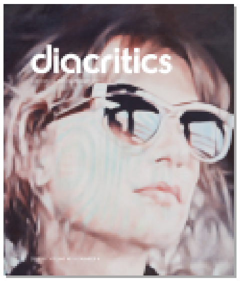
PROJECT MUSE®

The Ecologies of Data Visualization

Benjamin Mangrum



Diacritics, Volume 48, Number 4, 2020, pp. 52-75 (Article)

Published by Johns Hopkins University Press

For additional information about this article
https://muse.jhu.edu/article/845155

[Access provided at 19 Jan 2022 14:15 GMT from University of the South]

THE ECOLOGIES OF DATA VISUALIZATION

BENJAMIN MANGRUM

Benjamin Mangrum is an Assistant Professor of English at the University of the South. His monograph *Land of Tomorrow: Postwar Fiction and the Crisis of American Liberalism* (2019) examines the ways in which the U.S. literary marketplace after WWII provided cultural legitimacy to anti-organizational political sensibilities. He has published essays on the environmental humanities, twentieth-century "world literature," as well as the history of ideas and media underlying contemporary methods in the digital humanities.

Email: benjamin.mangrum@gmail.com

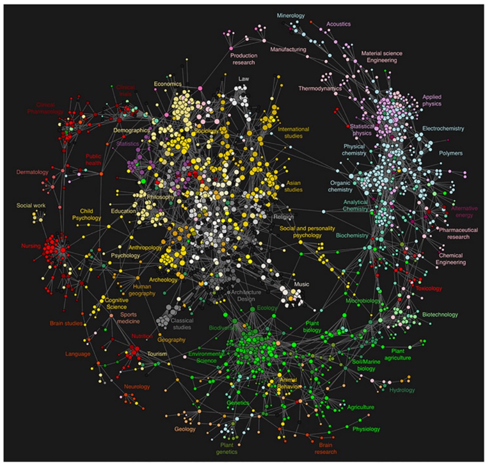
In 2009, an article in *Wired* magazine announced that the "pursuit of human knowledge has a shape."[1] This shape was produced by researchers at the Los Alamos National Laboratory and first published in *PLoS ONE*.[2] The Los Alamos group examined more than a billion user interactions on scholarly databases to create a spatial visualization of the relationship among fields of science (Figure 1). Reporting on this research, Brandon Keim observes that this "map of science looks like the Milky Way." In this visual representation of scientific research, fields like physics and geography swirl around one another. It is as though the study of the universe takes its shape from the universe itself.

The Los Alamos researchers produced this data visualization by mapping user interactions with scholarly web portals. As users move from one article or journal website to another, this data is recorded as a "clickstream," which is then aggregated by large publishers and institutions, such as JSTOR, Elsevier, and Web of Science.[3] The researchers used these aggregated logs to develop a "clickstream model." Each circle represents an individual journal, and the lines connecting the circles signify spatial relationships produced by a form of statistical modelling known as a Markov chain. This study was particularly notable because of the scale of the data collection: no previous study had accessed or analyzed so much information about online academic behavior.[4]

While both the *Wired* article and the Los Alamos researchers describe this visualization as a map of science, the academic journals represented in the visual structure include many fields outside the so-called hard sciences, such as the disciplines of religion and education. The yellow data points in this galaxy represent humanities disciplines and humanistic social sciences. Forming something like the center of the visualization, these humanistic disciplines tend to "cluster" more densely around one another.[5] The red circles represent health-science disciplines, green represents many environmental and biological sciences, while teal and purple signify disciplines like chemistry, physics, and various subfields of engineering.

The 2009 *Wired* article also presents another image from research previously published in both *Nature* and *Seed* magazines (Figure 2).[6] This visualization "looks like an amoeba," the author explains.[7] The connecting lines and data points comprise a scientific paradigm map, representing how disciplines in the natural sciences relate to one another. The small red circles signify papers that cite one another. A string of phrases is appended to each circle, and the heaviness and length of the line represents the degree of cross-linkages. Whereas the first visualization ostensibly represents knowledge at the level of the galaxy, the second presents the disciplines of science as though they resembled some of the smallest and most basic objects of study.

The *Wired* article's interpretation of these visualizations stands in contrast to how data scientists often eschew analogies between visualizations of their research and the physical entities that those images seem to resemble. Many scholars express this



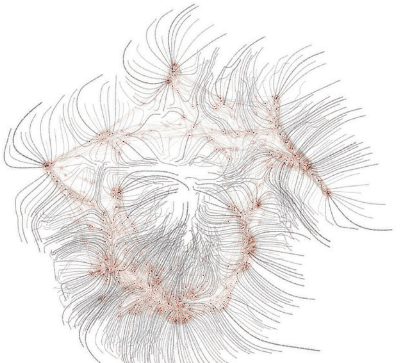


Fig. 1. Map of science derived from clickstream data (Bollen et al., "Clickstream Data Yields High-Resolution Maps of Science").

Fig. 2. Marris, "Brilliant Display," 985.

DIACRITICS Volume 48, number 4 (2020) 52–73 ©2021 Cornell University

reservation by asserting that the shape of a particular visual structure is “arbitrary” or only a “product of the algorithm.”[8] Despite these important qualifications—which I examine in greater detail later in this essay—the notion that the methods and products of data science are homologous with the so-called natural world persists in cybernetics, the philosophy of science, and computer engineering. A 2016 article in *Cybernetics and Systems Analysis*, for instance, associates a “general logic” with the “evolution of nature,” arguing that such a logic also appears in the “self-organization and self-development” of information structures.[9] This view, sometimes described as universal or global evolutionism, maintains that the logic of evolutionary systems governs the logic of social structures, including information itself.[10] This cybernetic sensibility understands information systems as sharing logical features with the organization of organic matter.

Ecology, in particular, has served as a repository of metaphors for understanding the analysis and visualization of data, beginning with the professionalization of graph theory in the nineteenth century.

Many data scientists view this cybernetic sensibility as an intellectual outlier, a kind of distant cousin who embarrasses the scientific family. Yet this essay shows how naturalizing metaphors have been longstanding features of data culture. Even when data scientists disavow analogies between data visualizations and certain physical referents, I demonstrate that many data visualizations nevertheless draw on a tradition of practice oriented around the reproduction of supposedly organic forms, the effect of which is to naturalize scientific methods, information systems, and engineering design.[11] Ecology, in particular, has served as a repository of metaphors for understanding the analysis and visualization of data, beginning with the professionalization of graph theory in the nineteenth century. Ecological analogies were also a prominent feature in twentieth-century computer and network design, and they have continued to inform many of the layout algorithms that generate present-day data visualizations. I argue that this genealogy of visual practices poses problems in the philosophy of science and engineering that are important to digital humanists and data scientists alike. This history shows how the constitutive metaphors of data analysis and visualization naturalize information systems in ways that obscure the material and social realities of those systems.

>> GRAPHS, METAPHORS, AND NATURAL OBJECTS

The language and techniques of data visualization derive mostly from the branch of mathematics called graph theory. Yet many of the terms of graph theory are themselves borrowed from other scientific disciplines. For example, the circles signifying academic journals in Figure 1 are known as “nodes,” which are objects that relate to other entities within a dataset. The connections between nodes are often called “edges,” “links,” or sometimes more simply “lines.” Nodes and lines are two “graph-specific objects,” as one group of research scientists explains, and the meanings of these two terms are entirely relational: "Nodes by nature have an attribute degree that is the number of links incident to that node."[12] In other words, graphs are meant to convey the significance of a node by reference to its links with other nodes. This "degree attribute" is a specific type of meaning, defined by reference to the relationships in a visual structure.

The terms "nodes" and "edges" entered into the vocabulary and design of graphs when data visualization practices were first formalized during the late nineteenth century.[13] Some key terms of graphing were adapted from geometry and have precedents in mathematical practices from Greece, North Africa, and China. Yet the term "graph" itself was first used to describe the visualization of data in a paper published in *Nature* in 1878.[14] In this paper, a scientist named J. J. Sylvester at Johns Hopkins University imports the term "graph" from a recent innovation in diagramming chemical compounds. Sylvester introduces the new term in the following way: "It may not be wholly without interest to some of the readers of *Nature* to be acquainted with an analogy that has recently forcibly impressed me between branches of human knowledge apparently so dissimilar as modern chemistry and modern algebra."[15] Sylvester explains that the term "graph" functions as a specific "analogy" between "atoms and *binary* quantics"[16] (binary quantics refers to a certain kind of differential calculus). As subsequent chemists and mathematicians debated Sylvester's idea, they determined that the analogy between the two fields was superficial, but they nonetheless adopted the practice of visualizing various types of numerical information under the banner of the "graph."[17]

This analogy between chemistry and algebra is part of a pattern in the development of graph theory, in which many visualization practices borrow from other domains of scientific inquiry to analogize their visual structures. I want to suggest in this section that such a pattern often creates a visual language that imagines the relationalities within a dataset as though they were naturally occurring phenomena. This representational pattern masks the metaphorical character and underlying abstractions of certain forms of scientific analysis by depicting both the methods of analysis and the data itself as though they were organic features of a material world. This is what I mean by "naturalization," and it is a common procedure in the direct analogies and unacknowledged metaphors of graph theory. Sylvester's contribution to the development of graph theory was to present graph intersections—the information that would be visualized—after the image of chemical bonding. Sylvester's analogy represents graphed information as combinations of basic chemical elements, rather than mathematical abstractions.

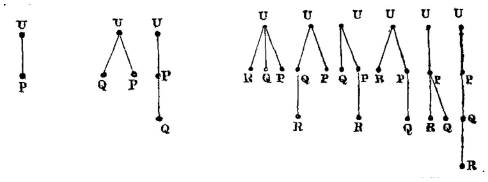


Fig. 3. Cayley, "On the Theory of the Analytical Forms Called Trees," 173.

The graphing form known as the "tree" is another important example that shaped early data culture, and it clarifies how the idea of the "node" would become a feature of graph theory. In 1857, the English mathematician Arthur Cayley first theorizes an "analytical form called trees" to address a particular set of problems in calculus (Figure 3). After discussing a few difficult operations, Cayley writes: "The inspection of these figures will at once show what is meant by the term [trees], and by the terms *root*, *branches* . . ., and *knots*."[18] Cayley's development of the tree as an analytical form imagined the intersection of points as *knots*, translating the Latin term *nodus* (knot). The Latin *nodus* had several connotations, ranging from a "tumor or swelling" to a "knot or joint on a stem or branch."[19] Cayley's re-description of problems in differential calculus through the analytical form of the tree recalled the latter meaning, for he implied that the intersecting points ("*knots*") resembled the points at which trees branch. The term *knots* would later fall out of use within the tradition of graphing practices, but it would be replaced with an Anglicization of *nodus*—that is, *node*. In this way, the imagery of organic branching persists in data visualization practices, even when the forms of those visualizations are quite removed from Cayley's trees.

The language of this tradition of practice—*graphs*, *trees*, and *nodes*—suggests how the technical terms of nineteenth-century graph theory were often abstracted versions of physical objects. Sylvester's and Cayley's key terms are metaphorical appropriations of so-called natural objects, bound up with modern techniques for mapping logic and order onto the environment.[20] Cayley describes his illustrations, for instance, as though one were taking in the thing itself through the unadorned and irrefutable senses: "The inspection of these figures will show at once . . . ." This self-evidence is an example of what the German philosopher of science Peter Janich describes as a common procedural technique in the naturalization of information culture. Janich argues that scientists and academics often use "information-theoretical or communications-oriented modes of speech as though they were *not metaphors at all* but rather actual, direct, original, nonmetaphorical representations of scientific processes. This shift, this slippage, lies at the very heart of the naturalization of information."[21]

This slippage is a recurring pattern in the development of trees, nodes, and graphs as visualization practices. These analytical forms pose as techniques for the nonmetaphorical measurement of differences and relations. Cayley's theorization of the tree frames this particular kind of calculus as though not only its objects of analysis but also the method itself were nonmetaphorical features of the natural world. It's as though natural objects—trees and their branches and knots—disclose abstract problems of measurement and relationality. The character of graphed relationality, then, is patterned after seemingly self-evident organic matter.

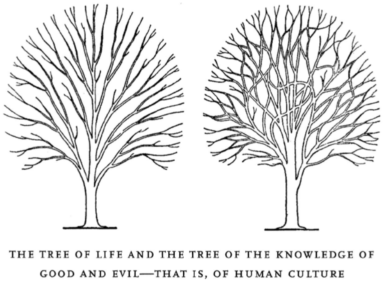


Fig. 4. Moretti, *Graphs, Maps, Trees*, 79.

>> Trees, Discourse Networks, and Digital Environments

These moments in the formation of graphing practices may seem technical and obscure, but they persist in twenty-first-century technoculture, including the visualization practices of the digital humanities. For example, Franco Moretti uses a related version of the analytical form of the "tree" in his 2005 *Graphs, Maps, Trees*. To explain the tree as a model, Moretti first looks not at Cayley's trees but at Charles Darwin's (Figure 4). The tree on the left is an abstract model for biological divergence. In contrast to the idea that evolution proceeds solely in terms of species divergence, Moretti offers the tree on the right, which represents both divergence and convergence. According to Moretti, the tree on the right is a more accurate model for the evolution of literary style. Moretti quotes the anthropologist Alfred Kroeber, who explains historical phenomena of literary convergence and divergence. According to Kroeber, the tree on the left is a bad metaphor for human culture, because it only diverges and branches. Human culture, represented by the tree on the right, is "a ramification of . . . coalescences, assimilations, or acculturations. This schematic diagram visualizes this contrast."[22]

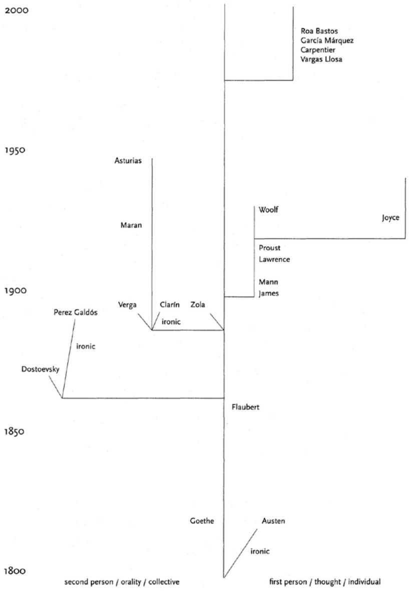


Fig. 5. Moretti, *Graphs, Maps, Trees,* 84.

Unlike Cayley and Sylvester in the nineteenth century, Moretti is much more attentive to the metaphorical character of his visualizations. Much like data scientists who note that a visual structure is a mere artifact of an algorithm, Moretti holds loosely to his analogies and metaphors. But the tree as an analytical form nonetheless is a semiotic choice, freighted with meaning that is conspicuously bound up with an environmental imagination. For instance, in a tree that resembles more closely Cayley's analytical form, Moretti provides what he describes as a tree of "free indirect style in modern narrative, from 1800 to 2000" (Figure 5). As a visualization of branching styles, the tree encodes the continuities, divergence, and growth of such stylists as Jane Austen, Fyodor Dostoevsky, and Marcel Proust. The knots or nodes and branching styles are notable for their relationship back to the trunk, which is represented by European men like J.W. von Goethe and Gustave Flaubert. Moretti's tree thus represents how ecological metaphors can be fitted to the normalizing power of visual-graphical analysis.

The visualization of a tree of free indirect style has multiple sources, including evolutionary biology, cultural anthropology, and the graphing practices of the nineteenth century. Each of these sources developed in the midst of what philosopher Ian Hacking describes as "a new type of law [that] came into being" during the nineteenth century. Part of a wider elevation of probability, this law carried "the connotations of normalcy and of deviations from the norm."[23] Similarly, the development of late-nineteenth-century graphing and visualization practices were attempts to identify calculable deviations. These modern forms of quantitative thinking were predicated on the measurement of normativity. The analytical form of the tree developed within these wider social imperatives and the professionalization of techniques for quantitative analysis.

Moretti's trees, in particular, suggest how a certain kind of normative history of literary style could become visible through an environmental imaginary. Moretti's visual-graphical images depict a lineage of literary influence as progressive, organic, and even self-generative. His visual imagery reimagines cultural style and the sphere of the social in the image of natural history. Whereas Cayley's *knots* borrow from so-called natural objects to understand differential calculus, Moretti's models of divergence and convergence invite us to think about changes in literary history as nodal points within an organic totality (the "tree of human culture").

The notion that cultural systems, like information systems, can be visualized through their structural similarities with natural objects is not a fringe or outmoded idea in the digital humanities. One of its most prominent and lasting influences has been on the aspiration to capture totality through graphical data analysis. Such visualizations often present an ecosystem of information, enclosed within networks, webs, or circular graphs that convey a naturalized kind of totality. For example, James Jaehoon Lee and Joshua Beckelhimer produce visualizations of early modern discourse networks by mining the historical archive of Early English Books Online and the HathiTrust Digital Library. Lee and Beckelhimer use this data to evaluate the thesis that "colonialism and the rise of early modern globalism catalyzed the Anthropocene."[24] The textual data makes possible a method of analysis known as statistical topic modelling, which yields topic clusters that are analyzed as a network. Lee and Beckelhimer produce several topic clusters, including a discourse network of topics related to the term *globe* (Figure 6). Their evidence supports the claim that "the British Empire was founded on a certain understanding of the relations among space, climate, sunlight, and suitability for life."[25]

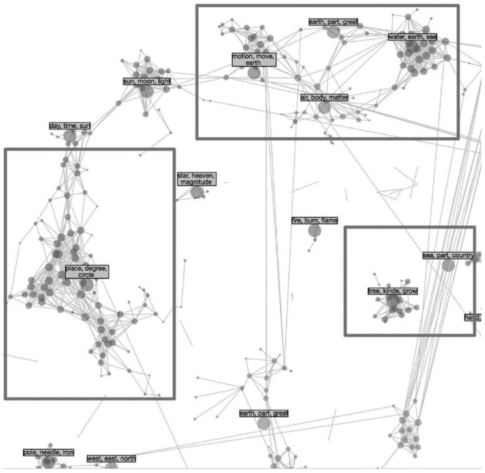


Fig. 6. "Discourse network of topics relating to the term globe" (Lee and Beckelhimer, "Anthropocene and Empire: Discourse Networks of the Human Record," 117).

Yet what historical contingencies run in the background of these data visualizations? How do their visual structures interpret and redescribe the underlying data?

The fact that such a visualization is legible to us as positing kinds of relationality—and, as a semiotic object, conveys some quantitative sense of totality—relies on what Orit Halpern describes as the new "forms of attention, observation, and truth" that were developed and disseminated by "cybernetics and the communication sciences after World War II."[26] According to Halpern's history of data and visual perception, a certain kind of reason was made feasible by computer designers and other engineers during the postwar period, and this form of reason was predicated on the idea that data was fundamentally interactive. Whatever could be represented as data could in turn be visualized to call attention to the relationalities at play in the dataset. Following "wartime imperatives of surviving by means of the identification and evasion of the enemy," postwar designers and engineers conceived of a new "communicative channel that could be algorithmically represented, materialized as technology, and circulated autonomously, separate from content."[27]

Postwar designers and cyberneticists sought to create information and communication systems that could produce interactive visual structures. Contemporary visualization practices in the digital humanities are still oriented around this postwar sensibility. The visualization of the discourse network, as a sign, performs a speech act that asserts the image's materiality. The image of the discourse network performs its status as an empirical object, one that is ontologically equivalent to the structure of DNA. Indeed, as Halpern's history suggests, the discourse network signifies its materiality by the very fact that it shifts in response to data inputs, much in the same way that genetic sequencing is dynamic, singular, but also mappable.

The manipulability of data visualizations recalls one other key idea in postwar cybernetics: feedback. The historian Daniel Belgrad shows how this idea informed computer design during the 1960s and 1970s. According to Belgrad, a "new ecology" emerged during the postwar decades, envisioning "nature as . . . an evolving, self-regulating system, governed by feedback loops that placed constraints on the behaviors of its various parts."[28] The cybernetic theorization of feedback informed the design of computational programs, network systems, and other digital practices that changed in response to inputs. This design was theorized as a natural function of information systems, such that generating and perceiving objects as responding to interactive inputs was to see those objects as manifesting natural behavior.[29] The idea of the ecosystem became "a significant alternative to the two dominant views of nature previously extant in American culture: that of nature as a savage wilderness to be subdued and civilized; and that of nature as a resource given significance only through human utilization."[30]

The development of dynamic data visualization techniques, beginning in the 1970s, was the child of this sensibility.[31] The discourse network, in particular, derives from this union of systems ecology and information theory, because, as an analytical form, it represents the visual structure of data as a system of feedbacks. This is what visualizations of a network *do*—they respond to inputs. Yet we shouldn't take this self-evidence for granted, because it can lead us to overlook the historical novelty of the network's visual structure and its underlying presupposition of a certain kind of totality. Data visualizations and analysis are techniques designed to be manipulated and dynamic. To take the fact that data is interactive as a justification for the notion of data as an ecosystem is to take a feature of design and elevate it the level of an ontological reality or epistemological principle. To view data visualizations as referring to, materially and self-evidently, a dynamic reality is to read those visualizations through an ecological way of seeing information.

Many visualizations invite us to see data as though the analyzed and represented numerical information were somehow "out in the world." Rather than making visible relationalities that have an independent ontological reality, data visualization practices instead represent statistical relationships or mathematical abstractions. In either case, an underlying theory of science and engineering posits "information" was defined "so that it would be calculated as the same value regardless of the contexts in which it was embedded."[32] The data visualized in graphs and discourse networks are predicted on a flattened notion of information. Visualizations embed data within the assumptions of layout algorithms and graphing conventions, while at the same time abstracting such data from their social embeddedness by the very process of translating phenomena into numerically represented information.

Visualizations embed data within the assumptions of layout algorithms and graphing conventions, while at the same time abstracting such data from their social embeddedness by the very process of translating phenomena into numerically represented information.

This is an ontological sleight of hand, and it has proved to be an especially influential one. As James Evans and Adrian Johns explain, the algorithms underlying digital quantification and analysis have become "recursive," which is to say that "algorithmic categories become increasingly real through recapitulation in the everyday lives of those subject to them."[33] Yet this widespread use and recursive authority are not based on "realist theories about the causal structures of the phenomena [algorithms] engage with."[34] Instead, the algorithmic processing of data is based on predictive models that "make explicitly false assumptions in order to streamline computation."[35] Taking algorithmic representations as authoritative can thus lead to a fallacy in which "*predictive* success reflects *descriptive* accuracy."[36] This fallacy—to which I return in the last section of this essay—is an epistemic feature of visualizations designed to recall natural systems. However, before turning to that point, I first examine twentieth-century computer engineers and network theorists who were heirs to the tradition of naturalized information culture. These engineers and theorists would adapt this tradition to depict computer networks as organic, self-generating, and self-contained systems.

>> Postwar Network Design and Ecosystems Thinking

The use of the ecosystems idea in postwar data culture owes a conspicuous debt to J.C.R. Licklider, who was the first director of the office that would later create ARPANET, the most immediate predecessor to the internet. Licklider, who preferred to be called "Lick," wrote several papers on what he termed an "intergalactic computer network."[37] For this reason, scholars of computer history often lionize Licklider as a founding figure in the development of network infrastructure. However, he contributed more directly to discussions about the relationship between humans and computers. In an influential paper titled "Man-Computer Symbiosis," published in 1960, Licklider begins with the following natural metaphor:

> The fig tree is pollinated only by the insect *Blastophaga grossorum*. The larva of the insect lives in the ovary of the fig tree, and there it gets its food. The tree and the insect are thus heavily interdependent: the tree cannot reproduce without the insect; the insect cannot eat without the tree: together, they consitute [*sic*] not only a viable but a productive and thriving partnership. This cooperative "living together in intimate association, or even close union, of two dissimilar organisms" is called symbiosis.[38]

In this example, the insect and the tree are not enhancements of independent biological functions; they are associative organisms that change one another's existence. Licklider applies this ecological relation to the "symbiosis" of humans and computational technologies. He uses this metaphor to imagine a kind of interdependence of judgment. For instance, he describes a technological relation in which "the contributions of human operators and equipment will blend together so completely in many operations that it will be difficult to separate them neatly in analysis."[39] It's as though the ecological metaphor of the fig tree and the insect clarifies the nature of technologically mediated thought itself.

The ecological metaphors deployed in Licklider's network theory differ in important ways from the understanding of an ecosystem outside the information technology industry. Arthur Tansley first used the term "ecosystem" in 1935, but it was popularized during the postwar era in Murray Bookchin's *Our Synthetic Environment* and Rachel Carson's *Silent Spring*, both published in 1962.[40] These popular versions of ecosystems thinking were more often a messy kind of science anxious about cause and effect, particularly as seemingly closed biological systems do not stay closed but are infiltrated by toxins, invasive species, or habitat loss. In Rachel Carson's influential use of this idea, she describes an "unseen world" in which "minute causes produce mighty effects; the effect, moreover, is often seemingly unrelated to the cause, appearing in a part of the body remote from the area where the original injury was sustained."[41] Changes within ecosystems produce a series of unpredictable consequences; networks of interdependence are porous and hard to regulate.

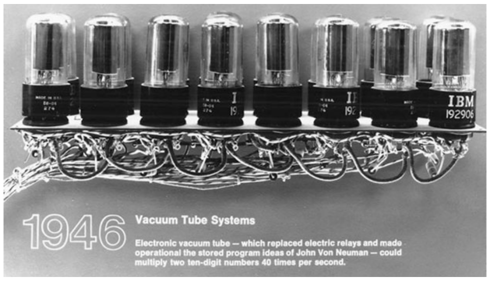


Fig. 7. IBM Vacuum Tube System (1946). Courtesy of International Business Machines Corporation.

Carson's understanding of ecosystems contrasts with one of the important technical innovations in the twentieth century: the vacuum tube (Figure 7). A vacuum tube created a largely closed system that laid the groundwork for binary computation. Within the vacuum of these tubes, on/off electrical charges functioned as switching elements. Early programmers designed *on* or *off* to correspond to 1 or 0, and this representational code allowed for certain types of calculations in early electronic computers from the 1940s through the 1950s. The vacuum tube thus facilitated early computer designs that imagined what cyberneticists sometimes referred to as circulatory ecologies of information. UNIVAC, one of the most important early computers, relied heavily on this idea. The computer's so-called "re-circulation Chassis" was based on a form of network thinking that tried to create supposedly self-sustaining closed systems.

The vacuum tube represented one version of ecosystems thinking, yet the idea that a machine can be built to be self-contained proved to be part of a wider technological fantasy, one rooted in the politics of the Cold War era. Elizabeth DeLoughrey, Kathryn Yusoff, and others have shown how postwar technological and scientific developments not only spread throughout global ecosystems but also disproportionately affected indigenous, Black, and island communities.[42] Regarding nuclear weapons testing, for example, DeLoughrey explains how the U.S. military justified such tests through a common form of systems thinking that she terms the "myth of isolates."[43] DeLoughrey shows how the bodies and ecologies of Pacific Islanders bear the marks of the impossibility of this myth. And indeed, technologies like the vacuum tube indicate that this mythology informed multiple domains of twentieth-century technoculture. The ideal of systems that could remain closed off by encasing their processes within vacuums may have allowed for efficient computing, but it was also an ideal bound up with military, industrial, and governmental fantasies about the containment of risk in experimentation.

We should consider Licklider's work on computer networks as part of this post-WWII version of systems thinking. In a 1966 paper, Licklider and collaborators recount their construction of a computer system, which they describe as a "system, consisting of a digital computer and a computer program, intended for exploration of man-machine interaction and computer assistance to man in the study of technical documents."[44] The group calls this system "Symbiont" because they want it to develop into a "truly symbiotic partner of the [user]."[45] The program includes the use of a "light pen" that underlines and annotates text as well as other interfaces that mediate between the computer memory and the human user. These ways of interfacing with computational technologies show how early designers and theorists imagined computer networks through the ecological language of symbiotic partnerships. They figured this symbiosis as a closed dyad: the human-computer. These figurations naturalized the socially and technologically mediated interactions envisioned by military and corporate designers, depicting these early computer technologies as new naturalized features of knowledge production.

Another paper published by Licklider and Robert Taylor, who also contributed to the design of ARPANET, develops this idea of computers as facilitating new types of symbiotic communication. "Computer programs," Licklider and Taylor explain, "transcend mere 'data'—they include procedures and processes for structuring and manipulating data."[46] Computational processes themselves are understood much like the analytical forms of trees and graphs: they give structure and interactivity to digital information. Licklider and Taylor's key visual metaphor for this symbiotic structuring and manipulation is what they call a "node" (Figures 8 and 9). As these figures suggest, their models of human-computer interactions come from so-called natural systems; they imagine users and software as integrated within a circulatory knowledge system. Communication technologies create a new kind of human-machine network, extending the notion of an information ecology from the recirculation chassis of the UNIVAC computer to a broader conception of uers in a network.

These visualizations express speculative theories and aspirations for information technology systems. We should view these images as performing speech acts in their own right. As W.J.T. Mitchell says, images are "not just a particular kind of sign, but something like an actor on the historical stage."[47] The images of scientific articles and network design *do things* rhetorically and aesthetically. Licklider and Taylor's images adapt the metaphor of the "node" to envision the relationship between a user and computer, but the images' function is as much to license that relationship as to explain it. In fact, these images anticipate the later idea of the personal computer, visualizing a distinct sensibility about the human-computer dynamic. In Figure 8, for example, the user is enclosed within what recalls a cellular wall. The node itself is a "computer," which includes a "user," computer processer, and software. The human

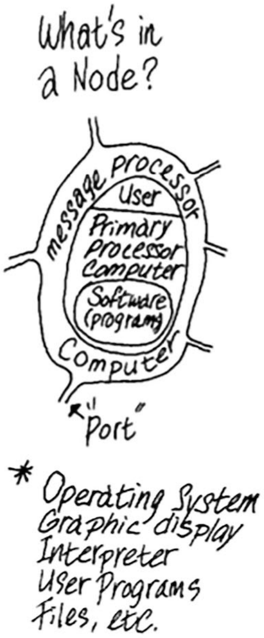


Fig. 8. Licklider and Taylor, "The Computer as a Communication Device," 32.

Fig. 9. Licklider and Taylor, "The Computer as a Communication Device," 32.

is thus part of the computer, rather than an entity distinct from the communications device. Figure 9 depicts these individual nodes as connected "via their message processors" to other nodes, such that the routes of exchange among computer users comprise a kind of nervous system of electronic signals. In other words, this naturalized image of an enclosed and self-generating human-computer does not separate; it is the basis for the dyad's links to wider networks.

These images express the symbiotic ideals that would culminate in the personal computer, but they also represent the ecological values associated with data in postwar technoculture. Computer programs, they assert, are not "mere data."[48] On its surface, Taylor and Licklider's derisive reference to "mere data" signals that data is not an end in itself. Computational technologies *do* more than "data" signifies. Yet the derision for "mere data" also expresses Taylor and Licklider's anxiety about the distance between simulation and material embodiment. Mere data would signify that the human-computer were only a simulation, a spectral kind of knowledge work. They present an alternative to this view of "mere data" through tactile verbs: computer programs enable "procedures and processes for *structuring* and *manipulating* data."[49] Data is at once coherent and concrete, as though data were physically available like materials for a construction project. Much like their figuration of the symbiotic relationship between humans and machines, the assertion of computational tactility likewise closes the gap between simulation and embodiment.

>> What Do Data Visualizations Want?

Assertions of the materiality of data are bound up with the ecological metaphors that appear so frequently in the language of technoculture. These metaphors are in part techniques for asserting the material character of information technologies. (This is also true of the term *corpus*, another technique for figuring embodiment in the digital humanities, although this term derives from much earlier philological practices.) The ecological metaphors of data culture convey a material situation, setting the scene for data that appears also in digitally produced visual structures. To put this point in a different way, we can borrow from Sherry Turkle, who has studied the cultures and tools of science at MIT, starting in the late 1970s. Turkle is interested in how simulations shape the modes of thinking adopted by engineers, architects, and lab scientists. Rather than simply embodying empirical truths, Turkle views those engineering-simulation tools as modes of thinking with their own kind of conceptual design. She asks: "What does simulation want?"[50] Similarly, we should ask: What do graphs and discourse networks want? What do data visualizations want?

Visualizations want naturalized interdependence; the visual structures of data want an ecology. The design of computational networks and data visualizations wants what Turkle calls "immersion," as though we were being immersed in a world made newly visible rather than one that is virtually accessible.[51] Data visualizations are therefore like what Finn Jørgensen calls digital armchair traveling, which has "seemingly extended the range and immersive depth of what we now think of as virtual travel experiences."[52] Much like geolocative technologies, such as the street-level view on Google Maps, data visualizations take us places. They build worlds and immerse us in a sense of inhabiting naturalized ecosystems of data.

Immersion within naturalized information remains a feature of many visualizations even when data scientists acknowledge the "arbitrary" structures produced by algorithms. This is because the very layout algorithms that data scientists employ often *want* forms of naturalized interdependence. For example, the group of scientists who produced the map of science (Figure 1) avoid direct analogies with natural systems, instead describing details of the map through a "wheel metaphor," with a central hub, spokes, and an outer rim.[53] They are also careful not to "explain or motivate" user interactions, thus eschewing the idea that their visualization's structure somehow discloses larger psychological structures or is "the only or best possible visualization."[54] Instead, the "exact geometric coordinates" of each circle in the visual structure vary "depending on the layout algorithm and are thus indeed considered artifacts of the visualization."[55] In other words, the Los Alamos researchers view the visual structure of their clickstream map of science merely as the product of an algorithm, not the expression of some ontological reality or epistemological principle. For these researchers, the structure describes relationships, not the structures behind those relationships.

Yet the layout algorithm that produced the map is itself a designed technology. The layout algorithm's design assumptions give shape to—inform—the very structure of the data visualization. In this particular visualization, each journal (node) is positioned in the map using a network layout method designed by Thomas J. Fruchterman and Edward M. Reingold. This method "optimizes journal positions so that they balance geometric node repulsion with node attraction resulting from the relationship strengths" in the study's matrix of clickstream data.[56] It was, in effect, an aesthetic choice about the geometric legibility of the relationships among nodes. The visualization is consequently structured according to the conceptual assumptions of the Fruchterman-Reingold (FR) network layout method.

As the theorists of the FR layout explain, this method was developed "in analogy to forces in natural systems, for a simple, elegant, conceptually-intuitive, and efficient algorithm."[57] Fruchterman and Reingold elaborate on the structuring assumptions of the different variants of their algorithmic program: "The basic version is called Nature because of the analogy between our layout algorithm and the forces of nature. We have a variant that lays out in three dimensions, called Nature3d, and the one that implements the grid variant called Naturev."[58] Regarding a feature of the program, they also explain how they "tried to find an analogy in nature that would suggest a way that such a blocking force could be overcome."[59]

The FR layout algorithm was designed to recall "natural systems," even if subsequent researchers explain that the structures of their visualizations are arbitrary and should not be identified with whatever material objects or natural phenomena they resemble. Data scientists may be careful to eschew naturalized metaphors in the language of their scholarship, but the design assumptions of an algorithm may belie responsible scholarly qualifications. Based on its design assumptions, a data visualization may *want* what researchers disavow: that is, the kind of interpretation that appears in *Wired's* reporting on the map of science.

Data scientists may be careful to eschew naturalized metaphors in the language of their scholarship, but the design assumptions of an algorithm may belie responsible scholarly qualifications.

Like Sylvester's "analogy" with chemical bonding or Cayley's "knots," the FR network layout method is part of a tradition of practice that visualizes and analyzes data through figurations of natural systems and ecological interdependence. Other network layout methods and circular drawing algorithms similarly refer to the naturalness of the relationalities made visible through data visualizations. As one textbook on data visualization explains, circular drawing algorithms are especially conducive to this kind of naturalized clustering: "The partitioning of the graph into clusters can show structural information such as biconnectivity, or the clusters can highlight semantic qualities of the network such as subnets. Emphasizing natural group structures within the topology of the network is vital to pinpoint strengths and weaknesses within that design."[60]

This technical discussion of graph theory raises a broader theoretical problem—namely, what makes the place, shape, and relation of clusters "natural"? The source of this feeling of naturalness is not elaborated upon in the textbook—it's not defined for student readers—as is often the case when the discourse of the natural creeps into our language. Instead, the naturalness of data structures seems to derive from the unstructured sensibilities or "background" of an imagined order.[61] A feeling of the natural—not a systematized logic—appears often and recursively in data science. It is an unnamed and unnamable structuring principle; it is a fundamental part of the architecture of what may be known, analyzed, and made visible.

These scholarly explanations of the structures of data visualization also employ another kind of natural metaphor used in contemporary technoculture: topology. Most data visualization practices use the language of topology to signify aspects of *topos* (place) existing in mathematical abstractions.[62] The language of graph theory and statistical analysis depicts those spatial relations and geometric properties as "nonmetaphorical representations of scientific processes," as Janich puts it.[63] The nonmetaphorical use of topological language represents data visualizations as if they existed in a material world, when of course the topology of a network is only made visible by an algorithm. The topology of a network isn't a feature discovered in data; it's an abstraction that facilitates data representation.

Scholars of information have noted how easily "charts lie" and visualized information can be used in irresponsible ways, but my point is less about usage and more about the representational structures of data.[64] Layout algorithms designed to resemble natural systems and technical descriptions of the topologies of data visualizations invite a feeling of an "electronic elsewhere."[65] There is no place or shape for those relations outside an algorithm. Yet the language of graph theory and data visualization practices convey the *feeling* of place. And this, too, is what data visualizations want, even if only by algorithmically produced resemblances to natural systems. The semiotics of data visualizations *perform* place and space, as though topological contours were quantified through the details of the visual structure.

>> Visualizing Data Culture

Natural metaphors for graph theory, ecosystems as models for networks, and algorithms that visualize data in the image of natural systems freight the interpretation of data with notions of organic unity. Such notions, in turn, associate data with autopoietic systems. The naturalization of networks, graphs, and data visualizations makes it seem as if the data produces itself. Indeed, some biologists and philosophers take the phenomenon of autopoiesis in, say, the process of mitosis as a basic principle that applies to all life.[66] While a minority position in the philosophy of biology and only rarely cited in data science, this fantasy of self-making appears in many of the forms associated with data culture.

I've demonstrated that the ecological, organic, and natural forms of data were products of traditions of practice, and among the many problematic aspects of associating data with autopoiesis is that it leads us to overlook the laborers, workers, and environmental costs of data infrastructure. Tung-Hui Hu, for instance, shows how we imagine the digital cloud as placeless, mute, ethereal, and unmediated. But in fact, the cloud is embodied in thousands of massive data centers that can use as much electricity as a midsized town. The cloud, as Hu explains, "is a resource-intensive, extractive technology that converts water and electricity into computational power, leaving a sizable amount of environmental damage that it then displaces from sight."[67] Hu's critique calls attention to how contemporary technoculture abstracts data from environmental and material processes of knowledge production. The ecologies of data visualization invite us to forget the ecologies affected by data visualization.

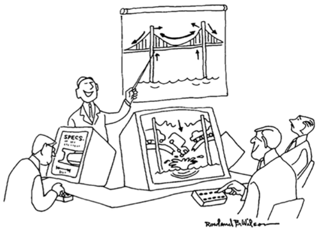
> The ecologies of data visualization invite us to forget the ecologies affected by data visualization.

The Canadian writer Rita Wong inverts the obfuscating effects of technoculture in her poem "sort by day, burn by night." Wong reveals a different kind of network, one characterized by the toxicity of our computational technologies that have been sent to a small village in China called Guiyu, supposedly to be recycled or repurposed. The *form* of the poem—the broken relations among lines and stanzas—recalls a disarticulated network, mirroring how the users of digital technologies only rarely connect their habits of consumption with the toxic colonialism that occurs when we discard no-longer-needed technologies. The poem begins: "Circuit boards / most profitable & most dangerous / if you live in guiyi village, / one of the hundred thousand people / who / 'liberate recyclable materials' / into the canals & rivers, / turning them into acid sludge, swollen with lead." For Wong, the connections between informational and technological systems are not self-contained. The relationality of the digital is one of seeping, not natural self-making or ecological containment.

Toxic chemicals leech from the materials; the poem, like a discourse network, traces the edges of these toxic materials: "Barium leachate, mercury bromide. / 0 keyboard irony: the shiny laptop a compilation of lead, / aluminum, iron, plastics, orchestrated mercury, arsenic, antinomy."[68] Whereas the edges of discourse networks visualize links according to statistical significance, Wong's poem visualizes a concatenation of chemical and material elements. The edges of data culture, in this view, are the byproducts and toxic waste generated by the technology that makes computation possible. The "antinomy" of e-waste, as environmental humanists call discarded electronic products, is that such information-technology systems connect us globally but often in literally poisonous and fragmented ways.

Wong depicts this technological production of a *demos* (people) as anti-democratic, signified most directly by channeling Walt Whitman: "Sing me the toxic ditty of silica: / '*Yet utter the word Democratic, the word En-masse.*'" The masses here are poisoned by our data systems, brought together by environmental harm that Western users never see because that harm has been displaced, mediated, and remediated for us by information technology that presents itself as environmentally friendly and self-contained. Microprocessors and computer hardware require resources—aluminum, iron, silica—but the sleek design of our technologies often obscures the environmental costs of this materiality. To call this materiality to mind, Wong's poem poses the questions: "Where do metals come from? / where do metals return?"[69] The answers to both involve a transnational network of resource extraction and waste disposal. Many scholars and activists have traced the ways that technology companies treat developing countries as "sites for manufacturing and assembling plants" as well as dumpsites for industrial waste.[70] The vocabulary, product design, and visualization practices of data culture, however, often obfuscate and deflect these problems of environmental justice. So much of the ethos of the tech industry is oriented around questions of privacy and the rigor of algorithmic thinking. But Wong's poem suggests instead that the industry relies on the transnational displacement of social and environmental responsibility.

The notion that information technology facilitates closed ecosystems of data can also conceal the social inequalities behind the production of those systems. For example, R. Arvid Nelsen complicates standard institutional histories of technological development in the 1960s. Historical accounts by Walter Isaacson and corporate histories produced by IBM often erase or fail to include the Black technicians, engineers, and laborers who helped produce computer technologies and early software programming.[71] Nelsen examines an archive of profiles in *Ebony* magazine to uncover a record of "women and men of color who held positions as computer scientists, engineers, and mathematicians in corporate, government, and military positions from the early days of computing to the present."[72] Official industry publications and influential postwar theorizations of data systems, in contrast, present information technology as almost exclusively white and male. For instance, one of the cartoons accompanying Licklider and Taylor's 1968 conceptualization of the computer network (Figure 10) whitewashes the computer as a communication device, inviting us to think of nodes and networks as displaced from all human bodies except the fingertips of white corporate users. The structures of inequality are veiled behind the iconography of data culture.



At a project meeting held through a computer, you can thumb through the speaker's primary data without interrupting him to substantiate or explain.

Fig. 10. Licklider and Taylor, "The Computer as a Communication Device," 26.

When we take data as factual, we often simultaneously commit the fallacy of taking data as natural and autopoietic. Yet visualizations, statistical relationships, and data sets don't make themselves. The fallacy of autopoiesis can lead us to overlook the bodies that make technoculture possible. For instance, in her analysis of technologies that track "quantum" or small-scale information, Jacqueline Wernimont argues that "nonwhite people have been refigured by quantum media as property, depersonalized data sets to be used as 'resources' or liabilities rather than as people."[73] Lisa Nakamura uncovers the experiences of Navajo women workers at Fairchild Semiconductor, which was "the most influential and pioneering electronics company in Silicon Valley's formative years."[74] These women were "exploited as a visual and symbolic resource as well as a material good" for the Fairchild Semiconductor brand.[75] The collection of essays *Challenging the Chip* similarly explores the environmental injustices underwriting the profits of the global electronics industry.[76] Such scholarship also suggests how the tech industry's history and supply chain belie the notion of information technology as a contained ecosystem.

The closely related notion of a dataset as an integrated and self-reproducing ecosystem is the product not of a quantitative or empirical method; such a notion is instead the fantasy of historically contingent sensibilities about the naturalness of information. One seemingly unintended consequence of these sensibilities is that they veil the material and social realities behind information technologies by depicting the products of those technologies as organic forms. Natural metaphors and ecological analogies figure the visual structures of information as though they expressed the very laws of nature.

The quantification of data is inextricable from its structuring metaphors. The naturalization caused by these metaphors creates problems for digital humanists and data scientists alike. If the layout method of an algorithm is based on naturalizing analogies, intentionality and responsible qualifications are moot. For many visualizations, the layout algorithm is at odds with scholarly assertions of the arbitrariness of a visualization's geometry or shape. The visual resemblances of data to so-called natural objects may only be an "artifact" of an algorithm, but such an acknowledgment avoids the fact that the design features of many algorithms invite us to read naturalistic resemblances into the data.[77] Such layout methods, much like Licklider's metaphors of natural symbiosis, present information technology in the image of organic forms.

Notes

I presented earlier versions of this essay at the Digital Studies Institute at the University of Michigan and in the Critical Conversations series at Michigan's English Department. I would like to thank the attendees at both presentations for their helpful comments.

1 Keim, "Map of Science Looks Like Milky Way."

2 Bollen et. al., "Clickstream Data Yields High-Resolution Maps of Science," 1–11.

3 Bollen et al., 2.

4 Butler, "Web Usage Data Outline Map of Knowledge."

5 Bollen et al., "Clickstream Data Yields High-Resolution Maps of Science," 5.

6 Marris, "Brilliant Display," 985; Boyack et al., "Scientific Method," 36–7; Börner, *Atlas of Science*; Schneiderman, "Communication," 1037.

7 Keim, "Map of Science Looks Like Milky Way."

8 For example, see the discussion of the 2009 map of science in Ware, *Information Visualization*, 324–25.

9 Kurgaev, "Evolution of the Structure of the Object of Science," 188.

10 See Popkova, "Controllability of Technosphere and Paradigm of Global Evolutionism."

11 Dana Phillips notes that ecocriticism often commits a similar fallacy, proceeding "haphazardly, by means of fuzzy concepts fashioned out of borrowed terms: words like 'ecosystem,' 'organicism,' and 'wilderness' are used metaphorically, with no acknowledgment of their metaphorical status" (Phillips, "Ecocriticism, Literary Theory, and the Truth of Ecology," 579). If scare quotes weren't so pretentious and cumbersome, we might heed Phillips's warning by marking each usage of terms like "natural objects," "organic forms," and "ecology" as patently artificial. Instead, I'll retain the use of such terms with the acknowledgment that they name sensibilities, not objects, entities, or processes.

12 Lee et. al., 1.

13 Biggs, Lloyd, and Wilson, *Graph Theory*, 9.

14 Biggs, Lloyd, and Wilson, 65. See also Henderson, *Algebraic Art*.

15 Sylvester, "Chemistry and Algebra," 284.

16 Sylvester, 284.

17 Biggs, Lloyd, and Wilson, 67.

18 Cayley, "On the Theory of the Analytical Forms Called Trees," 172.

19 "node, n.," in *Oxford English Dictionary Online*.

20 Consider, for example, the development of the U.S. Rectangular Land Survey, colloquially known as the grid, during the late eighteenth century. See Steinberg, *Down to Earth*, 61–3.

21 Janich, *What Is Information?,* 93–4.

22 Quoted in Moretti, *Graphs, Maps, Trees*, 79.

23 Hacking, *The Taming of Chance*, 1.

24 Lee and Beckelhimer, "Anthropocene and Empire," 112.

25 Lee and Beckelhimer, 118.

26 Halpern, *Beautiful Data*, 1.

27 Halpern, 81.

28 Belgrad, *The Culture of Feedback*, 20.

29 For another example of this sensibility, see Patten and Odum, "The Cybernetic Nature of Ecosystems."

30 Belgrad, *The Culture of Feedback*, 21.

31 For an overview of this period in the history of data visualization, see Friendly, "A Brief History of Data Visualization," 40–2.

32 Hayles, *How We Became Posthuman*, 53–4.

33 Evans and Johns, "The New Rules of Knowledge," 811.

34 Evans and Johns, 812.

35 Evans and Johns, 812.

36 Evans and Johns, 811.

37 Featherly, "Licklider, J.C.R.," 288.

38 Licklider, "Man-Computer Symbiosis," 4.

39 Licklider, 6.

40 Houser, "Ecosystem," 264.

41 Carson, *Silent Spring*, 189.

42 DeLoughrey, "The Sea Is Rising," 185–97; Yusoff, *A Billion Black Anthropocenes or None*.

43 See DeLoughrey, "The Myth of Isolates."

44 Bobrow et al., "A Computer-Program System to Facilitate the Study of Technical Documents," 186.

45 Bobrow et al, "A Computer-Program System," 186.

46 Licklider and Taylor, "The Computer as a Communication Device," 29.

47 Mitchell, *Iconology*, 9.

48 Licklider and Taylor, "The Computer as a Communication Device," 29.

49 Licklider and Taylor, 29 (emphasis is mine).

50 Turkle, *Simulation and Its Discontents*, 6.

51 Turkle, 6.

52 Jørgensen, "The Armchair Traveler's Guide to Digital Environmental Humanities," 96.

53 Bollen et al., "Clickstream Data Yields High-Resolution Maps of Science," 6.

54 Bollen et al., 9, 5.

55 Bollen et al., 6.

56 Bollen et al., 4.

57 Fruchterman and Reingold, "Graph Drawing by Force-directed Placement," 1129.

58 Fruchterman and Reingold, 1139.

59 Fruchterman and Reingold, 1148.

60 Six and Tollis, "Circular Drawing Algorithms," 285.

61 See Taylor, *Modern Social Imaginaries*, 25.

62 For the influence of topology on graph theory, see Biggs et al., 135–48.

63 Janich, *What Is Information?*, 94.

64 See Cairo, *How Charts Lie*.

65 Berry et al., vii.

66 For some of the original theorizations of nature as an autopoietic system, see Maturana, "The Organization of the Living: A Theory of the Living Organization" and "Autopoiesis."

67 Hu, *A Prehistory of the Cloud*, 146.

68 Wong, "Sort By Day, Burn By Night," 141.

69 Wong, 141.

70 Ku, "Human Lives Valued Less Than Dirt," 181.

71 Nelsen, "Race and Computing," 29–51. See also McIlwain, *Black Software*, 11–90.

72 Nelsen, "Race and Computing," 34.

73 Wernimont, *Numbered Lives*, 161.

74 Nakamura, "Indigenous Circuits," 920. See also Nakamura, "Don't Hate the Player, Hate the Game."

75 Nakamura, "Indigenous Circuits," 921.

76 See Smith, Sonnenfeld, and Pellow, *Challenging the Chip*.

77 Bollen et al., "Clickstream Data Yields High-Resolution Maps of Science," 6.

Works Cited

Berry, Chris, Kim Soyoung, and Lynn Spigel. "Introduction: Here, There, and Elsewhere." In *Electronic Elsewheres: Media, Technology, and the Experience of Social Space*, edited by Chris Berry, Kim Soyoung, and Lynn Spigel, vii–xxviii. Minneapolis: University of Minnesota Press, 2010.

Belgrad, Daniel. *The Culture of Feedback: Ecological Thinking in 1970s America*. Chicago: University of Chicago Press, 2019.

Biggs, Norman L., E. Keith Lloyd, and Robin J. Wilson. *Graph Theory, 1736–1936*. Oxford: Clarendon Press, 1976.

Bobrow, Daniel G., R.Y. Kain, Bertram Raphael, and J.C.R. Licklider. "A Computer-Program System to Facilitate the Study of Technical Documents." *American Documentation* (1966): 186–89.

Bollen, Johan, et al.. "Clickstream Data Yields High-Resolution Maps of Science." *PLoS ONE* 4, no. 3 (2009): 1–11.

Börner, Katy. *Atlas of Science: Visualizing What We Know*. Cambridge, MA: MIT Press, 2010.

Boyack, Kevin, et al. "Scientific Method: Relationships Among Scientific Paradigms." *Seed Magazine* 9 (2007): 36–7.

Butler, Declan. "Web Usage Data Outline Map of Knowledge," *Nature*, March 9, 2009. https://www.nature.com/articles/458135a

Cairo, Alberto. *How Charts Lie: Getting Smarter about Visual Information*. New York: Norton, 2020.

Carson, Rachel. *Silent Spring*. Boston: Houghton Mifflin, 2002.

Cayley, Arthur. "On the Theory of the Analytical Forms Called Trees." *The London, Edinburg, and Dublin Philosophical Magazine and Journal of Science* 13, no. 85 (1857): 266–68.

DeLoughrey, Elizabeth M. “The Myth of Isolates: Ecosystem Ecologies in the Nuclear Pacific.” *Cultural Geographies* 20, no. 2 (2012): 167–84.

——. “The Sea Is Rising: Visualizing Climate Change in the Pacific Islands.” *Pacific Dynamics: Journal of Interdisciplinary Research* 2, no. 2 (2018): 185–97.

Evans, James, and Adrian Johns. “The New Rules of Knowledge: An Introduction.” *Critical Inquiry* 46 (2020): 806–12.

Featherly, Kevin. “Licklider, J.C.R.” In *Encyclopedia of New Media*, edited by Steve Jones, 288–89. Thousand Oaks: Sage Publications, 2003.

Friendly, Michael. “A Brief History of Data Visualization.” In *Handbook of Data Visualization*, edited by Chun-houh Chen, Wolfgang Härdle, and Antony Unwin, 15–56. Springer-Verlag, 2008.

Fruchterman, Thomas M. J., and Edward M. Reingold. “Graph Drawing by Force-Directed Placement.” *Software—Practice and Experience* 21, no. 11 (1991): 1129–64.

Hacking, Ian. *The Taming of Chance*. New York: Cambridge University Press, 1990.

Halevy, Alon, Peter Norvig, and Fernando Pereira. “The Unreasonable Effectiveness of Data.” *IEEE Intelligent Systems* 24, no. 2 (2009): 8–12.

Halpern, Orit. *Beautiful Data: A History of Vision and Reason since 1945*. Durham, NC: Duke University Press, 2015.

Hayles, N. Katherine. *How We Became Posthuman: Virtual Bodies in Cybernetics, Literature, and Informatics*. Chicago: University of Chicago Press, 1999.

Henderson, Andrea. *Algebraic Art: Mathematical Formalism and Victorian Culture*. New York: Oxford University Press, 2018.

Houser, Heather. “Ecosystem.” In *American Literature in Transition, 1990–2000*, edited by Stephen J. Burn, 263–78. New York: Cambridge University Press, 2018.

Hu, Tung-Hui. *A Prehistory of the Cloud*. Cambridge, MA: MIT Press, 2015.

Janich, Peter. *What Is Information?* Translated by Eric Hayot and Lea Pao. Minneapolis, MN: University of Minnesota Press, 2018.

Jørgensen, Finn. “The Armchair Traveler’s Guide to Digital *Environmental Humanities*.” *Environmental Humanities* 4 (2014): 95–112.

Keim, Brandon. “Map of Science Looks Like Milky Way.” *Wired*, March 11, 2009. http://www.wired.com/2009/03/mapofscience/

Ku, Yu-ling. “Human Lives Valued Less Than Dirt: Former RCA Workers Contaminated by Pollution Fighting Worldwide for Justice (Taiwan).” In *Challenging the Chip: Labor Rights and Environmental Justice in the Global Electronics Industry*, edited by Ted Smith, David Sonnenfeld, and David Pellow, 181–90. Philadelphia: Temple University Press, 2006.

Kurgaev, A.F. “Evolution of the Structure of the Object of Science.” *Cybernetics and Systems Analysis* 52 (2016): 181–90.

Lee, Bongshin, et al. “Task Taxonomy for Graph Visualization.” In *Proceedings of the 2006 AVI Workshop On BEyond Time and Errors: Novel Evaluation Methods for Information Cisualization (BELIV ’06)*, 1–5. Venice: Association for Computing Machinery, 2006.

Lee, James Jaehoon, and Joshua Beckelhimer. “Anthropocene and Empire: Discourse Networks of the Human Record.” *PMLA* 135.1 (2020): 110–29.

Licklider, J.C.R. “Man-Computer Symbiosis.” *IRE Transactions on Human Factors in Electronics* (1960): 4-11.

Licklider, J.C.R., and Robert W. Taylor. “The Computer as a Communication Device.” *Science and Technology* 76, no. 2 (1968): 21–41.

Marris, Emma. “Brilliant Display.” *Nature* 444 (2006): 985–91.

Maturana, Humberto. “Autopoiesis.” In *Autopoiesis: A Theory of Living Organization*, edited by Milan Zeleny, 21–33. New York: North Holland, 1981.

——. “The Organization of the Living: A Theory of the Living Organization.” *International Journal of Man-Machine Studies* 7 (1975): 313–32.

McIlwain, Charlton D. *Black Software: The Internet and Racial Justice, from the AfroNet to Black Lives Matter*. New York: Oxford University Press, 2020.

Mitchell, W.J.T. *Iconology: Image, Text, Ideology.* Chicago: University of Chicago Press, 2013.

Moretti, Franco. *Graphs, Maps, Trees: Abstract Models for a Literary Theory.* New York: Verso, 2005.

Nakamura, Lisa. “Don’t Hate the Player, Hate the Game: The Racialization of Labor in World of Warcraft.” *Critical Studies in Media Communication* 26, no. 2 (2009): 128–44.

——. “Indigenous Circuits: Navajo Women and the Racialization of Early Electronic Manufacture.” *American Quarterly* 66, no. 4 (2014): 919–41.

Nelsen, R. Arvid. “Race and Computing: The Problem of Sources, the Potential of Prosopography, and the Lesson of *Ebony* Magazine.” *IEEE Annals of the History of Computing* (2017): 29–51.

“node, n.” In *Oxford English Dictionary Online* (2020). https://www.oed.com/view/Entry/127590?result=1&rskey=bCt60c&

Patten, Bernard C., and Eugene P. Odum. “The Cybernetic Nature of Ecosystems.” *The American Naturalist* 118, no. 6 (1981): 886–95.

Phillips, Dana. “Ecocriticism, Literary Theory, and the Truth of Ecology.” *New Literary History* 30, no. 3 (1999): 577–602.

Popkova, Natalia. “Controllability of Technosphere and Paradigm of Global Evolutionism.” *Philosophy & Cosmology* 21 (2018): 21–31.

Schneiderman, Ben. “Communication: Mapping Science.” *Nature* 468 (2010): 1037.

Six, Janet M., and Ioannis G. Tollis. “Circular Drawing Algorithms.” In *Handbook of Graph Drawing and Visualization*, edited by Roberto Tamassia, 285–315. New York: CRC Press, 2014.

Smith, Ted, David Sonnenfeld, and David Pellow, eds. *Challenging the Chip: Labor Rights and Environmental Justice in the Global Electronics Industry.* Philadelphia: Temple University Press, 2006.

Steinberg, Ted. *Down to Earth: Nature’s Role in American History*. New York: Oxford University Press, 2013.

Sylvester, J.J. “Chemistry and Algebra.” *Nature* 17 (1878): 284.

Taylor, Charles. *Modern Social Imaginaries*. Durham, NC: Duke University Press, 2004.

Turkle, Sherry. *Simulation and Its Discontents*. Cambridge, MA: MIT Press, 2009.

Ware, Colin. *Information Visualization: Perception for Design*. Cambridge, MA: Elsevier, 2020.

Wernimont, Jacqueline. *Numbered Lives: Life and Death in Quantum Media*. Cambridge, MA: MIT Press, 2018.

Wong, Rita. “Sort By Day, Burn By Night.” *Amerasia Journal* 33, no. 2 (2007): 141.

Yusoff, Kathryn. *A Billion Black Anthropocenes or None*. Minneapolis, MN: University of Minnesota Press, 2019.