Towards a Dynamic Multiscale Personalized Information Space

Beyond application and document centered views of information

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Abstract The historical moment when a person worked in front of a single computer has passed. Computers are now ubiquitous and embedded in virtually every new device and system, ranging from the omnipresent cellphone to the complex web of sociotechnical systems that envelop most every sphere of personal and professional life. They connect our activities to ever-expanding information resources with previously unimaginable computational power. Yet with all the increases in capacity, speed, and connectivity, information-based activities too often remain difficult, awkward, and frustrating. Even after six decades of design evolution there is little of the naturalness and contextual sensitivity required for convivial interaction with computer-mediated information.

We envision a future in which the existing world of documents and applications is linked to a multiscale personalized information space in which dynamic visual entities behave in accordance with cognitively motivated rules sensitive to tasks, personal and group interaction histories, and context. As a group of cognitive and computer scientists, we have come together jointly committed to this vision and convinced of the crucial importance of questioning the presupposition that information is fundamentally passive data disconnected from processes, tasks, context, and personal histories. We aim to redesignate the role that computers play in human life from devices with which we interact to partners with whom we collaborate.

The heart of the project is to rethink the nature of computer-mediated information as a basis to begin to fully realize the potential of computers to assist information-based activities. This requires challenging fundamental presuppositions that have led to today's walled gardens and information silos. Our goal is to catalyze an international research comunity to rethink the nature of information as a basis for radically advancing the human-centered design of information-based work and helping to ensure the future is one of convivial, effective, and humane systems. In this paper, we propose a new view of information, discuss cognitive requirements for a human-centered information space, and sketch a research agenda and approach.

Keywords activity history; cognitive tools; co-adaptive systems; distributed cognition; dynamic media; human computer interaction; information visualization; instrumental paradigm; Vega-Lite; Webstrates

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1 Introduction

For far too long we have conceived of thinking as something that happens exclusively in the head. Thinking happens in the world as well as the head. We think with things, with our bodies, with marks on paper, and with other people. Thinking is a distributed, socially-situated activity that exploits the extraordinary facilities of language, representational media, and embodied interaction with the world. Today we increasingly think with computers. But the computers we think with are rapidly changing. The monolithic computer of the recent past is coming apart and being reassembled in myriad new forms.

Computers are now ubiquitous and intertwined with every sphere of life. This evolution is accelerated by a radically changing cost structure in which the cost to use a thousand computers for a second or day is not appreciably more than to use one computer for a thousand days or seconds. Yet with all the advances in capacity, speed, and connectivity, using computers too often remains difficult, awkward, and frustrating. Even after six decades of design evolution, there is little of the naturalness, spontaneity, and contextual sensitivity required for convivial interaction with information. We argue that this is a result of a legacy document and application-centered design paradigm that presupposes information is static and disconnected from the context of processes, tasks, and personal histories. ***We propose a new human-centered view of information: as dynamic entities whose representation and behavior are designed in accordance with the cognitive requirements of human activity.***

Both user and activity-centered design paradigms have drawn attention to the myriad contextual factors that bear upon human interaction with computational media. Still, it is rare that modern software design reaches the true scope of situated human activity, too often supporting only simple component tasks. This is why we endlessly switch between applications, fragmenting activity across time (sessions), physical (devices) and digital spaces (documents). The job of coordinating activity falls to the user, taxing our precious time and attentional resources. We argue that to produce truly convivial interactions, designers should focus not only on the applications with which users interact, but also on the *information* that underlies, connects, and integrates complex cognitive activities.

Our primary objective is to develop a Human-Centered Information Space—a dynamic computational environment—linked to the existing world of information and operating according to empirically-grounded principles of behavior. We envision a future in which information *itself* is dynamic, interactive, and personalized to individuals, groups, contexts, tasks, and histories of interaction. Of course this future, one in which information transcends traditional application and device boundaries, cannot be achieved by a single research project. The motivation for this paper is to serve as a brief manifesto to hopefully help to catalyze a research community to begin to design, develop, explore, and evaluate the radical alternative we propose in which information entities operate in accordance with cognitively inspired rules of behavior sensitive to current task, context, and our perceptual and cognitive abilities.

To help convey the future we envision, we begin by sketching a brief scenario.

1.1 A Scenario

Samantha leads a research group in microbiology. After returning from a conference, she is ready to continue writing a paper she started before her trip, but is struggling to remember where she left off. Samantha is an early adopter of technology, and has been doing her writing in a new prototype system—a human-centered information space for her research activity. She thinks of the software as a kind of desktop, a virtual workspace for her information work where she can organize and easily access the resources that support it. The system offers a novel interface to her digital information, consolidating her data (e.g., email, messages, calendars, web pages, notes, sketches, and analyses and visualizations) across applications. When she interacts with the information in her workspace, it seems to be alive, aware of when and how it was last used, and sometimes even why she was using it.

To get back to her writing, Samantha browses a timeline of her past working sessions. She vaguely remembers last searching the web for an article she'd once read, but now can't remember if she successfully found and referenced it. She scrubs through the visualization of her activity to before she left for the conference. This timeline, like the workspace itself, is multiscale, enabling her to move up and down levels of abstraction. She shifts to a level where only major activities (like a session of data analysis, writing, or web browsing) are displayed, and sees a familiar view of her text editor. When she clicks it, the image centers and thumbnails of all the other applications that were open cluster around it. There are too many to deal with, so she uses a search shortcut to enter a keyword she remembers was in the article. The thumbnails are filtered and she is left with a subset of browser tabs and a pile of pdfs. This reminds her that she had found the article she was looking for, and also downloaded a few others she thought might be related. When she hovers over the pile, she sees a sort of iconic summary—a dynamic montage of images from the documents.

She moves down a level of abstraction, and the pdfs show her how they had been interacted with. She realizes that she had skimmed a few, and identified one to read more deeply. She wants to send a list of the articles to her graduate student to investigate, so she selects the pile, and from the context menu that's triggered selects 'create list'. The titles of the pdfs are extracted into a list, which she quickly gestures over to the area of her workspace reserved for email. When she opens the pdf of the article she had been reading, the workspace asks if she wants to resume her text editor as well. The space rearranges to show her the editor beside the pdf, and automatically scrolls to the places in each document where she had last been active. She appreciates that this transition is slow and animated, first zooming out to where she can see both her current location and the target, before zooming in. She likes how this gives her a sense of location in the workspace.

Taken back to the documents of her previous writing task, she triggers a movie-like replay of those moments in time. She knows this sort of visual summary would be difficult, if not impossible, for anyone else to understand, but because it is derived from her history, it is evocative. In the replay she sees her navigation between reading part of the pdf article, and writing a paragraph in her paper. She suddenly feels as though she has been transported back in time to that point in her writing, even remembering her prior train of thought. Just incase she gets interrupted again, she uses a hotkey to tag this activity, jotting down a short description, before resuming her writing flow.

1.2 Challenges of Developing a Human-Centered Information Space

This idealized scenario glosses over a host of complex issues. *How can a parallel space of digital information be linked with existing applications? What information about past activities should be captured, and how should the context of this activity influence how information is represented? What rules should govern how information behaves* *in different contexts?* Although the scope and complexity of these issues are clearly beyond what can be addressed in any single research project, we hope to entice others to join in developing a reseach program strategically targeting the core research challenges of developing a Human-Centered Information Space. Before detailing our research agenda and approach, we describe the core concept of a Human-Centered Information Space, its empirical grounding and associated architectural requirements, and an example domain problem of activity fragmentation.

2 Foundations of The Human-Centered Information Space

The sophisticated cognition demanded by contemporary information work has outpaced innovation in user interfaces. In modern computing systems, data is still encapsulated in application silos, leaving users to shuttle files between applications, cobbling together workflows, requiring troublesome context switching and increasing attentional demands. ***In short, we lack a cognitively convivial space for intellectual work.***

For us, a Human-Centered Information Space is both an idea, and a computational environment. It is the idea of a cognitive workspace—a desktop for intellectual activity—reified as a computational environment that actively supports the coordination of information-based work. develops awareness of the hierarchical structure of a user's action: how she accomplishes activities through discrete tasks across devices, programs, and working sessions. Through use, information in the environment will accumulate *context*: not only who accessed it and when, but concurrent activity and semantic relationships to other data. Just as awareness of the past influences human behavior, the content and context of the history of activity will drive the *behavior of information*. To the user, her information should seem alive, have awareness, know where it came from, how it got there, what it means—and behave accordingly. These representations and interactions will in turn guide the user's future action such that the struggle of resuming interrupted work is eased, much like finding a document is simplified by power of modern search engines. Importantly, the Human-Centered Information Space will not replace, at least initially, the user's ecosystem of applications and documents, but act as a home, a control center, a multi-modal but fundamentally spatial 'workshop' where information *across applications and documents* will converge with features that support the user in not only completing her tasks, but accomplishing activities.

In developing this concept we join with others (e.g., Kay [24], Victor [50, 48], and Berners-Lee [8]) in questioning the prevailing view of information. Our research agenda also draws inspiration from recent work of our collaborators Wendy Mackay and Michel Beaudouin-Lafon on *co-adaptive systems* and the *instrumental paradigm* [4, 28, 5]. The innovation of our approach lies in deriving general principles for the behavior of information in computational environments. We describe these behaviors as *cognitively convivial* because they are derived from the empirical science of cognition and designed to operate in ways attuned to our perceptual-cognitive abilities. We employ the notion of *conviviality* to emphasize that information should be lively, helpful, responsive, and enjoyable to interact with. By rethinking the nature of how computers mediate interaction with information, this project brings us closer to realizing the potential of computers to not only *assist*, but to *collaborate* in information-processing.

2.1 Requirements For A Human-Centered Information Space

The architecture of modern personal computing systems is insufficient for achieving our vision of a convivial, human-centered computing experience. The dominant unit of personal computing is the application/program. But people do not think or organize their work in terms of apps. We operate on goals, activities, and tasks. Thus, a truly human-centered architecture must support activity at the level at which people think about their work and assist in integrating it across applications. To accomplish this, we argue that information itself must become a first-class citizen: imbued with behavior (2.1.1), with the context of activity (2.1.2), made available outside applications (2.1.3).

These requirements build upon each other in an additive fashion. When information has behavior, it can support and be responsive to changing context. When information and context are available outside the silo of an application, the resulting information space can be designed to scaffold the coordination of complex cognitive activities. ***We propose three requirements for a Human-Centered Information Space.*** .

2.1.1 Information with Behavior: Animating Dead Bits Under Glass

In his *Brief Rant on the Future of Interaction Design* [49], Bret Victor describes modern digital interaction as, "Pictures Under Glass ... an interaction paradigm of permanent numbness". These pictures are lifeless; dead bits of data to be swiped and tapped, until acted upon by some program. As with Victor's call [1] for active representations, we envision a space in which information is dynamic, capable of representing itself differently depending on its surrounding context. An example of information with behavior from our sample scenario is the collection of pdf documents, represented as a pile of thumbnails, a list of titles, or montage of key images. Each representation afforded Samantha a contextually-appropriate subset of interactions, and she could navigate between them to suit the structure of her thinking at any given time. ***We propose that information entities should be imbued with behavior, capable, for example, of dynamically changing their representation and interaction in accordance with empirically-grounded rules derived from human cognitive abilities.***

2.1.2 Activity Context: Realizing the Potential of Activity History

As we move through the world, we leave rich traces of activity throughout our environment. These traces serve as the *context* for what, when, how, and potentially even indicators of why we do the things we do. Computationally, we record and make use of only a fraction of this context, storing it as metadata. In a document-centered paradigm, the user has easy access to administrative metadata: such as who created a document, of what type, and when it was last accessed. But imagine you could recall

[1] See Victor's talk entitled *Stop Drawing Dead Fish* (https://vimeo.com/64895205).

all of the times you accessed a particular document? Better yet, what if you knew what searches you performed while the document was open, what applications were in concurrent use, and how you developed the document's structure? In our sample scenario, Samantha's history of interaction was explicitly represented in a feature-rich timeline, and used to guide her interaction with information resources. The representation of some entities (pdf and browser search results) were enhanced with a history of her interaction (scrolling and click input). ***We argue that information should be responsive to the context afforded by a user's personal history of interaction.***

2.1.3 Beyond Application Silos: Integrating External Information

It is as difficult to conceptualize a computing paradigm *not* centered around documents and applications as it is to envision an interface paradigm not centered around windows, icons, menus, and pointers. Nonetheless, it is time to move beyond aging metaphors and software structures convenient for the design and maintenance of machines, to those conducive to the thoughts and actions of users. A fundamental aspect of our vision is that the nature of representation of an information entity should be flexible, integral to the structure of the entity itself rather than a function of a specific application. The complementary design challenge lies in ensuring that the behavior of a representation provides the cross-task generality, consistency, and learnability that is too often missing from today's applications. To accomplish this, a distinct but connected space for representations is required. In our sample scenario, Samantha could retrieve pdfs from her search activity from both her harddrive (those she had downloaded) and web browser (those she was perusing), from a single point of access. ***We argue that a Human-Centered Information space needs access to data across applications. Information must become a first-class citizen in such a computational environment, owned by the user, available for re-representation and instrumental interaction.***

2.2 Empirical Grounding for a Human-Centered Information Space

Much like the form and movement of matter through space is governed by the laws of physics, the representation and interaction of information should be governed by the requirements of its processors: humans, and other such intelligent agents. A primary motivation for us is to mitigate unnecessary cognitive resource expenditures during complex information activities, thus making computer-based work more efficient and enjoyable. Our approach is informed by our prior work on activity-enriched computing [37, 40, 39], and contemporary research in Cognitive Science which emphasizes the fundamental importance of *space* to *thought*.

In her new book, *Mind in Motion* [47], our collaborator Barbara Tversky cogently describes decades of research on how we think about space—and how we use space to think.[2] Based on decades of empirical work in spatial cognition and external representation, Tversky formulates two principles for cognitively-driven design:

- ***Principle of Correspondence:*** *The content and form of the representation should match the content and form of the targeted concepts.*
- ***Principle of Use:*** *The representation should promote efficient accomplishment of the targeted tasks.*

These principles offer useful guidance for the design of a Human-Centered Information Space, and also an explanation of why many applications fall short. While designers endeavour to craft representations conducive to their target concepts, in reality, most interfaces are driven by classic design heuristics [35]. Initially derived from empirical research on human perception, these simple heuristics are challenged by the complexity of contemporary information work. Similarly, progress in software engineering has (appropriately) trended toward encapsulation, maintenance, and agility, yielding a rich ecosystem of micro-applications with powerful offerings toward narrowly defined feature sets. The consequence for users is the need to piece together workflows across applications. Information in each application *might* be meaningfully persistent but is presented in a different encapsulated form in each application. Representations, especially those in information systems are *tools for thinking*, and so just as our thoughts transform one idea into another, so should we be able to transform one representation of digital information, into another. **We argue this requirement can only be met if information transcends applications and has the flexibility to dynamically alter its representation to support the changing state of a task as it evolves. This can only be accomplished if information representations are dynamic and re-mixable outside the walled gardens of applications.**

3 Research Agenda and Approach

The long-term research agenda for developing the *human-centered information space* concept is necessarily ambitious. Articulating the challenges that must be addressed will helps to characterize both the *need for* and the *potential of* the concept. We argue it should be approached incrementally and strategically by situating initial efforts in the context of specific *domain activities* and focusing on *central problems* of those domains. It should also be informed by theory and data. In our case, we plan to leverage the framework provided by distributed cognition [20, 17] and methods of cognitive ethnography [18]. The theory of distributed cognition seeks to understand the organization of cognitive systems. Unlike traditional theories of cognition, it extends the reach of what is considered *cognitive* beyond the individual to encompass interactions between people and with resources and materials in the environment. Methods of cognitive ethnography build on this framework, providing tools for determining what

[2] The importance of space in human thought also motivates our choice of the term 'Information Space' to conceptualize the computational environment we aim to build.

things mean to the participants in an activity and for documenting the means by which these meanings are constructed.

In our initial research we will focus on *data analysis and visualization* and the pervasive problem of *activity fragmentation*. In the next two sections, we briefly describe these choices and in a following section (4), we sketch a research plan as an exemplar approach to develop a dynamic multiscale personalized information space.

3.1 Domain Activity: Analysis and Visualization in Computational Notebooks

One cannot study complex cognitive activity in the abstract. Data analysis and visualization are exploratory processes of extracting insights from data and communicating those insights to others [46, 13, 23, 25]. These processes have become more visible due to the widespread use of computational notebooks. The fact that analysis and visualization tasks typically cross application boundaries and require a characteristic mix of formal and informal information make computational notebook use an ideal domain of activity to focus our initial research efforts.

In a series of studies reported in [39], Hollan and collaborators analyzed over a million Jupyter notebooks from a GitHub repository, selected 200 notebooks associated with academic publications for more detailed analysis, and interviewed 15 academic data analysts. A major finding was that many of the problems with notebooks result from a tension between exploration and explanation. Although notebooks provide tools for users to write rich computational narratives, analysts do not necessarily use them to great effect, as they continuously face a tension between exploring their data, or pausing to explain their process. Because users are torn between between using notebooks as a sandbox for exploratory work and as a repository for publication-ready analyses, they often delete intermediate and "failed" analyses. As a result, analysts lose the ability to retrace their steps at a later time, a task often crucial to reinstating the context of an interrupted analysis. In addition, the linear structure of current notebooks is constraining, failing to match the iterative and complex flow of most data analyses.

A primary feature of notebook environments like the increasingly popular JupyterLab [36] is the ability to combine code, commentary, and visualizations in a single document, rather than being scattered across multiple files. This unification attempts to reduce the time and effort needed to manage information and enable quickly retracing complex analyses or succinctly communicating them to colleagues. However, the scale, complexity, and exploratory nature of analysis means that notebooks quickly becoming "messy" and "too long" to understand. As a consequence users separate phases of their analyses into separate notebooks, fragmenting activity and reintroducing the issue of finding information across multiple files.

The challenges faced by users of computational notebooks are common to activities across many application domains. By situating our efforts in the realm of data analysis and visualization in computational notebooks, we address the management and navigation of multiple information resources (e.g., papers, notes, sketches, and the complex evolution of analyses and visualizations). Additionally, the infrastructure provided by Project Jupyter and the web-based JupyterLab environment mean that our systems engineering efforts will be concentrated on a platform that can be readily extended to domain-general web applications.

3.2 Domain Problem: Mitigating Activity Fragmentation

Research on activity-enriched computing [19] reveals that the need to coordinate activity over time and distributed media is a primary source of frustration and lost productivity in information work. Just as the need to employ multiple applications leads to increased complexity, rapidly expanding network connectivity brings a growing number and variety of *interruptions*—increasingly accepted as normal components of modern life. Observational studies of office workers reveal that real-life work is highly fragmented [29, 10, 22, 11, 21]. Mark et al. [29] found that during the course of a typical day information workers spend an average of only 12 minutes on any given task and most uninterrupted "events" average about 3 minutes in duration. Often, interruptions present serious challenges for resuming a task and re-familiarizing ourselves with the context of the interrupted activity. Many of the most challenging issues we face involve the disconnection of related information from our tasks and the associated problem of recreating the context required to resume activities that have been interrupted. Even when there aren't external interruptions, requirements of collaboration, time limitations, and the frequent requirement to switch back and forth between applications make interruptions unavoidable and fragment information resources. The preparation of this paper, for example, was distributed across email, sketches on whiteboards, text messages, recordings of video-conferences, annotated drafts, notes on paper, and the invisible histories of our individual activities.

In our view, a solution to fragmentation is unlikely to arise from a consolidation of functionality: a step back to the time of limited choice between feature-bloated programs. Rather, we argue that the sophistication of modern computing environments should be leveraged to combat this problem rather than exacerbate it. Because the problem of fragmentation is pervasive in our selected domain of analysis and visualization, we will use this problem as a focus of evaluation for our research efforts. The success of any prototype Human-Centered Information Space will be largely determined by its ability to mitigate the problem of fragmented activity, helping users recover from interruption and reinstate mental context.

4 Research Plan

Our research plan is structured by overlapping activities, each centered on developing and evaluating one of our requirements for a Human-Centered Information Space (Section 2.1). We present it here to serve as an example of a specific research plan. In stage one we leverage existing prototyping environments to develop a catalogue of behaviors for information entities. In stage two we leverage the web-based JupyterLabs infrastructure to develop a proxy Human-Centered Information Space and evaluate the use of system-wide Activity Context in notebook work. In stage three we extend this developing infrastructure to integrate data from external applications. This structure allows us to progressively evolve and evaluate component parts of the Human-Centered Information Space concept. Following a human-centered design approach, each stage will be informed by empirical research in applied cognition, design, and systems engineering.

As part of a recent project [39, 37] we have developed relationships with a number of research labs that are active users of Jupyter Notebooks (experts), as well as with instructors who require Jupyter Notebook use by students in their courses (novices). Over the course of our project we will perform three kinds of research activities with these groups serving as population samples. First, relying on methods of *cognitive ethnography*, we will conduct in-person observations, in-situ recording of activity, and interviews to understand how users distribute cognitive activity through the environment while analyzing and visualizing data. During the design of interfaces, we will use *participatory design* methods to ground our design-decisions in the context of how these artifacts might be used. Finally, to evaluate the efficacy of our designs and prototypes, we will perform *situated user studies*. These studies are typically quasi-experimental and collect a mixture of objective measures (e.g., time on task) and subjective feedback. We will refer to these canonical research activities throughout the research plan.

4.1 Designing Information with Behavior

Developing principled composable rules of behavior for information entities is our primary scientific focus, as such will serve as an overarching activity for the duration of the project. The outcome of this phase will be a catalogue of primitive information behaviors. We develop this by leveraging a series of existing environments (DynaPad, WritLarge, Vega-Lite) to prototype domain-general behavioral primitives, while continuously integrating promising behaviors into our domain-specific prototypes (stages 2 and 3). Through this work we aim to evaluate our proposal that a Human-Centered Information space requires *information be imbued with behavior*.

4.1.1 Designing Information with Behavior: Prior Work

When we refer to *information with behavior*, we are speaking to both the way information is represented, and its capabilities for interaction. Prior work on multiscale visual representation (Hollan), mechanisms of interaction (Xia), and specification of behavior (Satyanarayan) provide inspiration and a launchpad for our planned exploration of information with behavior.

Visual Representation. The Dynapad[3] system [2, 3], developed by Hollan and colleagues, realized a zoomable, multiscale virtual space with innovative user interactions that made information objects active and reactive, inspiring our vision of *information with behavior*. Chief among the facilities is *semantic zooming*—in which

[3] Dynapad was the last version of our Pad++ [7, 6] zoomable multiscale development environment. The Pad++ software was nonexclusively licensed to Sony for $500K. It consists of a highly efficient C++ rendering core and an application development level using the Racket lanaguage [1], which supports language-oriented programming [12].

representations of information objects at different levels of granularity are determined by semantic factors rather than simple geometric scaling. The implementation of *lenses* enable filtered views of portions of the space, such that users have a sense of viewing the same information in different contexts. *Portals* allow connected views to other portions of the space that are independently pannable and zoomable, and *hyperlinks* afforded rapid movement to specific virtual locations (while maintaining object permanence and supporting wayfinding, unlike the experience of hyperlinks in web browsers). Though developed in 2006, Dynapad remains the best approximation of the dynamic multiscale information environment we envision.

Interaction. The WritLarge system[4] [51], developed by Xia, exemplifies the dynamic representations we propose. WritLarge provides a free-form canvas environment (on tablet and digital whiteboard) where users can flexibly transition between 'equivalent' representations of information in three ways: *semantically, structurally, and temporally*. For example, if a user scribbles a note to themselves on the canvas, they produce a series of vector-based strokes. Along the semantic axis, they can transition 'up' a layer of abstraction, and have the system recognize the text they have written, or 'down' a layer, and edit the strokes as pixels. Along the structural axis, the user can alter the organizational structure of the representation, while the temporal axis offers the ability to 'scrub' forward and backward in time. These features are equally powerful should the user scribble text on the canvas, or import an image. This eliminates the need for the user to fragment her activity (and therefore her thinking) from one application to another, perhaps typing her scribbled notes into a word processor, or exporting a vector-based image to a raster-editing application. The movement along these axes enables flexible transformation of representations, empowering her to express her thoughts at a natural level, rather than being confined to the fixed level applications are typically designed to support. Although WritLarge is a discrete application, it demonstrates the representational flexibility we seek in a separate space of information representations linked to existing information and applications.

Specifying Behavior. One of the key insights in our concept of *information with behavior* is the simultaneous consideration of a representation and its afforded interactions. In the InfoVis community, it is widely known that much more attention is paid to the nature of a representation than the nature of its interactions [42], in part because the languages we have for specifying such behaviors confound the two aspects. We plan to address this challenge by leveraging the high-level declarative grammar approach of Vega-Lite [43, 41, 31][5]—developed by Satyanarayan—a widely used state-of-the-art substrate for developing dynamic interactive behavior for data. Vega-Lite employs a concise JSON syntax for rapidly generating visualizations by describing mappings between data fields and the properties of graphical marks. The Vega-Lite compiler automatically produces additional necessary components, such as scales, axes, and legends, and determines their properties (e.g., default color palettes)

[4] WritLarge received a Best Paper Honorable Mention Award at the ACM CHI Conference in 2017. It is challenging to describe dynamic representations with text. A video of WritLarge (https://www.youtube.com/watch?v=6lWe9PvabA0) is available.

[5] Awarded best paper at VIS 2016.

based on a set of carefully crafted rules for perceptual effectiveness. This approach allows specifications to be concise yet expressive. Vega-Lite enables authoring a wide range of interaction techniques including tooltips, brushing & linking, panning & zooming, focus+context, and interactive filtering. Critically, these techniques are not instantiated through top-down templates but rather with a set of bottom-up composable language primitives called "selections" and "selection transformations." These primitives allow simply describing the high-level intent of an interaction (e.g., "highlight points on click") and the Vega-Lite compiler synthesizes the lower-level details such as registering event-handling callbacks and updating visual encoding rules. Vega-Lite provides a layered stack of declarative representations (all expressed as JSON). Having multiple levels of abstraction, with a correspondence mapping between them, is critical for enabling the rich cognitively convivial behaviors we envision, allowing end-users to work with the representation most suited to the task at hand.

4.1.2 Designing Information with Behavior: Planned Research

Exploring the Design Space. We will structure the exploration of this massive design space by prioritizing the problem of activity fragmentation faced by users of computational notebooks. Although many challenges were identified in our earlier work (such as the tensions between exploration and explanation), we did not examine the *low-level interactions* required to address them. Using *cognitive ethnography*, we begin here with a formative study of Jupyter notebook users recruited from labs at UCSD and MIT, designed to address the question: What are the existing behaviors of information in Jupyter Notebooks? We will interview, observe, and capture system-wide activity history of participants performing data analysis and visualization work. From these data we will identify types and sources of information entities accessed, as well as the interaction behaviors provided by Jupyter. We will map these information entities to the temporal dynamics of participants' workflows (e.g. working sessions, false starts, abandoned efforts, resumptions) and use this mapping to identify the information entities most implicated in users' breakpoints. Through this study we will prioritize entities with the greatest potential for improvement (with more dynamic behavior), as well as articulate our concept of 'information with behavior' in the context of an existing system.

Prototyping Behaviors. This work involves prototyping alternative futures: envisioning alternative representations for standard information entities, and how they might behave (with the user, and with other entities) on the basis of their context (such as goal-hierarchy, device, or history of interaction). We will leverage the existing environments from Dynapad and WritLarge to accelerate this prototyping work. The behavior specification techniques employed in Vega-Lite will serve as the foundation for our approach, as it provides a sufficiently robust vocabulary to systematically generate alternative interaction techniques for a given set of visual encodings (and vary their constituent properties). As a result, it allows us to begin to develop and empirically evaluate cognitive rules of interactive behaviors in conjunction with the design of visual representations and mechanisms of interaction.

Evaluation. We will evaluate the conviviality of the information behaviors we design in two ways. First, we will take the promising candidate behaviors and continuously integrate them into our stage two and three prototypes, thus testing their efficacy in support of notebook activity via *user studies*. In addition, we will take the opportunity provided by working with the Vega-Lite specification language to test the relative efficacy of select behaviors in the context of Information Visualization activity. We will conduct a series of studies implementing behaviors in Draco [30], a constraint solving system developed by Satyanarayan's collaborators. First we will decompose the most promising behaviors into component primitives to be used to elaborate the interaction design space. Candidate points in this space will then be mapped to established task and analytic task taxonomies [15, 52, 9] to identify which ways a user might use a particular interactive behavior. Once two (or more) designs are mapped for a task, a comparative study can be run. We expect some of the studies could be conducted on crowdsourcing platforms such as Amazon Mechanical Turk, but others will benefit from our access to both expert and novice Jupyter users. We will collect quantitative metrics (e.g., task completion time, accuracy of both performing the interaction and the insights yielded) and qualitative metrics (e.g., which technique did users prefer), as well as demographic information to understand whether novice users prefer particular techniques over more advanced analysts, for example. Quantitative data will then be fed back to Draco to learn a series of weights that codify interaction effectiveness criteria. From these results, we will develop a grammar of interactive behavior for information entities. As the development of the substrate architecture, derivation of rules and development of prototypes will proceed in parallel, we will have the unique opportunity to evaluate the ecological validity of rules from the domain of visual analytics applied more generally to information tasks in our prototype information spaces. In our knowledge, this work will be the first large-scale study focused specifically on the cognitive effectiveness of behavior and interaction in data visualization, complementing the large body of work devoted to empirical assessment of visual encoding effectiveness [14, 45, 26].

4.2 Activity Context

The primary goal of our second phase of research is the development and evaluation of a prototype to support researchers performing data analysis and visualization in JupyterLabs, offering users access to the context of their system-wide activity history. Over the course of this research phase, we will engineer a JupyterLabs extension to function as a proxy Information Space. We will gather field data and conduct participatory design to develop an activity-enriched interface for our human-centered space. The prototype will be evaluated based on its technical stability and effectiveness in supporting users' recovery from interruptions in activity. Through this work we aim to evaluate our proposal that a Human-Centered Information space requires *the context of activity history*.

4.2.1 Activity Context: Prior Work

Hollan's early Edit Wear and Read Wear [16] work pioneered capturing and visualizing activity history. As with subsequent research, however, the focus was on capturing history within a specific application. Today it is common for applications to include similar facilities (e.g., track-changes in Microsoft Word) to provide access to the modification history of a document. Of course, most modern computational workflows span multiple independent applications. A data scientist might search for open data sets in a web browser, write Python scripts within an IDE to scrape and wrangle that data, connect those scripts to black-box Unix command-line applications to run proprietary machine learning algorithms, and then feed the resulting models into a Jupyter Notebook with embedded Vega-Lite widgets to interactively visualize the results. The functions available in each application fail to support the user's higher level activity; the complete history of her interactions across all of these applications operate independently without awareness of one another.

To provide cognitively convivial interactions that support semantically meaningful higher level activities it is essential to first be able to capture cross-application interaction histories in a generic, application-independent manner. The approach we pursue in this phase of the project is based on operating-system-wide activity tracing, as pioneered by Guo in a series of systems: Burrito [13], Torta [32], and Porta[6] [33]. Each of these systems transparently monitor application activity at the OS level, creating a timestamped trace of activities such as which files were opened and/or modified, which system calls were executed, which GUI windows were opened/closed, and which sub-processes were launched. They also provide a layered architecture to connect this generic trace with application-specific tracers such as those that track editing/navigation actions within text editors (similar to Edit Wear and Read Wear [16]) and page interactions within web browsers.

4.2.2 Activity Context: Planned Research

Systems Engineering. The platforms developed by Guo [13, 32, 33] will serve as our starting point for systems engineering in this stage, enabling our prototype information space to access the full timestamped interaction history of a user working concurrently in multiple applications on their computer. A key challenge will be to determine the data structures most effective for persistence and real-time access of this expanded scope of metadata. We will leverage the JupyterLabs API to develop a web-based extension that can access this OS-level activity history, serving as a proxy Information Space for JupyterLabs-based work. The interface design will be informed by the results of our cognitive research and the functional requirement of representing cross-application history that is relevant to the notebook-based activity.

Cognition and Design. Though our own prior work has demonstrated that visual summaries of activity can help users recover from interruption [38, 40] knowing what aspects of history to present is an open empirical question. Theoretical models of event segmentation [53, 44] suggest our memory is better for the boundaries

[6] Best paper award UIST 2018.

of events—the transitions—than for event contents. To apply this literature means that we need to determine what *boundary* versus *content* means when representing activities with digital information. Informed by the ongoing cognitive ethnography with our collaborative research subjects (as described in section 4), we will, as just one example, design two visualizations of personal activity history: one that gives preferential attention to information about the content of events, and a second emphasizing transitions between them. After gathering feedback on these visualizations from interviews with participants in our continuing fieldwork, we will design and run controlled between-subjects laboratory studies aimed at evaluating their efficacy in supporting resumption of an interrupted task. We expect the results, of what we anticipate will be a series of similar laboratory studies, will inform the applicability of the event segmentation literature to the design of activity history visualizations, suggesting what aspects of it we should emphasize in our stage two prototype.

Evaluation. The result of stage two research will be a prototype information space with activity history developed for JupyterLabs. We will evaluate the success of this prototype via a situated *user study* with expert notebook users based on: (1) technical stability (Does the prototype function as designed, is its performance stable, and can its architecture scale to support growing activity data?), and (2) the degree of support provided for resuming interrupted activity (as determined by user studies on both our participatory and control subject groups) as evaluation criteria. If resources allow, we may also run a laboratory user study with novice notebook users to assess the discoverability of the included information behaviors, and the extent to which they might support scaffolding of best practices in notebook use.

4.3 Integrating External Application Information

The primary goal of the third phase of research is to develop and evaluate a prototype information space that expands on the functionality developed in stage two to include an integration of information from external applications. This prototype will offer users the ability to not only access external information by launching an application through from a history of activity, but to manipulate the information *from* the external application in the Information Space itself. Over the course of the final phase, we will expand the functionality of our JupyterLabs extension, leveraging the affordances of cross-domain affordances of the *Webstrates* [27] framework. Through this work we aim to evaluate our proposal that a Human-Centered Information space requires *access to data across applications*.

4.3.1 Integrating External Application Information: Prior Work

While the prior work of Guo [13, 32, 33] enabled the collection and visualization of data across web and native applications, these projects did not involve the integration of information into an independent space. Of course, in an application-centric paradigm, one might construe such consolidation as an instance of yet another application. The closest approximation of the cross-application integration we envision is realized in the realm of enterprise computing. To manage the integration of data and business processes across an ecosystem of enterprise-level applications requires standard data interchange formats, service oriented architectures, middleware infrastructure and business logic engines. One construal of the Human-Centered Information Space concept is as the personal-computing analog to the enterprise integration engine, plus a user interface. Such a solution does not exist in the world of personal computing, owing to the rapid pace, prolific number and democratic nature of application development. In recent years, an alternative solution to the problem of application silos has emerged via point to point integration services like *If-This-Then-That*, and Zapier. These (primarily cloud-based) task automation systems allow end-users to construct cohesive workflows without programming by mapping API triggers and data objects. Although this automation can ease the user's experience of manually porting information from one application to another, she is still limited to the features and representations of each application, and constrained by the expressiveness of each application's API.

A closer approximation of this integration concept is realized in the Webstrates framework. During a recent sabbatical, Hollan began a collaboration with the developers of *Webstrates* (web + substrates) [27], a novel browser-based approach for creating sharable dynamic media. Webstrates consists of a custom web server that serves pages, called webstrates, to ordinary web browsers. Each webstrate is a shared collaborative object, and changes to the webstrate's DOM (Document Object Model), as well as changes to its embedded JavaScript code and CSS styles, are transparently made persistent on the server and synchronized with all clients sharing that webstrate. By sharing embedded code—behavior typically associated with browser-based software—can be collaboratively manipulated across devices. An initial example [27] [7] was collaborative editing, enabling authors to interact with the same document via functionally and visually different editors. By making the DOM of web pages persistent and collaboratively editable, content and functionality become re-programmable and extensible. This is achieved through a conceptually simple change to the web stack that effectively blurs the distinction between applications and documents. The removal of the traditional hard distinction between applications and documents is crucial for the dynamic information environment we propose.

Webstrates employs *transclusion* [34, 27] to allow one webstrate to be embedded in another. This transforms the computing environment so as to support dynamic information and web-based collaboration. Importantly for our project, Webstrates provides mechanisms to enable cross-device collaboration with dynamic information entities. As a proof of concept demonstration of the type of multiscale information environment we envision, our Webstrates collaborators recently implement a Pad++-like zoomable information prototype in Webstrates that also allows pen-based collaborative sketching on an iPad. [8] In a similar proof of concept demonstration, Satyanarayan and Hollan collaborated with Klokmose to explore integration of Vega-Lite facilities with Webstrates.

[7] Awarded best paper at UIST 2015.

[8] For the past several years graduate students from Aarhus have been funded by the Danish government to spend program-mandated graduate study abroad time at the DesignLab at UC San Diego, furthering this fruitful collaboration.

4.3.2 Integrating External Application Information: Planned Research

Cognition and Design. From a design perspective the greatest challenge of accessing information across applications is maintaining the user's understanding of provenance. To address this challenge, we will again leverage the method of *cognitive ethnography* with JupyterLabs users, this time focused on the user's workflow across the scope of an analysis and visualization project. Through the collection of observational, interview and activity tracking data we will determine what external applications (e.g. text editor, web browser) are most common to analysis workflows, and how users access them in concert with notebook-based work. Identification of these applications will constrain the scope of our systems engineering activities. We will also target our questioning to expose users' mental models of the provenance of notebook data, addressing questions such as: if I update information in application A, should I expect that the changes be reflected in application B?

Systems Engineering. The fundamental architectural challenge of this stage is supporting integration of information and interoperability across applications in a principled, standards-based fashion while maintaining the flexibility required for re-representation and instrumental interaction. Because our plan is to provide a unified treatment of all representations involved in an interactive behavior, this necessitates extensions to both Vega-Lite and Webstrates. We leverage the Webstrates infrastructure to extend our stage two prototype with access to information from the external applications scoped via our cognitive ethnography, such that users can flexibly access and re-represent this information without the need to launch the external application.

Evaluation. The result of stage three research will a final prototype information space in JupyterLabs with both activity history and access to information from select external applications. As with prior stages, we will evaluate the success of this prototype via a situated *user study*, with respect to criteria for technical stability and functional support for resumption of interrupted activity.

4.4 Towards a Domain-General Web-Based Information Space

As a final phase of the project we will take what we have learned from the accumulation of formative and evaluative studies to critically assess our concept of a Human-Centered Information Space. We will appraise the architecture of our prototype systems, with the goal of describing the requirements to scale our approach beyond the scope of analyzing and visualization data in Jupyter notebooks. We will generalize what we have learned about supporting notebook activities to the more general case of supporting personal information management. Where appropriate, we will derive design principles and theoretical models. We will formalize our specification of information behaviors into a catalogue of primitive components that are useful for the generative design of representations and interactions. Finally, as the work we've described has been limited to the scope of supporting the activity of individuals, we will elaborate the challenges needed to be addressed to extend it to support groups of users performing collaborative work, such as in the context of a research lab.

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