White-Collar Foragers:
Ecology, Economics, and Logics of Information Visualization

I. Introduction

At the intersection of technological change and economic growth there is no measure more important than productivity. Defined as the ratio of output to input, productivity tracks the efficiency of labor. Increases in productivity allow us to produce more from less, leading to rising in standards of living. Productivity growth is used implicitly and explicitly as a justification for interventions in markets, governance, law, education, and many other social fields.

In this essay I show how computers and information visualization reconfigured the concept of productivity to fit emerging modes of knowledge work in the late 1980s and early 1990s. I describe the historical emergence of information visualization as a field of computer research, focusing specifically on Information Foraging Theory, a model for visual human-computer interaction. Information Foraging Theory drew on analogies from ecology, psychology, and economics and helped clarify the relationship between computers and productivity in three specific ways: it adapted neoclassical economic categories of scarcity and utility to the domain of information; it incorporated creative, non-mechanistic frameworks of human-computer interaction (HCI); and, through ecological analogy, it grounded adaptive models of knowledge work in economic values of maximization and efficiency. Information Foraging Theory redefined white-collar workers as "informavores" who forage in graphical information environments to produce meaning and value. This historical transformation of productivity was not simply descriptive; it actively defined categories, models, and practices of knowledge work. Far from a purely discursive construct, these new models of productivity would be embedded in the technological systems at the interface of labor, production, and value.

II. Visualizing Productivity

In the summer of 1993, Robert DeLine, then a computer science PhD student at Carnegie Mellon University, took an internship at Xerox's Palo Alto Research Center (PARC). During the summer, he worked with PARC researchers Jock Mackinlay and George Robertson to develop the Spiral Calendar, an electronic calendar application. The calendar was developed within a software environment called the Information Visualizer, which employed 3D graphics and animation to facilitate human interaction with information. Users could interact with daily schedules and shift between different time scales, such as weeks and months through an animated interface.

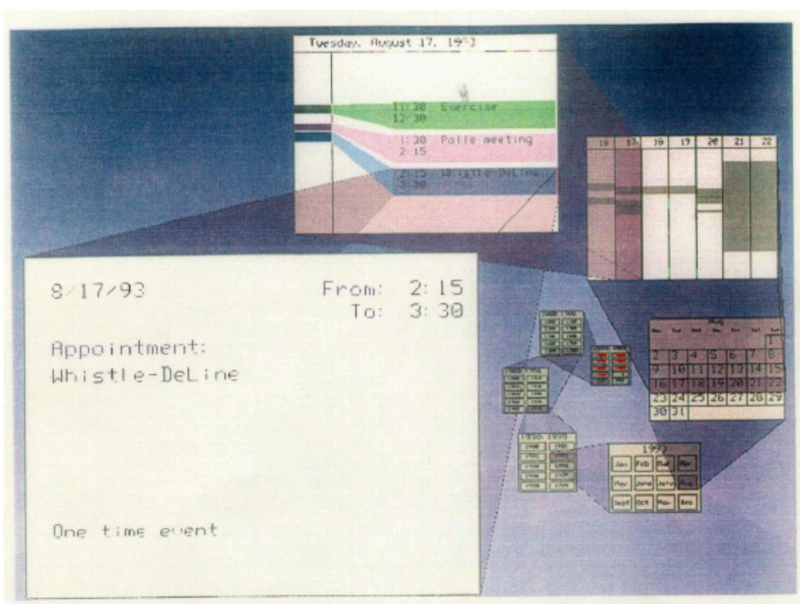

Figure 1. The Spiral Calendar interface showing multiple windows with different calendar displays and temporal scales. Reproduced from Jock Mackinlay, George Robertson, and Robert DeLine, "Developing Calendar Visualizers for the Information visualizer," 117.

Calendars have long contributed to the bureaucratic texture of white-collar work. But the Spiral Calendar was developed at an auspicious moment that marked transformations both in Human-Computer Interaction (HCI) paradigms that were redefining the nature of work and productivity. At PARC, the Spiral Calendar was used to test emerging frameworks for evaluating the productivity of information work in a computerized office. In a paper reflecting on the design and development of the Spiral Calendar and Information Visualizer, the Mackinlay, Robertson, and DeLine made the stakes of this project clear. Their goal was "to tap human perceptual abilities to increase both the volume and rate of information work"—to increase productivity.[1]

The form of the Spiral Calendar makes visible some of the distinctive logics of knowledge work. If Fordist manufacturing and mass production relied on repetition and rationalization, the calendar serves a means for organizing contingent events. Its purpose is to provide temporal structure in an environment that lacks the natural rhythms of the agricultural day or the mechanical rhythms of manufacture. Although knowledge workers might feel like slaves to the calendars, their purpose is to organize what is, at least formally, a much less determinate mode of labor and production, one that relies on collaboration and creativity. By structuring this freedom, the calendar makes knowledge work more productive.

However, on closer inspection, this narrative of progressive, linear increases in productivity begins to look more complicated. Is it really so simple to compare productivity in mass production and the knowledge economy? The output of these two economic modes look very different: the former produces material, countable, commodities while the latter deals in

[1] Jock D. Mackinlay, George G. Robertson, and Robert DeLine, "Developing Calendar Visualizers for the Information Visualizer," in *Proceedings of the 7th Annual ACM Symposium on User Interface Software and Technology* (ACM, 1994), 109.

creative insights, software code, or intellectual property. Given the heterogeneous nature of these types of work, we might instead ask how computer systems and productivity were mutually adapted to one another in response to the new demands of the knowledge economy. Information visualization would play an important mediating role in this historical transformation of productivity.

II. Redefining Productivity

Aspirations to historically stable productivity measurement are undermined by changes in both measurement techniques and the underlying economic practices that productivity measures.[2] Technological innovation makes measurement a moving target. For measures to remain accurate and relevant, they must reflect changes in the economy such as the spending habits measured by U.S. Consumer Price Index (CPI) or the makeup of large public corporations included in the Dow Jones index. However, these same changes may also introduce biases that reduce commensurability of productivity measures over time. For example, Eric Brynjolfsson and Adam Saunders highlight the difficulties in accounting for the changing quality consumer goods, particularly in high-tech fields like computing.[3]

This tension between accuracy and commensurability leads to anomalies and even paradoxes in which convictions and intuitions fail to appear in measurements. Such was the case

[2] The robust economic literature in productivity measurement is in itself a testament to its mutability. Measures and methods are constantly refined and the historical validity of is debated. One particularly important example is the fallout from the Boskin Commission report, which suggested that biases in the measurement of the Consumer Price Index (CPI) had lead the federal government to overestimate the magnitude of inflation. For a summary, see Robert J. Gordon, "The Boskin Commission Report: A Retrospective One Decade Later," *International Productivity Monitor* 1 (2006), no. 12: 7-22.

[3] Erik Brynjolfsson and Adam Saunders, *Wired for Innovation: How Information Technology is Reshaping the Economy* (Cambridge: MIT Press, 2010), 32-33.

of computing during the so-called productivity paradox in the late 1980s, just as information visualization was emerging as a distinctive field. In 1987 the economist Robert Solow summed up this mystery in a single sentence: “You can see the computer age everywhere but in the productivity statistics.”[4] The productivity paradox ran counter to the intuition that information technology was a driving force Western economic growth, particularly in the U.S.

Since the 1990s, there has been much effort to unravel the productivity paradox. One explanation holds that existing indicators failed to account for the gains and consumer surpluses inaugurated by computers and information technology.[5] The economist Paul David offered a historical explanation, predicting that productivity gains are only measurable over a longer time scale. Drawing an analogy between the dynamo and computer David argued that measurable productivity gains tend to lag behind the introduction of transformative technologies.[6] More recent surges in productivity growth have quelled some of the skepticism regarding IT and productivity. After stagnant growth from the 1970s through the early 1990s (around 1.4 percent), U.S. labor productivity growth increased by an average of 2.6 percent from 1996 to 2000 and by an average of 3.6 percent from 2000 to 2003. [7] Although productivity growth has since leveled off (while remaining healthily above the stagnant 1970s rates), many economists now agree that investment in IT has, at least in part, played a role in productivity increases in the 1990s and

[4] Robert Solow, “We’d Better Watch Out,” *The New York Times*, July 12, 1987, sec. Book Review.

[5] Brynjolfsson and Saunders, *Wired for Innovation*, 38.

[6] Paul A. David, “The Dynamo and the Computer: An Historical Perspective on The Modern Productivity Paradox,” *American Economic Review* 80, no. 2 (May 1990): 355.

[7] Brynjolfsson and Saunders, *Wired for Innovation*, 43.

early 2000s.[8] These observations are consistent with David's theory on the temporal lags between innovation and productivity gains.

However, the critical historical question in this case is not *whether* the productivity paradox has been explained, but rather *how* it was resolved. The case of information visualization shows specifically how productivity and knowledge work was defined, measured, and evaluated. Productivity, rendered abstractly or numerically is easily decontextualized, resulting naturalized or black box explanations that reinforce determinist accounts prevalent in both economics and computing. Moore's law, for example, implies a progressive link between computer hardware improvements and productivity, a faith in the future. The case of Information Foraging Theory, in contrast, shows that productivity is not merely a matter of linear growth but rather one of qualitative redefinition. By returning to the moments in which historical categories were being modified and defined, I emphasize their contingency, and uncover the conceptual analogies and constellations of knowledge that undergird our seemingly neutral interfaces and graphics. How did computer scientists understand the relationship between productivity and information technology. How did these researchers they adapt computational models and systems to the demands of knowledge work? What innovations, technical and conceptual, made information visualization a candidate for a new models of productivity?

These questions, in turn, relate to larger shifts in capitalist production, a set of changes variously described as transitions to a knowledge economy[9] or post-Fordism.[10] I use the term

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[8] There is significant disagreement about IT's impact on productivity relative to other factors, such as organizational and managerial innovations in other sectors. This position is outlined in depth in: William W. Lewis, Vincent Plamade, Badouin Regout, and Allen P. Webb, "What's Right with the US Economy," in *The Productivity Imperative*, ed. Diana Farrell (Boston: Harvard Business School Press, 2006), 44.

[9] Walter W. Powell and Kaisa Snellman, "The Knowledge Economy," *Annual Review of Sociology*, 2004, 201.

"knowledge economy" to describe this periodization because it best captures the cognitivist view of resources and value embraced by information visualization researchers. At the height of its fashion, theorists of the knowledge economy described what they thought to be a fundamental movement away from the mass production of material commodities toward an economy in which knowledge would be the major output. This lead to the redefinition of traditional economic categories and concepts. For example the firm was redefined as a "knowledge-creating entity."[11] Management theorist Peter Drucker captured the enthusiasm of this moment in his prematurely titled, *Post-Capitalist Society*, in which he confidently declared "knowledge is the only meaningful resource today."[12]

Viewed retrospectively, the productivity revolution prophesized by theorists of the knowledge economy has been only partially realized. However, this does not mean that we can ignore the changes in labor and distribution that it wrought, trends that also open normative and critical questions. For example, the recent revitalization of U.S. productivity has coincided with less auspicious changes in other macroeconomic indicators. These include increasing inequality, precarious, temporary, or flexible employment, and stagnating middle class wages.[13] The benefits of productivity growth have not accrued equally, as demonstrated by the "wedge"

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[10] Ash Amin, "Post-Fordism: Models, Fantasies, and Phantoms of Transition," in *Post-Fordism: A Reader*, ed. Ash Amin (Malden, MA: Blackwell, 1994), 12.

[11] Ikujiro Nonaka, Ryoko Toyama, and Akiya Nagata, "A Firm as a Knowledge-Creating Entity: A New Perspective on the Theory of the Firm," *Industrial and Corporate Change* 9, no. 1 (2000): 1–20.

[12] Peter F. Drucker, *Post-Capitalist Society* (New York: HarperBusiness, 1994).

[13] Luc Boltanski and Eve Chiapello, *The New Spirit of Capitalism*, trans. Gregory Elliot (London: Verso, 2007), xviii.

between productivity growth and median wage growth in the U.S. since the 1970s.[14] The contradictory relationship between increasing productivity and decreased demand for labor is at the heart of current economic anxieties about automation and robotics. More broadly, technical innovations can enable new relations of exploitation and dominance just as they increase efficiency. This ambivalence demands a historical account of technology that can account for its costs as well as benefits.

III. Method

I track the historical development of information visualization through a set of papers published by a select group of computer science researchers as the field emerged and developed. This group of texts has both a temporal and institutional coherence. They date primarily from the years 1991 to 1995 and were authored by researchers affiliated with Xerox's Palo Alto Research Center. PARC is widely known as a site of technological innovation, and its success in applying computing research to create "the office of the future".[15] Little has been written on later PARC research from the late 1980s and 1990s, which included important work on information visualization. Many PARC researchers involved in visualization research during these years, especially Stuart Card, George Robertson, Jock Mackinlay and Peter Pirolli continue to hold central positions in the field. Following his time at PARC, Robertson helped direct the Visualization and Interaction Research Group at Microsoft Research. Mackinlay worked as a director of visual analysis at Tableau Software, a leading private sector visualization and big data

[14] Lawrence Mishel, "The Wedges between Productivity and Median Compensation Growth," *Economic Policy Institute*, April 26, 2012, http://www.epi.org/publication/ib330-productivity-vs-compensation/.

[15] Michael Hitzik, *Dealers of Lightning: Xerox PARC and the Dawn of the Computer Age* (New York: Harper Business, 1999).

analytics provider. Card's *Readings in Information Visualization*, published in 1999, continues to be an important reference and serves as a retrospective documentation of the field's development. Pirolli has continued visualization research at PARC, and published an updated overview of Information Foraging Theory in 2007.[16] Along with academic sites of visualization research during this time, such as Ben Bederson's Human-Computer Interaction Lab at the University of Maryland, PARC was a crucible in the development of information visualization as a field of computer science research.

IV. The Emergence of Information Visualization

Returning to the example of the Spiral Calendar, Mackinlay, Robertson, and DeLine contextualized their work historically, describing the gradual improvements that previous electronic calendar applications had introduced. However, they criticized the conservative pattern of this development: "Although electronic calendars have been improving, they use the same hierarchy of calendars that were developed for paper without particularly exploiting the new medium for visualization…A key question when designing calendar visualizers is how to use the new medium to design visualization techniques that support the user's navigation through the calendar hierarchy."[17] This brief description, part of a larger discourse on moving beyond the limits of the paper office,[18] contains a number of concerns that would animate larger discussions on the innovations and contributions of information visualization. The electronic calendar represented a new medium, with specific visual qualities and signaled a cognitive perspective on

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[16] Peter Pirolli, *Information Foraging Theory: Adaptive Interaction with Information* (New York: Oxford University Press, 2007).

[17] Mackinlay, Robertson, and DeLine, "Developing calendar visualizers for the information visualizer," 110.

[18] See, for example, Alan Kay and Adele Goldberg, "Personal Dynamic Media," *Computer* 10, no. 3 (1977): 31–41.

labor and productivity. The Spiral Calendar permitted users to access multiple temporal scales. Through animation, it allowed users to infer logical connections between temporal events and scales. The Spiral Calendar also allowed multiple user and organizational calendars to be compared, allowing for efficient coordination of collective action. These self-conscious reflections on the novelties and potential of visual modes of interaction were characteristic of the emergent field of information visualization.

Information visualization has always been an interdisciplinary endeavor, emerging from a constellation of research fields, including computer graphics, cognitive psychology, scientific computing, communications, symbolic programming, and graphic design. One early confluence of these sources was a special issue of the journal *Computer Graphics* that published the proceedings of the Panel on Graphics, Image Processing, and Workstations sponsored by the National Science Foundation (NSF).[19] The participants in this workshop applied techniques from computer science, particularly graphics and image processing to visual applications in the natural sciences. They named the resulting intersectional field scientific visualization.

More specialized than information visualization (which would be formally defined later), the proceedings nevertheless introduced a number of ideas that would help define the larger field. One was the familiar specter of information overload. Using aquatic metaphors, the writers described the "*fire hoses* [emphasis in original] of information" and scientists "deluged by the flood of data."[20] These researchers saw a threatening economy of abundance, in which the profusion of data would render meaningful inference and interpretation scarce. The authors

[19] Bruce H. McCormick, Thomas A. DeFanti, and Maxine D. Brown, eds., *Visualization in Scientific Computing*, vol. 21, Computer Graphics 6 (New York: ACM SIGGRAPH, 1987).

[20] Ibid., 4.

reprised Richard Hamming's 1962 observation, "the purpose of computing is insight, not numbers."[21] In this context, Hamming's observation can be interpreted as an alternative formulation of a productivity paradox in the case of computing. The ability of computers to store and represent ever-larger volumes of data threatens our ability to interpret it in meaningful ways, necessitating technological and analytical innovations to transform data from an input into a productive, informational output.

As Ann Blair has shown[22] the experience of information overload is a historically recurrent theme. However, even if the experience of overload in the late 1980s and 1990s was not historically unprecedented, its specific articulation proved an effective justification for information visualization projects and organizing research agendas. At this moment, overabundant information was seen as a threat to knowledge production where valued output is creative or scientific insight. The question, then, is how did visuality emerge as a compelling resolution to a productivity impasse at this historical moment?

The authors of "Visualization in Scientific Computing" emphasized the unique cognitive capacities of human vision as a means to efficiently harness the growing power of supercomputers, translating vision in terms of signal processing: "The gigabit bandwidth of the eye/visual cortex system permits much faster perception of geometric and spatial relationships than any other mode, making the power of supercomputers more accessible."[23] Visual cognition also represented larger shifts in the philosophy of computer science, influentially formulated by

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[21] Ibid., 3.

[22] Ann M. Blair, *Too Much to Know: Managing Scholarly Information Before the Modern Age* (New Haven: Yale University Press, 2010).

[23] McCormick, DeFanti, and Brown, *Visualization in Scientific Computing*, vii.

Winograd and Flores, away from computation as a self-sufficient form of artificial intelligence and instead toward an interactional approach that matched computational processes to human cognition.[24] "Visualization in Scientific Computing" contrasts dynamic visualization with the inefficiencies of the discrete batch processing, in which scientists had to wait for the results of a set of calculations in order to proceed to the next calculation or interpretation. By representing data in visual form, scientists would be able to interact and steer their calculations, gaining new scientific insights into processes and simulations. Anticipating concerns regarding efficiency and productivity, the visual mode of interaction also promised means to make efficient use of increasing hardware capabilities: "Raw computing power would be more effectively harnessed than it is today if calculations could be understood pictorially and their progress guided dynamically."[25]

Although its implications would be broad in retrospect, "Visualization in Scientific Computing" focused explicitly on the needs of scientists and their funding bodies, principally the NSF. However, researchers at PARC, working on interfaces and human-computer interaction problems, recognized that newly accessible hardware, notably the Silicon Graphics Iris line of workstations, would soon allow for a wider application of the visualization paradigm, outside of supercomputer labs. The broader term "information visualization" was probably first used in a technical sense in a 1989 paper published by Robertson, Card and Mackinlay at PARC that described an interface architecture called the Cognitive Coprocessor and an application called the Information Visualizer. Much like visualization in supercomputing applications, the Information

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[24] Terry Winograd and Fernando Flores, *Understanding Computers and Cognition: A New Foundation for Design* (Reading, MA: Addison-Wesley, 1986).

[25] Ibid., 12.

Visualizer was presented as the means of unlocking graphics hardware: "…in order to fully utilize these capabilities in a systematic way, new software architectures are needed."[26] At this early stage, the distinction between information and scientific visualization was murky, but Robertson, Card and Mackinlay signaled information visualization as a domain for future research: "The application area is *Information Visualization*, [emphasis in original] analogous to Scientific Visualization. In Information Visualization, 2D and 3D animated objects (or visualizations) are used to represent both information and the structural relationships of information. Direct manipulation of these objects causes changes in the actual structure of the information or changes in the actual information."[27]

Over time, the boundaries between these two fields became more distinct, and by 1999 Stuart Card, Jock Mackinlay, and Ben Schneiderman formalized a retrospective definition of information visualization that distinguished it from purely scientific applications: "the use of computer-supported, interactive, visual representations of abstract data to amplify cognition."[28] This definition retrospectively incorporated a number of key conceptual innovations. The domain of "abstract" data broadened the potential scope of information visualization and marginalized scientific visualization. The latter, as defined by Card, Mackinlay, and Schneiderman, represents data grounded in a physical or spatial form, whereas information visualization deals with the

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[26] George Robertson, Stuart K. Card, and Jock D. Mackinlay. "The Cognitive Coprocessor Architecture for Interactive User Interfaces." In *Proceedings of the 2nd annual ACM SIGGRAPH symposium on User interface software and technology*, p. 10. ACM, 1989.

[27] Ibid., 11-12.

[28] Card, Stuart K., Jock D. Mackinlay, and Ben Shneiderman. *Readings in Information Visualization: Using Vision to Think*. San Francisco: Morgan Kaufmann, 1999, 7.

question of "mapping non-spatial abstractions into effective visual form."[29] A second innovation in this broader definition is that it no longer refers to specific hardware improvements for justification. The goal is no longer to make effective use of graphics capabilities or supercomputer power, but instead, to "amplify cognition." Harkening back to Hamming's formulation, information visualization connected questions of numbers, representation, vision, cognition, and knowledge. The ambitious scope of this field would have clear repercussions on patterns of organization and production of the emerging knowledge economy.

V. Information Foraging Theory

Up to this point, I have described the economic transitions that were forcing economists and policy makers to think differently about productivity, and I have described how computer science researchers identified vision as a privileged means to harness increased computational and graphics capabilities in order to productively augment human cognition. In order to bring these two trends together, practitioners needed to build both a plausible model and actual systems to reconcile vision, graphical displays, and new forms of knowledge work. For computer scientists, this meant reconciling theories of productivity with the material structures of existing office environments and hardware and software. How did computer scientists configure information visualization to meet the demands of cognitive tasks, to increase productivity? Drawing from the disciplines of ecology, cognitive psychology, and microeconomics, Information Foraging Theory represented a particularly robust framework for understanding historical relationships between computing technology and visualization, one that would be applied to visualization applications and systems far beyond the Spiral Calendar.

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[29] Ibid.

Information Foraging Theory defines users as "informavores," who seek to optimize their intake of information in a given environment.[30] The model draws analogically on a formal, quantitative literature on animal foraging behavior in ecology, stemming from the Marginal Value Theorem developed by the evolutionary ecologist Eric Charnov.[31] According to this theory, animals forage for food, which is distributed unevenly in patchy environments. Animals face an optimization problem in which they seek to maximize caloric intake in a given patch before its returns diminish and they seek out a new patch. Information Foraging Theory adapts this insight to human information seeking, adding important modifications based on human cognition.[32] This model of human computer interaction provided three conceptual tools for redefining labor and productivity in the knowledge economy: (1) a microeconomic model that configured the dynamics of scarcity and abundance in terms of information, (2) a non-mechanistic framework for knowledge working characterized by uncertainty and creativity and (3) an ecological, adaptive model of knowledge work grounded in economic values of efficiency.

Another return to the Spiral Calendar application can show how this framework was applied. Card, Pirolli, and Mackinlay evaluated the calendar's functionality by defining a task and measuring a user's time of task completion.[33] Users were asked to position the calendar to a series of 11 dates at different temporal intervals, and the researchers reported the mean

[30] Pirolli, *Information Foraging*, 13.

[31] Eric L. Charnov, "Optimal Foraging, the Marginal Value Theorem," *Theoretical Population Biology* 9, no. 2 (April 1976): 129–36, doi:10.1016/0040-5809(76)90040-X.

[32] Pirolli, *Information Foraging Theory*, 7-12.

[33] Stuart K Card, Peter Pirolli, and Jock D. Mackinlay, " The Cost-of-Knowledge Characteristic Function: Display Evaluation for Direct-Walk Dynamic Information Visualizations," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pp. 238-244. ACM, 1994.

navigation times along standard deviations. Although this experiment had clear limits of validity—it relied on a very small, nonrepresentative samples of lab workers and the authors provided no evidence of repetition—the more important conceptual movie is how these quantitative results were fit into models for classifying and evaluating information-oriented work. This process required the researchers to define a set of assumptions and concepts that could be empirically measured, made commensurable, and compared. Their experimental model allowed researchers to converge on a set of shared, quantitative indicators and to tie visualization knowledge outcomes, allying anxieties about the usefulness of visualization. However, operations of categorization and commensuration also came with costs; through abstraction they closed off information visualization to alternative possibilities and pluralities of localized uses. Nonetheless, practitioners saw model building as crucial to the development of HCI as a rigorous field. Even a decade later, Ed Chi and his colleagues complained, "the lack of empirically validated HCI theoretical model has plagued the development of our field…"[34]

Models and evaluative criteria have been shown in a variety of fields not to simply describe systems and phenomena, but also to create, intervene, and reinforce categories and indicators, resulting in a "mirror effects,"[35] "reactivity,"[36] or performativity. If models produce as well as describe effects, then it is crucial to follow metaphors and translation of concepts as they

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34 Ed H. Chi, Adam Rosien, Gesara Supattanasiri, Amanda Williams, Christiaan Royer, Celia Chow, Erica Robles, Brinda Dalal, Julie Chen, and Steve Cousins, "The bloodhound project: automating discovery of web usability issues using the InfoScent simulator," In *Proceedings of the SIGCHI conference on Human factors in computing systems*, ACM, 2003, 505.

35 Alain Desrosières, "The Economics of Convention and Statistics: The Paradox of Origins," *Historical Social Research/Historische Sozialforschung*, 2011, 64–81.

36 Wendy Nelson Espeland and Michael Sauder, "Rankings and Reactivity: How Public Measures Recreate Social Worlds," *American Journal of Sociology* 113, no. 1 (2007): 1–40.

were operationalized to evaluate visualization systems. This performative character of Information Foraging Theory reproduced neoclassical economic understandings of productivity and efficiency in a new context of human-computer interaction.[37]

VI. Information, Knowledge, and Scarcity

In order to model the data obtained in the Spiral Calendar evaluation, Card, Pirolli, and Mackinlay defined a "the Cost-of-Knowledge-Characteristic Function" that represented a number of informational units (such as documents) on the y axis and cost (time) on the x axis.[38] Any information management system could be plotted according to the number of elements it contained and the time (or other resource) expended to access the information. Visualization researchers could then work to shift this curve (see elements a and b in Figure 2) through new technologies or interfaces that either increased the number of accessible elements of a system at a given cost and/or decrease the resources expended to access such a system.

[37] For an introduction to performativity in another context, see: Michel Callon, "What Does it Mean to Say That Economics is Performative?" In Donald A. MacKenzie, Fabian Muniesa, and Lucia Siu, eds. *Do Economists Make Markets?: On the Performativity of Economics* (Princeton University Press, 2007), 311-357.

[38] Card, Pirolli, and Mackinlay, "The Cost-of-Knowledge Characteristic Function," 238.

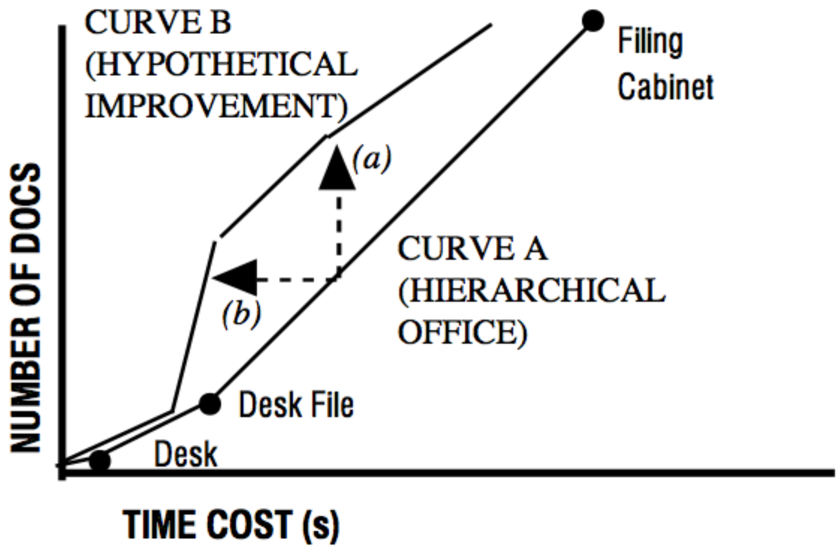

Figure 2. Defining the value of knowledge in terms of cost, utility, and optimality in the office environment. Reproduce from Stuart Card, Peter Pirolli, and Jock D. Mackinlay, "The Cost-of-Knowledge Characteristic Function: Display Evaluation for Direct-Walk Dynamic Information Visualizations," 239.

This graph represented the office environment as in terms of an economic optimization problem. Each information system, the desk, the desk file, and the filing cabinet, has a discrete environmental structure in which the knowledge worker navigates the costs and benefits of a given problem. For example, while the desk is presumably close to hand, minimizing time cost, its surface is small, limiting the number of accessible documents. The file cabinet, on the other hand, is much more costly to access in terms of time (one has to stand up from one's desk, walk to the cabinet, and sort through the files) but has a richer payoff in terms of number of documents.

At the outset of the paper, Card, Pirolli, and Mackinlay described the motivation behind this model:

> We have argued that, at least in a world of abundant information, but scarce time, the fundamental information access task is not finding information, but the optimal use of a person's scarce time in gaining information. That is, the important thing is to maximize information benefits per unit cost (The unit of cost considered in this article is primarily the user's time). To aid in doing this, we need to know how much additional information becomes available for each additional amount of time expended.[39]

The language of scarcity, optimality, benefits, and unit costs refers to a specific set of neoclassical or marginalist economic criteria for the evaluation of information-oriented tasks.[40] Following the marginalist insight, Card, Pirolli, and Mackinlay conceptualized a user's time as a scarce resource that can be allocated in different ways. The optimal allocation of this resource is subject to diminishing returns and depends upon finding an equilibrium where the marginal utility of a unit information equals the time cost needed to obtain it.[41] Michel Foucault locates this optimal perspective historically in the notion of "security," at the origin of the liberal and neoliberal modes of governance in which power operates not by making prohibitions but by defining ranges in which an optimal distribution of persons and social forms can be defined.[42] As Foucault demonstrates in his neoliberalism lectures, the science of economics holds a privileged position, both historically and epistemologically in this regime. Information visualization researchers reconfigured this economic definition of personhood *homo economicus* as the

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[39] Ibid.

[40] Lawrence Birken, "From Macroeconomics to Microeconomics: The Marginalist Revolution in Sociocultural Perspective," *History of Political Economy* 20, no. 2 (1988): 255.

[41] Mark Blaug, *Economic Theory in Retrospect*, Fourth Edition (Cambridge: Cambridge University, 1985), 297.

[42] Michel Foucault, *Security, Territory, Population: Lectures at the Collège de France, 1977—1978*, trans. Graham Burchell (Picador, 2009), 20. See also, Pierre Dardot and Christian Laval, *The New Way Of The World: On Neoliberal Society*, trans. Gregory Elliot (London ; New York: Verso, 2014).

"informavore."[43] The definition of this anthropomorphic model forms a key site of mediation between computational power and human cognition, configuring both computers and users for knowledge work.

If scarcity and utility are the universalizing assumptions of a neoclassical economic perspective, information visualization researchers needed to reconfigure these concepts to fit new modes of productivity based on knowledge, creativity, and insight. These new knowledge goods challenged conventional theories of scarcity, supply, and demand. As visualization researchers insisted, computing power and accessible information was no longer scarce but abundant, and becoming ever more so. Information and knowledge outputs, unlike other material commodities also had a marginal cost that is close to zero, making them difficult to account for in terms of monetary value.[44]

The solution to this problem was to locate a resource category that conformed to neoclassical assumptions of scarcity. As early as the 1970s, the influential social scientist Herbert Simon (who would later receive a Nobel Prize in Economics for his work on decision-making), had conceived of attention as a key resource constraint within computational environments.[45] With cognitive attention as a scarce input, the output, to reprise Hamming's terms, are insights, not numbers. In a knowledge or attention-based economy, information visualization can be placed into a precise, quantitative relationship with productivity. After this redefinition, information visualization could increase productivity by increasing the amount of

[43] Pirolli, *Information Foraging Theory*, 13.

[44] Brynjolfsson and Saunders, *Wired for Innovation*, 93.

[45] Simon, H. A. (1971), "Designing Organizations for an Information-Rich World", in *Computers, Communication, and the Public Interest*, ed. Martin Greenberger (Baltimore: Johns Hopkins Press, 1971).

knowledge output per unit of scarce cognitive input. Information Foraging Theory provided a formal means to evaluate these marginal costs and benefits.

VII. Working with Uncertainty

In addition to incorporating economic models of rationality and scarcity, Information Foraging Theory made legible and measurable new modalities of knowledge labor. In this sense, it provides a specific case for understanding how computers were incorporated into the practice of knowledge work, distinct from prior from Taylorist and Fordist models of scientific management. The Taylorist mode is characterized by intensive, mechanical division, an analytical separation of productive tasks into their smallest component parts. Frederick Taylor described this management style in his classic, *Principles of Scientific Management*, as "a science for each element of a man's work."[46] If Taylorist management was an atomistic science of analysis and mechanics, knowledge work introduced an ecological or biological sense of systems and holism, modeling the worker as a coherent, individual, economic maximizing agent.

In Peter Pirolli's writings on the development of Information Foraging Theory, he describes a formally similar transformation, from repetitive, Taylorized tasks to creative knowledge work in the domain of HCI. However, this change, as Pirolli recognized was a matter of contingency rather than necessity—computers could and did function in either mode. For, example Pirolli notes the preponderance of mechanistic, HCI tasks, such as text editing or data entry, a paradigm that he critiqued as a "computer-centric approach.[47] Instead, Pirolli situated Information Foraging Theory within a more creative, "information-centric" framework of

[46] Frederick Taylor, *The Principles of Scientific Management* (New York: Harper & Brothers, 1911), 36.

[47] Pirolli, *Information Foraging Theory*, 15.

Human-information interaction (HII). This latter paradigm redefined the office as an undetermined, "probabilistically textured environment," in which agents need tools for "decision making under uncertainty."[48] Information foragers dealt with open-ended information seeking tasks and needed to allocate their cognitive and temporal resources efficiently and adaptively (rather than mechanistically) in these spaces. The movement from deterministic to probabilistic modalities of labor employed new models based on rational choice theory (deriving from microeconomics) and Bayesian approaches to probability. Instead of a factory worker repeating tasks at a machine, the knowledge worker would organize information in their environment, perhaps by structuring the workday through a calendar application.

Information Foraging Theory posited a different type of agency in workers, based on flexible, expected utility calculations.[49] Human-information interaction, in its assumption of individualized rationality, is more holistic than the hyper-specialized Taylorist model, divided the worker to the smallest possible unitary task. Instead of exploiting the division and intensification of *biomechanical* labor, information visualization exploited the *cognitive* symmetries between the worker and a given information environment. In *The Age of the Smart Machine*, Shoshana Zuboff writes, "As the new technology integrates information across time and space, managers and workers each overcome their narrow functional perspectives and create new roles that are better suited to enhancing value-adding activities in a data-rich environment."[50] Besides describing new styles of work, the purported holism of knowledge work

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48 Ibid., 23.

49 Ibid., 106.

50 Shoshana Zuboff, *In The Age Of The Smart Machine: The Future Of Work And Power*, (New York: Basic Books, 1988), 6.

also had the advantage of defusing critiques of capitalism based on the alienation of labor. A probabilistic, nondeterministic working process demands workers who are flexible, adaptable, creative and autonomous. In this respect, Information Foraging Theory aligns with aspects of Boltanski and Chiappello's model of the "projective city" of creativity and commitment, which serves as a normative justification for involvement in work under capitalism.[51]

To make a provocative summary, Information Foraging Theory appeared to resource neoclassical economics' framework of desire and utility maximization in consumption for knowledge-based production. In this model, the rational microeconomic agent allocates his or her scarce cognitive resources not to maximize personal or individual utility, but instead to produce a maximum amount of knowledge in conditions of abundant information. The logic of work, flexible, indeterminate, and individualistic, mirrors that of consumption. While computers are obviously still used to intensify rote, alienating tasks in way consistent with Taylorist management, Information Foraging Theory shows how they were also adapted to less mechanistic, more creative knowledge work by the cognitive means of visualization.

VIII. Ecology and Economy

In the previous sections on scarcity and uncertainty, I have obliquely referred to the most radical feature of Information Foraging Theory: it's incorporation of ecological analogies into a model of human-information interaction. These symmetries between ecology and economics contributed to adaptionsist models of information visualization grounded in economic values of maximization and efficiency. These criteria configured computers in a way in which they could productively be incorporated into knowledge work.

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[51] Boltanski and Chiapello, *The New Spirit of Capitalism*, 112.

Many computer historians have noted the mutual influence of biological and ecological frameworks on computing. To take only a few examples, Wendy Chun has analyzed the "biological abstractions" that Von Neumann introduced in his concept of memory.[52] Fred Turner has chronicled the importance of biology and systems theory for helping shift the cultural meaning of computing.[53] Lily Kay has shown how the discourse of information was incorporated into biological sciences.[54] This discursive entanglement between organism, system, and machine also played an important role in the emergence of information visualization, whose practitioners sought to build interfaces between computational processes and the physiology and psychology of human vision.

While the relationship between biology and computing has deep roots, it was not an obvious or even necessary scientific methodology in which to ground Information Foraging Theory. Pirolli, aware of this contingency, explained that Information Foraging Theory was a departure from "the historical bulk of experimental psychology" in its incorporation of methods from biology rather than physics.[55] Similarly, economic historian Phillip Mirowski has demonstrated the deep affinities between physics and neoclassical economics, whose

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[52] Wendy Hui Kyong Chun, *Programmed Visions: Software and Memory* (Cambridge: MIT Press, 2011), 140.

[53] Fred Turner, *From Counterculture to Cyberculture: Stewart Brand, the Whole Earth Network, and the Rise of Digital Utopianism* (Chicago: University Of Chicago Press, 2008).

[54] Lily E. Kay, "How a Genetic Code Became an Information System" in *Systems, Experts, and Computers: The Systems Approach in Management and Engineering, World War II and After*, eds. Agatha C. Hughes and Thomas P. Hughes (Cambridge: MIT Press, 2000), 462–85,

[55] Pirolli, *Information Foraging Theory*, 4.

assumptions would also be reproduced in Information Foraging Theory.[56] In addition the displacement of physics by biology, Information Foraging Theory, expanded the scope of the biological metaphor beyond the sensory field of vision, introducing an adaptive, evolutionary agency or subjectivity into models of information visualization.

Information Foraging Theory built on prior cognitive models of visualization and interfaces developed by PARC researchers but in a more formal and systematic framework. These prior models introduced an adaptionist framework to information work and included the cost-of-knowledge-characteristic function, which was used to evaluate the Spiral Calendar as well as the idea of the "information workspace" and "cost structures," which used biological analogies to describe the costs and benefits of different working environments. Card, Robertson, and Mackinlay observed in a 1991 paper that, "In general, information processing systems, whether artificial, like this office, or natural biological systems, like the human eye, tend to be organized to minimize the cost structure of information processing."[57] However, the key conceptual innovation of Information Foraging Theory would be to condense these models into a unified (but modifiable) ecological analogy with optimal foraging theory.

Canonically formulated by David W. Stephens and John Krebs, optimal foraging theory dated from work beginning in the 1960s and used mathematical models to understand the strategic behavior of predators seeking to maximize caloric or energy intake in a given time

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[56] Philip Mirowski, "Physics and the 'Marginalist Revolution,'" *Cambridge Journal of Economics* 8, no. 4 (December 1, 1984): 361–79.

[57] Stuart K. Card, George G. Robertson, and Jock D. Mackinlay, "The Information Visualizer, an Information Workspace," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '91 (New York: ACM, 1991), 182.

period.[58] At their height, these theories exerted considerable influence in the fields of ecology and even areas of anthropology[59] and were mobilized by information visualization researchers, particularly Pirolli. These theoretical analogies are not exact correspondences but open a space for embedding ideas in systems, machines, and practices. Pirolli himself recognized the productive nature of this difference. “There are certainly differences between food and information, the most notable being that information can be copied, and the same content viewed twice often is not informative the second time around. But it is the nature of metaphors and analogies that they are productive, but not completely equivalent.”[60]

Taken analogically, the triangular relationship between ecology, economics, and information visualization worked through a series of mediations. First, optimal foraging theory imported signature concepts from economics, which, in turn were incorporated into Information Foraging Theory, resulting in an economistic model of information environments that could be empirically tested and improved. From the perspective of intellectual history, the difficulty of working at this first level is that ecologists rarely cited across disciplinary boundaries. However, their debt to neoclassical economics can be inferred through both the use of a shared set of signature concepts (“marginality” “optimization,” “diminishing returns”) and through a common methodological interest in formal mathematics. The cross disciplinary link is also made explicit in response to critique. For example, writing in 1978 biologist John Maynard Smith recognized, “In recent years there has been a growing attempt to use mathematical methods borrowed from

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[58] David W. Stephens and John R. Krebs, *Foraging Theory* (Princeton, N.J: Princeton University Press, 1986).

[59] Eric Alden Smith, “Optimization Theory in Anthropology: Applications and Critiques,” in *The Latest on the Best: Essays on Evolution and Optimality*, ed. John Dupré (Cambridge: MIT Press, 1987), 201–249.

[60] Pirolli, *Information Foraging Theory*, 43.

engineering and *economics* in interpreting the diversity of life" [emphasis added].[61] This point is crystallized later in the article in a discussion of optimization criteria and game theory criteria, which relied on signature concepts from neoclassical economics such as the Pareto equilibrium (a concept introduced by one of the founders of mathematical economics, Wilfredo Pareto) and the Nash equilibrium, which has been applied in a variety of microeconomic contexts.[62] Although biological sources make up the vast majority of the sources for this article, Maynard Smith does cite Von Neumann and Morgenstern's classic *Theory of Games and Economic Behavior*.

Concepts like optimality can have *both* specific meaning in evolutionary terms and implicit economic senses. This analogical slippage can be quite productive, as in David W. Stephens' article, titled, "On Economically Tracking a Variable Environment."[63] Here the word "economically" works in a biological sense, relating to the efficiency of food intake during foraging. However, the environment that Stephens describes looks very similar to that of the microeconomic agent in a condition of bounded rationality, where "information is imperfect or costly (or both)," and where "the cost of finding out which resource is best might outweigh the advantages of selectivity."[64] Moreover, the emphasis on information in these cases demonstrates the short conceptual distance required to adapt these biological theories to problems in information visualization.

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[61] J. Maynard Smith, "Optimization Theory in Evolution," *Annual Review of Ecology and Systematics* 9 (January 1, 1978): 31.

[62] bid., 42.

[63] D. W. Stephens, "On Economically Tracking a Variable Environment," *Theoretical Population Biology* 32, no. 1 (August 1987): 15–25, doi:10.1016/0040-5809(87)90036-0.

[64] Ibid., 15.

In a 1995 paper Peter Pirolli and Stuart Card formally introduced Information Foraging Theory as a generalizable approach for developing and evaluating interface and interaction systems under conditions that will now seem familiar: "We have argued that in an information-rich world, the real design problem is not so much how to collect more information, but rather, how to optimize the user's time…"[65] In order to incorporate the optimal foraging theory, Pirolli and Card made a series of translations in order to configure foraging behavior to the demands of information work. For example, the variable of energy intake is translated into "information value," which, in turn is determined by a dynamic and variable task environment, such as "choosing a good graduate school, developing a financial plan for retirement, developing a successful business strategy, or writing an acceptable scientific paper"[66] These tasks are distinguished from Taylorist forms of work in that they are less defined and susceptible to mechanistic rationalization. They can be formally represented probabilistically, in stochastic equations, and the authors spend much of the article defining parameters and functions for tasks such as scanning or scrolling through lists of documents.[67] The mathematical treatment of information work is therefore less concerned with static rates of output than discovering optimal maximum rates of information gain and shifting these curves and tangents in order to decrease the time cost per unit of "information value," increase the latter per unit of the former, or both.

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[65] Peter Pirolli and Stuart Card, "Information Foraging in Information Access Environments," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '95 (New York, NY, USA: ACM Press/Addison-Wesley Publishing Co., 1995), 51.

[66] Ibid., 52.

[67] Ibid., 53.

The mode of optimality therefore can be applied not only to power and governance as Foucault so brilliantly demonstrated, but also to labor and production.

Pirolli and Card concluded their paper with a quote from Stephens and Krebs's preface to *Foraging Theory* where they discussed the different teleological questions that we ask about machines and organisms. Both the biologist and the mechanical engineer are concerned with purpose. For the engineer, purpose works through the mechanism of intentionality. Machines are designed with tasks in mind. The biologist frames questions of purpose in terms of adaption and natural selection. However, Pirolli and Card place these two frameworks in contact: "In this paper, we have tried to make a start at reversing the above analogy—exploiting theory developed in the service of behavioral ecology to analyze information ecologies and the design of interactive information systems."[68] The three terms in this framework (biology, machine, and purpose) coalesced in information visualization. Beginning with the biological capacities of human vision, Information Foraging Theory conceptually remodeled the office as an information environment in such a way that its economic purpose could be formally described and measured. As concepts from biology and economics were translated into design thinking, purpose as intention or design could be reintroduced. Information visualization could be designed, as was the case with the Spiral Calendar, "to tap human perceptual abilities to increase both the volume and rate of information work,"[69] to increase the productivity of knowledge work.

In this influential strand of information visualization research, ecology acted as a mediating framework through which computers could be designed configured to increase productivity in the information economy. This historical confluence of biology, economics and

[68] Ibid., 58.

[69] Mackinlay, Robertson, and DeLine, "Developing Calendar Visualizers for the Information Visualizer," 109.

computing technology shaped many discourses at the intersection of computers and the economy. For example, in 1988 researchers at the Santa Fe Institute published a set of papers under the heading of *The Economy as an Evolving Complex System*.[70] In 1993, management expert James F. Moore described capitalist competition in the ecological term of a "business ecosystem" in which firms compete, cooperate, and co-evolve in response to technical innovations. Moore used the rise of the personal computer as a case study of a business ecosystem, suggesting an affinity between computing and ecological frameworks of capitalism. Somewhat later, critical theorists, such as Tiziana Terranova, have described how the "entanglement…of the natural and the technological" has lead to new forms of emergent production and soft control.[71] These wider analyses, however, tended operate at the macroeconomic level, describing the behavior of firms, sectors, the national economy, and even the nature of contemporary capitalism as system. In contrast, Information Foraging Theory shows how ecological models could be used in microeconomic contexts to adapt computers to both the cognitive capabilities of human users and the new displays, hardware, and structures of information that structured their environments. If the paradox of computers and productivity was measured and expressed at the macroeconomic level, information visualization revealed how this paradox could be resolved at the micro level of the individual worker, by adapting interfaces and applications to the demands of information work.

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[70] Philip W. Anderson, Kenneth Arrow, and David Pines, eds., *The Economy As An Evolving Complex System* (Redwood City, Calif.: Westview Press, 1988).

[71] Tiziana Terranova, *Network Culture: Politics for the Information Age* (Ann Arbor: Pluto Press, 2004), 100.

IX. Conclusion

From a contemporary vantage point, the origins of information visualization might appear humble. The Spiral Calendar, for example did break with the metaphorical character of the desktop interface but it did so in order to deliver a more efficient means of what office workers already did: scheduling meetings, events, deadlines, and to-dos. The mundane white-collar practices aided by productivity software of the early 1990s seem totally disconnected from the far-reaching epistemological claims supported with data-visualization today. Data journalists promise charts to "explain the jobs report,"[72] or, more ambitiously "explain the world."[73] Visualization techniques that were originally developed to quantitatively increase the rate and volume of knowledge work now undergird new forms of knowledge itself, new visual means of computationally interpreting the world. The rise of big data has reconfigured the historically recurrent anxiety of information overload in fields as diverse as journalism, business, or even digital humanities.

The purpose of this history is to return to the decisive but contingent moments that shaped the development of information visualization. In the case of Information Foraging Theory, I have emphasized the economic and ecological models and metaphors that shaped the development of software interfaces and visualization systems. The contingent nature of these design decisions troubles progressive or necessary accounts of the relationship between computing and productivity. Instead, material or hardware innovations such as the increasing

[72] Neil Irwin, "Six Charts That Explain the Jobs Report," *The New York Times*, August 1, 2014, http://www.nytimes.com/2014/08/02/upshot/five-charts-that-explain-the-jobs-report.html.

[73] Dylan Matthews, "40 Charts That Explain the World," *The Washington Post*, January 15, 2014, http://www.washingtonpost.com/blogs/wonkblog/wp/2014/01/15/40-charts-that-explain-the-world/.

power of graphics processing and displays, had to be configured in interactional frameworks that allowed human users to redefine economic output. Vision was seen by early researchers as a particularly efficient means to match human cognitive capabilities to computational tasks in order to increase productivity. Information Foraging Theory represents a particularly rich and influential (but far from the only possible) framework in which productivity could be produced and measured. Its analogical incorporation of both models and metaphors from neoclassical economics and ecology both described and produced conditions of labor in the knowledge economy: new configurations of scarcity and abundance in relation to digital information and attention, work characterized by creativity and uncertainty (as opposed to repetitive division of labor), and ecological understandings of adaption and efficiency.

Clearly, information visualization was not the only causal factor to explain productivity increases in the U.S. during the late 1990s. It would be exceedingly difficult to disembed information visualization from concurrent innovations in computing, such as miniaturization, networking and wide scale Internet adoption, as well as computing's complex relationship the other sectors of the economy.[74] Instead, I have shown how information foraging theory modeled and, through interface design and measurement, effectively produced a type of working agency, "informavores" that operate through economic logics of optimality, utility, and rational choice and ecological logics of adaption and maximization. The productivity paradox exposes the lack of a natural, progressive relationship between productivity and computing at the macro level. The case of Information Foraging Theory shows how these relationships could be locally constructed at the level of individual user or interface.

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[74] Brynjolfsson and Saunders, *Wired for Innovation*, 74-75.

The specificity of Information Foraging Theory also provides a means for critically evaluating political and economic claims made about computing, a salient point given that productivity gains attributed to computer technology have tended to accrue in highly unequal ways. To take a broad measure of the economy, inflation-adjusted median income in the United States has failed to reach its pre-recession levels and is more than 8 percent below its 1999 peak. Increases in per-capita GDP over the same period have accrued disproportionately for those at the upper levels of the income distribution, increasing inequality. [75] Although, inequality increases are complex, multicausal phenomena, a historical perspective on computing allows us to critically appraise received notions regarding inequality such as, "evolving technology favors those with the most advanced skills and allows companies to replace formerly middle-class workers with machines."[76] Just as the productivity paradox forces us to question naturalizing accounts of the relationship between technology and productivity, we should also be suspicious of accounts of naturalized relationships between technology and high levels of skill[77] or knowledge. The case of Information Foraging Theory shows that these relationships are created by designers, researchers, and users as well as material assemblages and intellectual contexts, including hardware, display technologies, and cognitive capacities.

From a different angle, histories of individual technologies can complicate critical accounts of the relationship between technology and contemporary capitalism. Too often,

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[75] Neil Irwin, "You Can't Feed a Family With G.D.P.," *The New York Times*, September 16, 2014, http://www.nytimes.com/2014/09/17/upshot/you-cant-feed-a-family-with-gdp.html.

[76] Ibid.

[77] For an introduction to these debates, see: Daron Acemoglu, "Technical Change, Inequality, and the Labor Market," *Journal of Economic Literature* 40, no. 1 (March 1, 2002): 7–72.

information technology is identified reflexively with capitalist exploitation. For example, David Harvey describes "neoliberalism's intense interest in and pursuit of information technologies (leading some to proclaim the emergence of a new kind of 'information society')."[78] Reversing the syntax of the skills debate, Harvey seems to endow neoliberalism with an autonomous agency and ability to shape technologies. Specific technological histories offer a more sophisticated account of these relationships. For example, the ecological logic of competition could be a framework for analyzing the ideological symmetries between proponents of neoliberal governance and information visualization research. The biological metaphors embedded in visualization systems could be linked to the structure of biopolitical power. Alternatively, as media theorist McKenzie Wark suggests, new forms of productivity and modes of information work may reconfigure old class alliances and strategies.[79] In either case, computing, so often understood as a driving technological force, material base, or other historical motor, must also be understood as the embodiment of historically specific cultural, scientific, and economic concepts, models, and beliefs.

[78] David Harvey, A Brief History of Neoliberalism (New York: Oxford University Press, 2005), 3-4.

[79] McKenzie Wark, "Designs for a New World," *E-Flux*, no. 58 (October, 2014), http://www.e-flux.com/journal/designs-for-a-new-world/.

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