane. In numerous incidences the angular deviation in tilt was degenerate, because the estimated normal projected to a single point, and it was not clear how to appropriately handle these cases. We could not simply exclude these samples from our error calculations, because their occurrence was not uniform but tended to predominate in "bad texture" conditions, where the cues to shape were inadequate and subjects reverted to the default assumption that the surface lay in the plane of the image, or subjects

> simply gave up in frustration and left the probes untouched at their default original positions. (Publication)

To rephrase: The grid of probes that Marie set upon the texture-map created a flat plane relative to the computer monitor (see Figure 4.2). In the experimental trials, portions of the texture-map appeared to run parallel to this plane, confusing the subjects who then often left the probes unadjusted. Because the problem was exacerbated in those cases that use poor topology emphasizing textures (the *object* of Marie's study), she was unable to simply remove these outliers. Marie's solution was to abandon traditional quantitative technique in favor of less accepted statistical methods, which nevertheless yielded poor results: "We therefore reluctantly decided to break with tradition and simply use as an error metric the angle in $\Re^3$ between the estimated normal direction specified by the probe and the true surface normal direction at the probe center" (publication). Marie described this statistical technique as a "fallback position" that is notably weaker: "If you are a statistician, or experimentalist, you can read between the lines of what it means to use this [error metric]." Only by careful massaging of the data, through analytic approaches, and by tailoring of subjects' responses did she achieve relatively clean results for this experiment.

Here we can begin to trace the two distinct trajectories for Marie's findings: publication and application. It is a well-established tradition within experimental science, when writing up a paper for publication, to present both the weaknesses in design and avenues for future research. In this tradition, Marie provided a critical analysis of her own work in her papers. Her critiques were of the effects of measurement/probing on the subjects, and the limited use of textures:

> Unfortunately, we neglected to recognize, before beginning the experiments, that our decision to place the probes at exactly evenly spaced intervals over a rectangular grid would interfere with observers' ability [to] perceive all of the probes as lying in the surface at the same time, due to violation of the generic viewpoint assumption. (Publication)

Marie divulged to her readers that the probes placed in a regular grid pattern on the "surface" of the texture-mappings—intended to measure subjects' perception of topology—are almost certainly contributing to the perception of shape. Secondly, the patterns used were themselves relatively simple: six variations that map lines in relation to topology. Finally, Marie admitted that her statistical analysis may not have been up to the task of determining clear results: The statistical significance was positive but relatively low, and she had not yet devised a sophisticated analysis of individual mean results. From a scientific viewpoint Marie noted that there is a great deal of room to devise a more sophisticated experimental design for the development of more complex mapping algorithms and that current statistical techniques were inadequate for the task.

And yet her experimental system produced results. As we have seen, despite complications, she still felt able to conclude that "texture pattern anisotropy impedes surface shape perception in the case that the direction of the anisotropy does not locally follow the direction of greatest normal curvature" (publication). Marie *did* develop a series of texture-mapping algorithms. She also invested the time and effort to experimentally test which of these algorithms produced a maximization of topology identification accuracy in subjects. But her data were admittedly flawed, and there were clear avenues for future research. Did Marie wait for more definitive results before embedding her work in computer programs? In this case, no.

In a practice-driven field like human-computer interface, where career rewards are tied to production as much as publication, Marie chose to develop applications from her visualization research data. Moreover, her experimental work was tied to a particular usage: She was building visualization devices to assist medical practitioners in planning cancer therapy schedules—this was a professional relationship between medicine and computing that operated on a schedule independent of refereed publication. In scientific research it is not rare for the results of an experiment to remain inconclusive, but in her software engineering practice Marie must occasionally forgo maximizing understanding of visual acuity in order to satisfy production requirements—that is, make a useable tool.

There is a split between Marie's academic publishing and system design. She is contributing to a body of scholarly work by publishing in the refereed journals of a community of experimental perceptual psychologists. This work is reviewed and critiqued, revised and resubmitted. Her methods are open to evaluation, and Marie made public a self-critique of her experimental approach. But Marie is *also* contributing to a repertoire of technology, to a software visualization program. Marie incorporated her findings into an already existing visualization suite; this program will now automatically determine what texture pattern to overlay on a topology to maximize visual acuity.

The trajectory of this scientific object– texture perception—concluded with its introduction to a new experimental system. Her visualization tool is now used by medical scientists to analyze data and make determinations about treatment regimens. The end result of the automation of art visualization is the background incorporation of these techniques within computer applications. Artistic technique and design-practice were delegated to computer applications and incorporated within scientific and engineering practice in order to render data. Marie's textures from a renaissance wall-hanging, once her object of study, were translated into scientific findings intended to become the tools of scientific data visualization. Historian of science Hans-Jörg Rheinberger points out that "*things*" cease to be scientific objects as they lose their recalcitrance, their resistance to manipulation and predictability. Once they are *sufficiently* malleable to scientific practice they take on a new life, which he describes as "both marginal and central" (Rheinberger 2000, p.275). In the case Rheinberger explores of cytoplasmic particles, these entities became marginal in that they were less the object of scientific scrutiny and investigation and instead became newly central as the platform for further scientific research. That is, cytoplasmic particles became the tools for investigating new phenomena.

This is very much the case in the automation of visualization, where a particular representational schema is initially the object of research for a computer scientist but later, as it becomes incorporated into visualization tools, becomes the platform for research within another science. In this transition, the various uncertainties about this mode of texture representation are largely left behind. The experimental system remains only in traces, all but invisible to a user of the visualization software, and this original output itself becomes a tool for scientific or design visualization, central as another experimental system in the research projects of a domain science.

Marie's research work was simultaneously published in refereed journals, but was also placed in circulation through their designs as visualization tools, resulting in two distinct trajectories for her findings. Neither trajectory ended at findings: Following publication, the trajectory of an article continues as citations within related academic disciplines, standing in as markers for advances in representational capacity and method in computer science. But the trajectory of the representational tools followed another path, as they were used within the research of scientists. As we will see, Marie's rendering algorithms not only were used for dosage regiments but also came to be incorporated into the experimental systems of other kinds of scientific researchers, broadening the span of this material multidisciplinary link.

Mobile Code—Tracing the Multidisciplinary Link

The production of texture in Marie's work is only a piece of a visualization tool; in sum, a plethora of additional code is necessary to configure and render a full image. The particular visualization software features that I have traced in the first half of this chapter are not a whole rendering device, but merely individual algorithms among the many required. Much of this code will be borrowed, with modification, from previous applications.

Marie describes algorithms and tools as relatively mobile and adaptable: while many of her studies are tied to application *as well as* pursuing a research interest, each application does not "begin from scratch," she draws from past findings and on code from previous applications. With expert work, code can be transferred from one visualization application to another (Rolland and Monteiro 2002; Pollock and Williams 2008) just as many visualization specialists themselves move across domains.

In the case of Marie, the empirical studies that led to the creation of a tool for rendering images of medical dosage regimes later informed the production of a tool for visualization of vein topology. With what Marie described as "some tweaking of the code," her texture algorithms designed for representing dosage regimens were later utilized for producing an internal view of vein structure. Marie justifies this movement, or, more precisely, explains the logic permitting movement across disciplines, through the articulation of similarities between the data:

> Because we designed these algorithms by excluding extrinsic shape-markers [i.e., edges] in studying how the presence of texture might facilitate shape judgments across non-trivially structured interior regions where shape from contour information is not available, we understood the algorithm to be useful in cases where shape-edge is not available as a perceptual cue. (Publication)

The vein-structure data Marie modeled were taken from sensors placed within bodies. The sensors were thus "enveloped" in the body and could not provide data as to edges, or other extrinsic topology markers—this is the same case as with her original topology perception experiments that excluded markers such as shape. For Marie, these topological data generated comparable perceptual difficulties and thus their representation could be aided by using similar rendering techniques. Over the years she has built up a repertoire of "functionalities" alongside her research findings. Just as her findings build up over time, so too does her code base. Each finding in research inspires the writing of rendering code that operates according to the principles of that research.

The "functionality" of texture rendering described in the previous two sections was originally developed for permitting medical practitioners to visualize treatment regimens. Thereafter, Marie also worked closely with, for example, nanotechnologists in order to produce a similar effect with particle flows: maintaining a sense of particle movement without rendering cues such as edges. She described how selected portions of the program for visualization were transferred from one application site to another, with local adaptation traveling with Marie across received boundaries of disciplines and expertise. Marie recounted a familiarity with her own code and how this facilitated its incorporation into new applications. Her repertoire of code was amassed over time, each element informed by a particular empirical research project and application, but then "traveled" with her to new projects.

Here is a list of eight articles, in reverse chronological order, published by Marie and her coauthors:

1. Directional Enhancement in Texture-Based Vector Field Visualization
2. Illustrative Rendering Techniques for Visualization: Future of Visualization or Just Another Technique?

3. Visualization of Nanoparticle Formation in Turbulent Flows
4. Conveying Shape with Texture: An Experimental Investigation of the Impact of Texture Type on Shape Categorization Judgments
5. Line Direction Matters: An Argument for the Use of Principal Directions in 3D Line Drawings
6. Visualization Needs More Visual Design!
7. Art and Visualization: Oil and Water?
8. Strategies for Effectively Visualizing 3D Flow with Volume LIC

The ranges of her domain applications are quite broad. From the titles alone it is easy to see that her empirical applications in research are extraordinarily diverse, including the flow of nanoparticles (1,3), scheduling cancer radiation treatment (4,5) and mapping vein topology (4). Marie does display consistent interests, such as position papers on rendering with no direct reference to empirical applications (2,6,7) or theoretical discussions of how texture impacts shape perception (1,2,3,4,5,8).

These applications are from differing disciplines, departments and knowledge domains, tied together only by an underground stream of visualization technologies. While the fields of application are diverse, requiring expert domain science training, the particular visualization algorithms are not necessarily so. A flow representation for nanoparticles was informed by the same findings—and some of the same code—that was used for planning radiation exposure as part of cancer treatment.

Marie's algorithms may become incorporated in data visualization programs for domain scientists in innumerable academic and industrial fields. In using a data visualization produced by Marie's algorithms, her past work of capturing human perceptual properties vis-à-vis texture, of coding her findings or adapting previous code will be completely obscured from end users. These programs will produce detailed texture-maps that are intended to maximize particular topological features to the human eye. In each case of application to a new domain Marie describes ongoing interactions with domain scientists as she tailors her software for application. It is beyond the scope of this paper to explore these local modifications; instead I have focused on the backgrounded work that is common to all the applications (Pollock and Williams 2008). From the perspective of the trajectory I have explored in this chapter, each rendering can be taken as the end point in a long genealogy of technology design.

SINKING DEBATE INTO INFRASTRUCTURE

Such boundary crossing work is increasingly common to the sciences. However, in studies of multidisciplinarity it is usually approached as a matter of human-to-human collaborations. We have come to understand scientists to be the arbiters of representational validity within their domain. But with the redistribution of representational work described in this chapter, I ask, where do we locate authority over representation? Does a biologist have the technical expertise to interrogate the visual images produced by the software Marie designed for her lab?

Often the introduction of novel representational technique is a site of contestation (Bowker 1988; Bastide 1990; Daston and Galison 1992; Cambrosio, Jacobi et al. 1993; Gooday 1995; Edwards 1999; Golan 2004), but in this case the debates about technique occur in "another field"—in this case human-computer interface and data visualization. This separation of disciplinary research and representational work is significant for us as analysts and scholars of scientific visualization. Scholars in studies of scientific visualizations have come to agree that the knowledge of a science, and its consequences, are tied to representation devices and practice (Latour 1986; Suchman 1988; Lynch and Woolgar 1990; Daston and Galison 1992). This argument is occasionally extended by assuming that studying the visual elements of a science can be taken as a stand-in for practices in the science as a whole. For example, in his canonical article on visual languages in geology, historian Martin Rudwick outlines what has become a classic methodology for studies of scientific visualization:

> [V]isual means of communication necessarily imply the existence of a social community which tacitly accepts these rules and shares an understanding of these conventions. It is therefore worth studying the historical development of the visual language of geology . . . as a reflection of the growth of a self-conscious community of geological scientists. (Rudwick 1976: 150)

Rudwick takes visual conventions as a shorthand for the existence of an epistemic community with rules for evidentiary acceptance, of representational authorization and communicative coding and decoding. The visual language, and its historical evolution, is taken as a surrogate for the development of a self-identified scientific community of geologists.

Similarly, with carefully crafted historical detail, Cambrosio, Jacobi and Keating (1993) have outlined the case of the emergence of the visual conventions within Paul Ehrlich's work in immunology. Mirroring Rudwick's claim that representational technique and ontological entities co-emerge, they argue that Ehrlich's images are closely tied to the understanding of immunological entities themselves:

> The debate concerning the establishment of an immunological iconography appears to have been part of the constitution of immunological entities. . . . in order to record the existence and properties of entities, the development of a heuristic imagery was first needed, which would allow the work of inscription and representation to take place . . . the development of inscription or representation devices was cosubstantive

> not only with the establishment of a given set of phenomena, but also with the constitution and definition of the nature and properties of the entities made responsible for those same phenomena. (Cambrosio, Jacobi et al. 1993)

In both Rudwick's and Cambrosio et al.'s work a tight configuration holds: What ontological entities exist *and* how to visually represent them were negotiated within the same disciplinary community of researchers. But with the redistribution of labor between information technologists and domain scientists described in the first half of this chapter, it becomes less clear that we as scholars of visualization may link the constitution and definition of the nature and properties of the entities with debates over representational convention. These debates may occur in only marginally overlapping social worlds.

Marie critiqued her own work, noting the deficiencies in interface design and statistical results: Did her experimental setup skew an understanding of shape perception? These criticisms were recorded in peer-reviewed publications, but they also independently informed the design of visualization tools for use in science and engineering. Ties between representational devices and epistemic commitments are weak (or nonexistent) in this configuration. Unearthing the controversies within HCI would require a kind of archaeological work unlikely for the "average user" of visualization software. Designers and users of the tool are separated by the gulf between publication and production.

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In his study of the visual and statistical traditions within particle physics, Peter Galison (1997) demarcates three groups of practitioners within the community: theoreticians, experimentalists and instrument makers. He describes an "intercalation" of these groups: active collaborations that, at times, can be characterized as sharing epistemic commitments while at other times diverging. The various groups are primarily oriented to the activity within their own groups and may even be located in buildings, institutions or even countries that differ from the others. However, these diverging groups still interact productively in what Galison calls the "trading zone," where common language and modes of interaction have been established across professional specializations (Galison 1997). Here, Galison describes a *systematic disciplinary tie* between technicians, theoreticians and experiments. However, as I have described in this chapter, other configurations are also possible and increasingly likely.

We can roughly outline three kinds of relations between visualization experts and domain scientists. In the first case a group of domain scientists consistently work with their IT programmers through either a contractual relationship or shared research funding; the result is a tight interaction between social worlds. If the relations become systematic (or institutionalized) at the disciplinary level—as with Galison's physicists or the emerging fields of bioinformatics—a trading zone may emerge in which tropes for interaction and pidgins for communication develop. However, many researchers do not necessarily form such tight expert relations. For example, Star and Griesemer characterize how bird trappers and curators in a museum develop agreements about how to work together in gathering specimens. In this second configuration there is a loose familiarity across knowledge domains through collaborations that last years or decades but that are not based on a shared epistemic interest: Trappers do not "care" about taxonomy while still actively seeking to meet the informational requirements of curators, such as recording the location where a specimen was found (Star and Griesemer 1989). Susan Leigh Star describes this as "collaboration without consensus," a set of sustained relations that are quite different from the tight ties maintained by Galison's physicists.

Thirdly, the case I have explored with Marie is of a "light relationship," in which information technologists only loosely understand the domain but draw on combinations of novel, reused and prepackaged IT resources to provide tools *for* the domain. Visualization tools may be designed for one domain and then recompiled for another; here we have the movement of a black box, in which the inputs and outputs are only slightly adapted to the informational requirements of a domain. Marie consistently works with biology, but only in the broadest sense of the term. Her applications range from medical applications to the movement of subcellular particles. Software, or elements of code, is shifted across significantly heterogeneous epistemic communities. These are loosely framed collaborations of an informationally *adequate* nature that may be short-lived but thereafter materially solidified by relations through technologies of visualization.

In these cases, a correlation between community and the history of its rendering practice becomes murky at best and arguably altogether ruptured. Any approach to the studies of visualization in contemporary scientific practice should no longer *assume* continuity between representational and epistemic evolution. Continuity and rupture across disciplines must be investigated. The visualization conventions embodied in the applications that render data as image may be determined outside the confines of even the most broadly defined disciplinary arenas.

As scientific work becomes distributed in such novel configurations the analyst must be capable of tracing movements that, as the work of Marie shows, do not always occur on the "same disciplinary plane" as their use. This configuration also begs a much broader future research question: How do the automation of visualization and the distribution of representational work inform the co-emergence of representational form and ontological entities?

CONCLUSION: ELIDED CONFLICTS AND REPRESENTATIONAL WORK

We have seen how visual representation conventions are imported from other disciplines or extrascientific institutions such as art; moreover, the techniques of representation have been slightly (sometimes radically) transformed. Marie's textures are neither woven nor drawn; they are algorithmically generated. Her tool is indirectly inspired, but in no sense equivalent to the loom that produced the original textures. They are *isomorphic renderings*, mirroring a visual appearance but not the method of production. Above and beyond this we have seen how research techniques such as experimental psychology come to inform the creation of those systems. Congealed as applications and technology, and used by scientists to visualize data in other fields, those findings sustain a multidisciplinary link that is difficult to trace.

Capturing the *arts and design* is a particular instance of visualization automation. I have met only a handful of researchers that explicitly define themselves as drawing technical inspiration from the arts. However, it *is* common for designers to study the "contexts of use" for technologies, to attempt to augment and support existing practices, and for digital design technologies to mirror their analog counterparts (Berg 1998). Rather than making a claim for generalizability, this research points to a social form: an organized activity that bridges between disparate media and links across disciplinary boundaries through tools.

The story I have told here is *not* a study in controversy, of "behind the scene battles informing the creation of a software function"; instead these are stories of an elided conflict, a possible tension left aside. Debate is always possible, but is made more difficult through the distributed organization of expert activity.

I have traced a backgrounded process for the creation of visualization tools. At the end of the process we do not have a representation, but rather a tool for building representation. It is a tool with particular properties—or affordances—but these properties cannot necessarily be deduced from the nature of the output representations. Most importantly, the use of the technology for visualizing data does not reveal the weaknesses in its design. In the case explored here, these weaknesses are documented in a stream of academic publications; it is possible to recover the flaws in rendering algorithms, but this requires a kind of archaeological work unlikely for most practicing scientists. It is *possible* for user-scientists to investigate the conditions of production for their visualization tools, but this is a challenging endeavor involving kinds of technical knowledges they are unlikely to have ready at hand.

Understanding the representational tendencies of a digital visualization technology requires understanding both their use in action (Amerine and Bilmes 1988; Suchman 1988; Winkler and Van Helden 1992; Prentice

2005) and the process by which they were produced; in this chapter I have traced the latter. Representational work is distributed between domain scientists analyzing data and information scientists who produce the means by which those data are analyzed, yet the work of both disciplinary groups never meets *in practice*; rather, they intersect at the product software.

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