Sense and Senseability: Exploring Future Immersive Environments for Scholarly Sensemaking

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ABSTRACT

Scholars must often make sense of vast amounts of complex and diverse scholarly information, much of which is not "senseable": crucial information like questions, concepts, or assertions, along with key properties like truthlikeness or evocativeness, are primarily identified through effortful search or reasoning, rather than direct perception through the senses. In this pictorial, we explore how we might augment scholarly sensemaking by making the full range of scholarly information more senseable. First, we systematically reviewed systems for scholarly sensemaking, and enumerated key types of scholarly information and their properties. Then, we synthesized design patterns for materializing abstract information in modern artworks, and connected them with our enumerated scholarly information and properties to develop three novel conceptual designs for senseable scholarly sensemaking in immersive environments. Our work lays the foundation for a novel design framework for exploring future immersive environments for scholarly sensemaking.

Authors Keywords

Sensemaking; Immersive Environment; Design Framework

CSS Concepts

• Human-centered computing ~ Interaction design ~ Interaction design theory, concepts and paradigms

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INTRODUCTION

Scholars must often make sense of vast amounts of complex and diverse scholarly information. For instance, when interpreting a surprising empirical result, scholars need to juxtapose it against other existing empirical results (and their context and relationships to each other), as well as key theories and alternative claims that might explain the result. To construct a theory of a phenomenon, they need to survey key concepts from existing empirical results, and consider key claims about the relationships between those concepts, and how they cohere together into a systematic theory; to provide guidance for future research directions, they also need to consider the degrees of (un)certainty for the key components of the theory. This process can be understood as creative sensemaking: a cognitive process that transforms captured information into novel insights [50, 54, 74].

In this paper, we consider one potential underexplored challenge in scholarly sensemaking: much scholarly information that is critical for sensemaking is not "senseable": that is, crucial information like questions, concepts, or assertions, along with their key properties like truthlikeness or evocativeness, are primarily identified through effortful search or reasoning, rather than direct perception through the senses. For instance, scholars often want to make sense of claims and their context [7, 43, 77], but need to laboriously extract or infer them from the long acadmic documents and passages in which they are "trapped" [32], or attempt (and often fail) to retrieve them across a fragmented, unstructured mess of notes and information "scraps" [24, 77]. This lack of senseability, and the resulting effortful labor it necessitates, has been extensively documented in empirical studies of scholarly sensemaking [7, 24, 32, 77]. This effortful work stands in stark contrast to compelling visions in HCI of smooth, skilled action that might be possible with more tangible and embodied interaction paradigms that enable sensemakers to fully leverage their senses and bodies to interact with information [26, 31, 67, 77]. We are thus motivated to wonder: **How might we augment scholarly sensemaking by making the full range of scholarly information more senseable?**

Immersive environments, such as virtual reality, could provide a compelling solution to the senseability problem. These environments can implement and mimic the physics and affordances of the existing material world, but can also implement novel physics and affordances that augment and extend, rather than simply replicate, our existing senses [1]. Our work here builds on prior research that has already begun to augment scholarly sensemaking by materializing abstract scholarly information into a more manipulate-able and senseable forms, such as manipulable data visualization axes [15], overlaying forensic information onto a 3D model human body [51], and immersive environments for comparing maps [56]. Much of this work has focused on the materialization of geospatial data for sensemaking; here, we aim to extend exploration into types of scholarly information that do not yet have obvious senseable forms and affordances, such as theories, questions, and concepts.

To do this, we ask and answer two sets of questions:

(1) **RQ1: What types of scholarly information and their properties are important "raw material" in scholarly sensemaking? Which of these types of information and properties are (currently) lacking senseability?** We answer this question with a **systematic review** of HCI research on scholarly sensemaking, from which we enumerated key types of scholarly information and their properties, and analyzed how senseable they are in existing systems for scholarly sensemaking.

(2) **RQ2: How might we design immersive environments that materialize scholarly information and their properties into more senseable forms?** We answer this question by **synthesizing visual design patterns** for materializing abstract information in modern artworks, and connecting them with our enumerated scholarly information and properties to develop three novel **conceptual designs** for senseable scholarly sensemaking in immersive environments.

Together, these design explorations constitute the beginnings of a design framework for future immersive environments for scholarly sensemaking that take senseability of scholarly information seriously.

RELATED WORK

Sensemaking and the Body

Our work is rooted in in HCI models of sensemaking, such as Russell et al's cost structure model [54], and Pirolli et al's Notional Model of Sensemaking [50]. A key insight from these models is that sensemaking is deeply *iterative*: instead of a linear process that begins with information and sequentially adds increasing levels of structure to the information to produce a final schema, sensemakers frequently loop back over previously retrieved information materials, reflect on how they compare to their schema, and either integrate them into their schema or revise their schema, if they sense important information that does not "fit" their current schema. We see this iterative nature of sensemaking in empirical studies of scholarly sensemaking, which frequently document how scholars need to revisit past notes and papers [24, 43, 45, 48, 66, 77].

In line with the turn to tangible and embodied interaction in HCI [26, 27, 31], recent models of sensemaking emphasize that much of this iterative reflection on materials and schemas happens via interactions with external materials [75]. Drawing on models of embodied and distributed cognition [26, 40], this line of research calls for much closer attention to how sensemaking emerges from interactions between (embodied) sensation and perception of external information representations, such as visualizations or tangible materials, and internal representations of information, such as mental models and schemas. This attention to the body and its senses resonates with information foraging models of the iterative search for information in the sensemaking process [49], which draw from optimal models of animal foraging to model sensemaking as involving active foraging for potentially profitable patches of information by sensing and following information "scent". We are inspired to juxtapose these models with broader calls in HCI to expand our vision of interaction paradigms to encompass the full range of senses and the body: as Victor [67] so eloquently put it, "*[existing] representations, having been invented for static media such as paper, tap into a small subset of human capabilities and neglect the rest. Knowledge work means sitting at a desk, interpreting and manipulating symbols. The human body is reduced to an eye staring at tiny rectangles and fingers on a pen or keyboard*". These insights highlight how the struggles of scholars during iterative revisiting of information can be related to the lack of materiality and senseability: needed information is often not explicitly represented [7], fragmented across information 'scraps' [24, 77], or must be laboriously extracted or inferred from other material forms like long academic documents [32].

In this paper, we systematically explore how this emphasis on the body and senses in sensemaking might yield new interfaces and environments for augmenting scholarly sensemaking.

Sensemaking Support Systems

There is a substantial body of work on systems for supporting scholarly sensemaking in traditional "non-immersive" environments. Examples include innovations in graph-based representations [14], exploratory search interfaces [13, 29, 30], dialogue with LLM agents [39], and mechanisms for increasing access to provenance, definitions, and related data within reading interfaces [41]. Our work here systematically reviews the key information objects and properties in these systems and explores how to support sensing and sensemaking of this information in a more embodied fashion.

A separate, emerging body of work explores immersive sensemaking support systems, in technologies such as virtual, augmented, and/or extended reality. This work has primarily focused on sensemaking with information with clear mappings to geospatial coordinates, such as geospatial data [16, 56, 76], forensic data on the human body [51], or more quantitative visualizations and their respective axes [15]. Some work in this area has also explored immersive sensemaking with more abstract or qualitative data such as documents and hypotheses, documenting, for example, how scholars might develop strategies to leverage *space* in immersive environments [3, 17], or explore links to related metadata for papers [25]. We extend this research by exploring how to enable more embodied and sense-able interactions with a wide range of types of non-geospatial scholarly information.

METHODS

Systematic Review of Scholarly Information Objects and Their Properties

Our first goal was to identify the types of information and their properties that are important to scholars when making sense of scholarly materials. To achieve this, we systematically reviewed previous empirical studies that examined the information involved in scholarly sensemaking, as well as system designs that support scholars in sensemaking tasks.

We used the following query to retrieve articles from the ACM Digital Library (https://dl.acm.org):

"Abstract:(sensemaking OR synthesis OR sense-making) AND Abstract:(scient* OR scholar*)". This query returned 949 research articles in total. From these research articles, we retained 83 papers that addressed human scholars making sense of scholarly information, rather than general or everyday sensemaking, or studying unrelated topics like speech synthesis. From these 83 papers, we then retained 38 articles that addressed scholarly sensemaking with abstract, qualitative information like research papers, rather than quantitative information like databases or datasets (Our PRISMA [47] diagram is in https://osf.io/f2hpa/files/osfstorage/67fe0eff0c3d3cbe17763d70).

After identifying the 38 related research articles, we manually extracted mentions of scholarly-sensemaking-related information objects and their properties (The full list of extracted quotes is in https://osf.io/f2hpa/files/osfstorage/67fe0dc8bd14cb8e72d567aa), and then exported them to a Miro digital whiteboard (A screenshot of our Miroboard is in https://osf.io/f2hpa/files/osfstorage/67fe0eedcc654e6929fe306f) and iteratively clustered them into sets of information objects and properties.

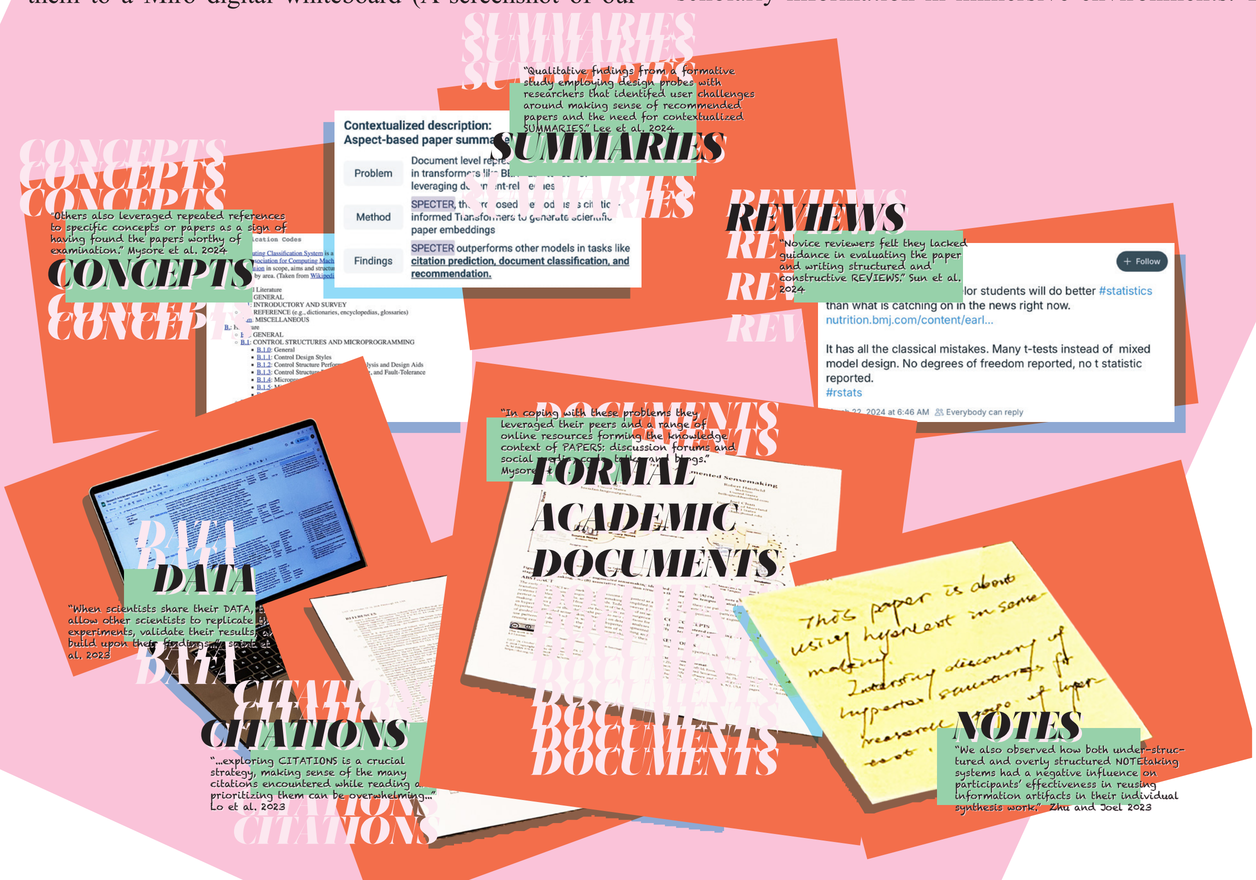
Synthesizing Visual Design Patterns for Materializing Abstract Information in Modern Artworks

Our second goal was to identify potential design patterns that could help make abstract scholarly information more senseable. We were interested in exploring design patterns that were very different from existing material forms like papers and search interfaces and notes. Therefore, we sought inspiration from modern art, which is known for its broad exploration of visual approaches to capturing and conveying abstract aspects of human experience like immersion, tranquility after bustle and self perception [19]. To do this, the first author visited three well-known modern art museums to collect visual design patterns that can be adapted to materialize abstract scholarly information in immersive environments. The museums visited include the Andy Warhol Museum in Pittsburgh, PA, the Hirshhorn Museum, and the National Gallery of Art East Building in Washington, DC. While the selection of these museums was not systematic, they showcase iconic and representative works that reflect key trends and critical thinking in modern art. In total, the first author explored 113 artworks and captured 365 photos across visits.

After the museum visits, the first author created mood boards in Miro using the collected artifacts, identifying patterns and techniques that artists used to convey abstract and emotional ideas.

Conceptual Design Explorations

Finally, we used the information objects and properties from the systematic review, and visual design patterns from the modern artworks, as a visual toolkit to generate a set of conceptual designs for immersive environments for supporting scholarly sensemaking.



RESULTS

Scholarly Information Objects

We identified two major types of information objects from our systematic review: materialized information objects and immaterial information objects. Materialized information objects refer to entities of scholarly information that have a concrete, tangible format. Immaterial information objects are information objects that currently lack a concrete form and remain abstract or fluid in nature. The full list of information objects is shown in Figure 7A.

Materialized Information Objects

Some information objects are traditionally presented in physical or tangible formats, such as formal academic documents, their content, notes, and citations. These types of information objects are the easiest to perceive and engage with during sensemaking tasks.

Formal academic documents are referred to using various terms, such as "*papers*" [2, 5, 13, 14, 18, 29, 30, 35, 37, 41, 44, 62], "*publications*" [64], "*literature*" [39], "*prior (research) work*" [13, 37, 41], "*passages*"

[41], and "*articles*" [5, 8, 14]. **Citations** are numerical markers or references including the author's name and publication year, typically embedded within the body of a text or listed in bibliographies following the main text. In research articles from the review they were referred to as "*citations*" [13, 18, 30, 41, 58] and "*citances*" (i.e. citations and its context in the text) [37]. **Contents** of formal academic documents include both the regular textual content [37] and mathematical content [44, 62]. **Notes** are intermediate artifacts that researchers and scholars create during the sensemaking process. Zhu et al. categorized these into source notes, summary notes, and synthesis notes [77].

Other information objects, such as summaries, concepts, data, and reviews, are materialized in more latent forms. While they lack a fixed or standardized structure, scholars and researchers engage with them using established conventions.

Summaries are condensed versions of longer documents, created by researchers, scholars, or large language models (LLMs) to facilitate easier dissemination and reuse [13, 37]. **Data** serves as the cornerstone of research. Scholars and researchers require data that is both findable and accessible [55] to engage deeply with scholarly materials and conduct detailed sensemaking. **Reviews** are formal written reflections in which scholars and researchers synthesize and interpret academic papers, contributing to the broader process of scholarly sensemaking [14, 62]. **Concepts** are terms that serve as tokens representing abstract ideas within scientific discourse. They appear in various forms, such as "*keywords*" [20], "*topics*" [5, 13], "*concepts*" [58, 72], "*vocabulary*" [65], and "*research entities*" [46].

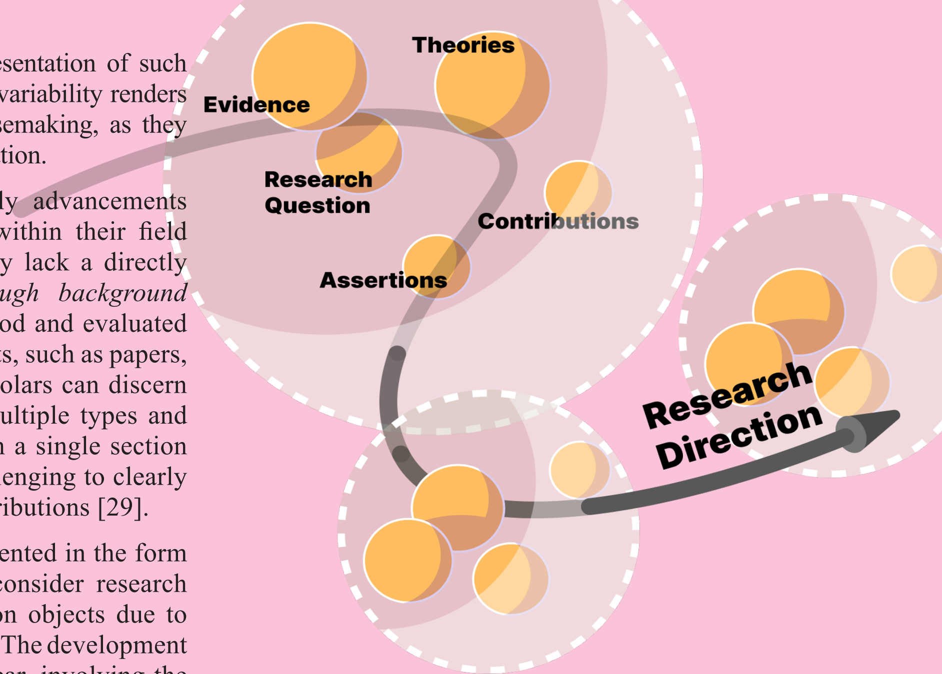
Immaterial Information Objects

In contrast, some information objects lack conventional forms, whether physical or digital. While certain information objects may take on specific forms in particular contexts, they do not adhere to standardized formats. Examples include evidence, theories, and assertions. Scholars and researchers can formalize these elements within their writing; however, the structure and presentation of such information is often idiosyncratic. This variability renders them immaterial in the context of sensemaking, as they resist consistent, standardized representation.

Contributions represent the scholarly advancements that a researcher or scholar makes within their field of study. These contributions typically lack a directly perceivable form and require "*enough background knowledge*" to be effectively understood and evaluated [62]. While formal academic documents, such as papers, serve as a medium through which scholars can discern contributions, authors often embed multiple types and levels of research contributions within a single section of text. This practice can make it challenging to clearly identify and interpret the specific contributions [29].

Research questions are typically presented in the form of explicit questions. However, we consider research questions to be immaterial information objects due to their hierarchical and branching nature. The development of research questions is often non-linear, involving the gradual refinement of ideas across multiple levels. As one participant in a prior study noted, "*creating research questions naturally resembles the form of a mind map, where the development of ideas gradually narrows down but could have different branches*" [34].

Evidence consists of direct findings derived from data collected during research. It is considered immaterial because the ability to accurately interpret evidence often depends on the level of detail provided [23, 28]. Evidence can be represented in various forms, including "*products*" [58], "*results*" [5, 21], "*findings*" [65], and "*evidence*" itself [23, 28]. Assertions represent the claims and propositions made by sensemakers. While assertions often take concrete forms within texts, such as formal academic documents, they are considered immaterial due to their flexible nature and the contextual understanding required to fully interpret them. The senseability of assertions depends on how they are presented and supported within a given context. For example, scholars must assess whether the assertions in a paper are "*convincingly supported*" [5].



Theories provide systematic explanations of phenomena, aiming to predict, interpret, or deepen understanding of various elements of the world. By nature, they are highly abstract [52]. Consequently, theories are not directly observable and cannot be validated solely through empirical data [53].

Research directions refer to the evolving trajectories or trends in the work of individual scholars or research communities. Researchers may articulate these directions using "*keywords*" and "*concepts*" [20]. However, research directions are considered immaterial because they lack a standardized format and often emerge organically through intensive scholarly discussions [44].

Properties of Scholarly Information Objects

These information objects displayed a wide range of properties in the reviewed articles. These properties are fundamental attributes that shape how researchers and scholars perceive information objects during the scholarly sensemaking process. After categorizing these properties on the Miro board, we found they could be differentiated by the extent to which they are inherently geo-spatial. Properties that are inherently geo-spatial are referred to as tangible properties, while those that are not are termed intangible properties. The full list of properties is shown in Figure 7A.

Tangible Properties of Information Objects

Tangible information properties contain some geo-spatial aspects that provide ways for scholars and researchers to interact with information like an everyday material.

Position encompasses both the physical location and semantic orientation of an information object. Information objects may have a specified orientation, such as "*incoming citations*" [18, 37]. The spatial distribution of information objects also demonstrates the features of information objects' position. For instance, the contents of formal academic documents may appear "*scattered*" [37] due to the varying position of individual contents.

Quantity describes the amount of information objects in the sensemaking process. This property mostly belongs to materialized information objects. For example, "*citation counts*" [13] and "*enormous amount of data*" [58].

Accessibility reflects whether these objects are findable or visible. Please note that "*accessibility*" here differs from the "*accessibility*" as a subdomain of HCI, which ensures the inclusiveness of technologies for diverse users. Some formal academic documents lacks accessibility because they are "*pay-per-view*," requiring readers to bypass pay walls by asking friends with access to download and share the documents [8]. Another example is data that can be described as "*transparent*" [34] when it is both "*findable*" and "*accessible*" [55].

Intangible Properties of Information Objects

In contrast to tangible properties, intangible information properties lack inherent geo-spatial aspects, making them more difficult to sense.

Timeliness describes how old or how new information objects are relatively. For example, some articles in the review described formal academic documents as "*timely*" [30], "*new*" [29], or "*recent*" [18].

Structure describes relations between internal elements of information objects. For example, formal academic documents have structures for their contents [5, 14, 37, 41]. Scholars' notes can also be "*under-structured*" or "*overly structured*" [77]. The property structure also describes a hierarchical relationship (e.g., "*a tree of*", "*branches of*", and "*hierarchical*" [39]).

Similarity indicates the resemblance between information objects, emphasizing the shared characteristics. Both materialized information objects (e.g., formal academic documents [13]) and immaterial information objects (e.g., research directions [30]) can exhibit this property.

Connections are relationships between different information objects. Unlike similarity, connections describe associations and even types of associations between information objects. For example, two papers may be connected because they reference the same scientific theory to support their arguments. Materialized information objects, such as formal academic documents [13, 14, 18, 29, 35, 37–39, 41, 62], and citations [13, 30, 58] exhibit connections. Similarly, research directions [29, 30] and research works [13, 41, 59] are examples of immaterial information objects that possess connections within their respective categories.

Context is the properties of information objects defined by the circumstance in which the information objects are situated or processed. For example, the context of citations includes its surrounding text. These sentences that a citation is situated in are called "*citances*" [37] or "*citation context*" [30]. This sentence helps sensemakers understand the citations' connection to the documents they are in. In contrast, the context of a summary [37] presents the provenance that creates this summary. Immaterial information objects also have context. However, different from materialized information objects, context of an immaterial information object is usually abstract. For example, research ideas have community context [44]; contributions of a research work can have roots in organizational and societal context [57].

Evocativeness is the capacity of information objects to offer insights to sensemakers. Materialized information objects like formal academic documents [30] and immaterial information objects like contributions [5] and research ideas [39] can be insightful.

Quality represents the strength of an information object. Immaterial information objects like research works and research ideas have this property. For example, if research work is low in quality, it might be described as a "*reluctant study*" [59]. On the other hand, if an idea is high in quality, it may be described as having "*value*" or being "*creative and unique*" [39]. Materialized information objects, such as data, can also possess quality [20].

Truthlikeness indicates how accurately the information reflects reality. Truthlikeness differs from quality: while truthlikeness focuses on the accuracy of the information, quality emphasizes its value or usefulness. Although related, these properties are distinct within the context of scholarly sensemaking. Both materialized and immaterial information objects can exhibit truthlikeness. Examples include the soundness and correctness of formal academic documents [5, 44], the correctness of evidence [5], and the "*truthlikeness or verisimilitude*" of theories [53].

Completeness reflects how integrated or comprehensive a logical system is. Examples include the completeness of evidence [21] and the completeness of research directions [30].

Explicitness describes the level of detail and clarity of an information object, indicating its level of abstrac- tion—whether it is broad and vague or detailed and specific. For instance, a research article that only discusses high-level concepts might be perceived as broad or vague. In contrast, if it provides sufficient examples to contextualize these concepts, it becomes more explicit. Based on the review, this property is observed exclusively in immaterial information objects. Examples include research directions (e.g., "*level of granularity*" [46], "*too broad to be meaningful*" [30], "*clarity*" [20]), assertions (e.g., "*explicit design propositions*" [53], "*general* *high-level scientific claims*" [10]), and concepts (e.g., "*extremely specific research keywords*" [20], "*more general topic*" [13], "*too broad keywords*" [20]).

Fairness denotes whether an information object is biased. Both materialized and immaterial information objects can exhibit this property. Examples include the fairness of reviews (e.g., "*biased reviews*," "*more fair reviews*" [62]) and the fairness of research works (e.g., "*biases inherent in case studies*" [72]).

These intangible information properties are hard to sense for sensemakers compared to those tangible properties. Materialing the associated information objects into a form that makes these intangible properties more senseable could enable better scholarly sensemaking.

Visual Design Patterns for Communicating Abstraction

We synthesized 6 visual design patterns for communicating abstraction in modern art that we felt had the potential to inspire new ways of materializing abstract scholarly information.

Space refers to the environment that surrounds the user. In artworks, it helps artists engage visitors as part of the art, allowing them to experience subtle and implicit emotions like being encompassed and feeling small. For example, in *Silver Clouds* [71], Andy Warhol placed several floating metallic "pillows" in the space, making visitors part of the driving forces that nudge these pillows. We hypothesize that the use of space could help express properties such as *position* and *quantity*. Space could be a specially designed environment that prompts and contains "interactive objects," which are the fundamental elements of new designs that support scholarly sensemaking.

Composition refers to the way in which all elements are put together to create an overall effect to the user. It helps artists achieve an overall effect on artworks, such as dynamic or static. For example, the kinetic artwork *Mobiles* [11] uses a composition of lines and shapes to convey not just interconnected blocks of color but also an emotional sense of instability and constant change. We hypothesize that the use of composition could help express properties such as *quality*, *structure*, and *evocativeness*. Compositions could be tuned for supporting better scholarly sensemaking because it has the potential to visually describe the semantic and logic structure that is behind an argument.

Fidelity refers to the level of details in a design or an artwork. Artists use fidelity to leave space for the audience to imagine, which is helpful for translating abstract concepts into a visual form. For example, in the oil painting *Lipstick, Lip Gloss, Hickeys Too* [73]. Yukhnovich's creatively employs large brushes to form bold color blocks, reducing the visual fidelity that is typical of Rococo paintings while introducing a blurred effect. This deliberate abstraction effectively captures the essence of the Rococo style, conveying an implicit understanding of its defining characteristics. We hypothesize that the use of fidelity could help convey properties such as *explicitness* and *completeness*. Lowering fidelity forming information objects could be increasingly helpful for materializing the abstractness of information, which might be helpful for scholarly sensemaking of those immaterial information objects.

Figure 1. Silver Clouds

Figure 2. Mobiles

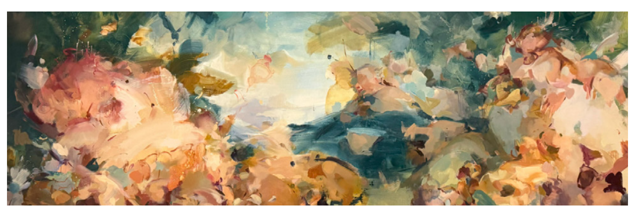


Figure 3. Lipstick, Lip Gloss, Hickeys Too

Texture refers to the visual effects caused by the surface structure of materials and their combinations. Artists enriches the artwork with implicit background and cultural information. For example, the *Cubi XI* [60] by David Smith has scratches on its metal surface, revealing the sculpting technique and conveys the force and energy applied by the grinder, adding a dynamic, tactile element to the work. We hypothesized that the use of texture could help convey properties such as *quality* and *timeliness*. Adding textures to immaterial information objects might be helpful for scholars to better sense the intangible properties and utilize them for better sensemaking.

Figure 4. Cubi XI

Figure 5. Night

Figure 6. Album of a Mat Queen

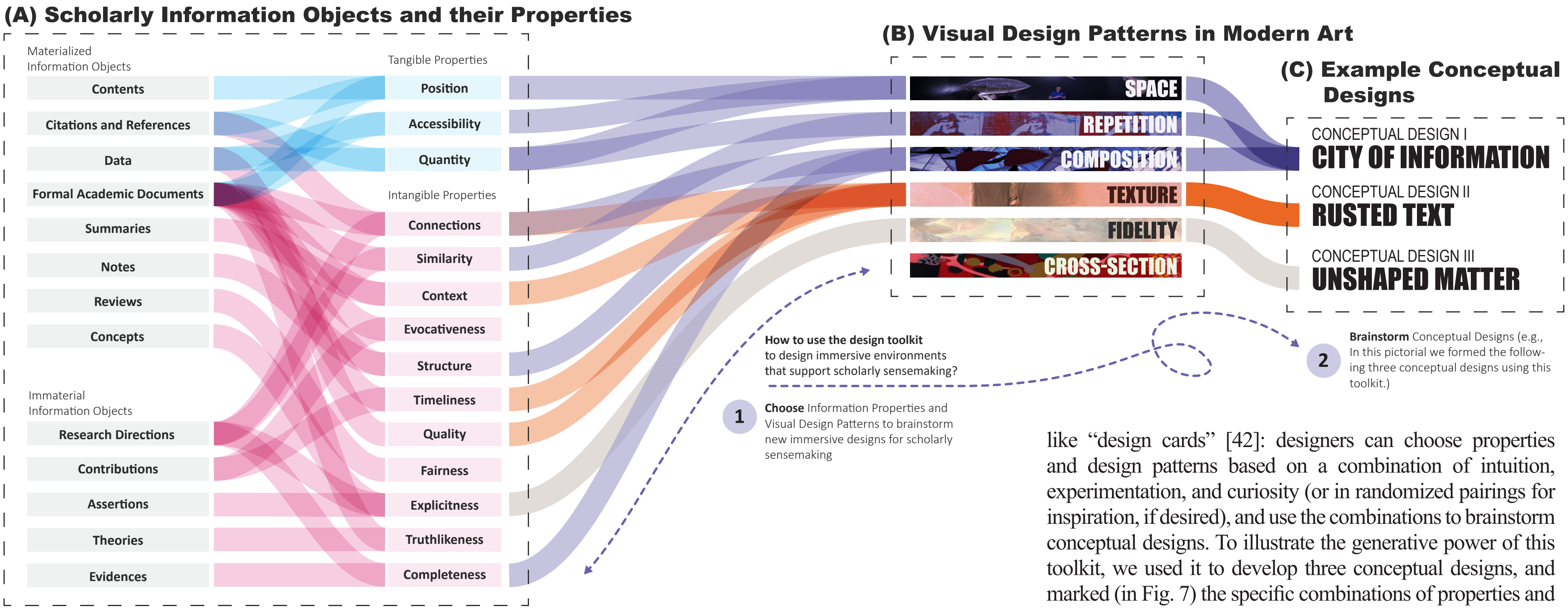


Figure 7. Design toolkit for designing senseable scholarly sensemaking support systems, consisting of (A) a set of scholarly information objects and their associated properties, and (B) a list of visual design patterns generated from the modern arts. A list of conceptual designs brainstormed from choosing properties and visual design patterns is also shown as examples of how to use the toolkit.

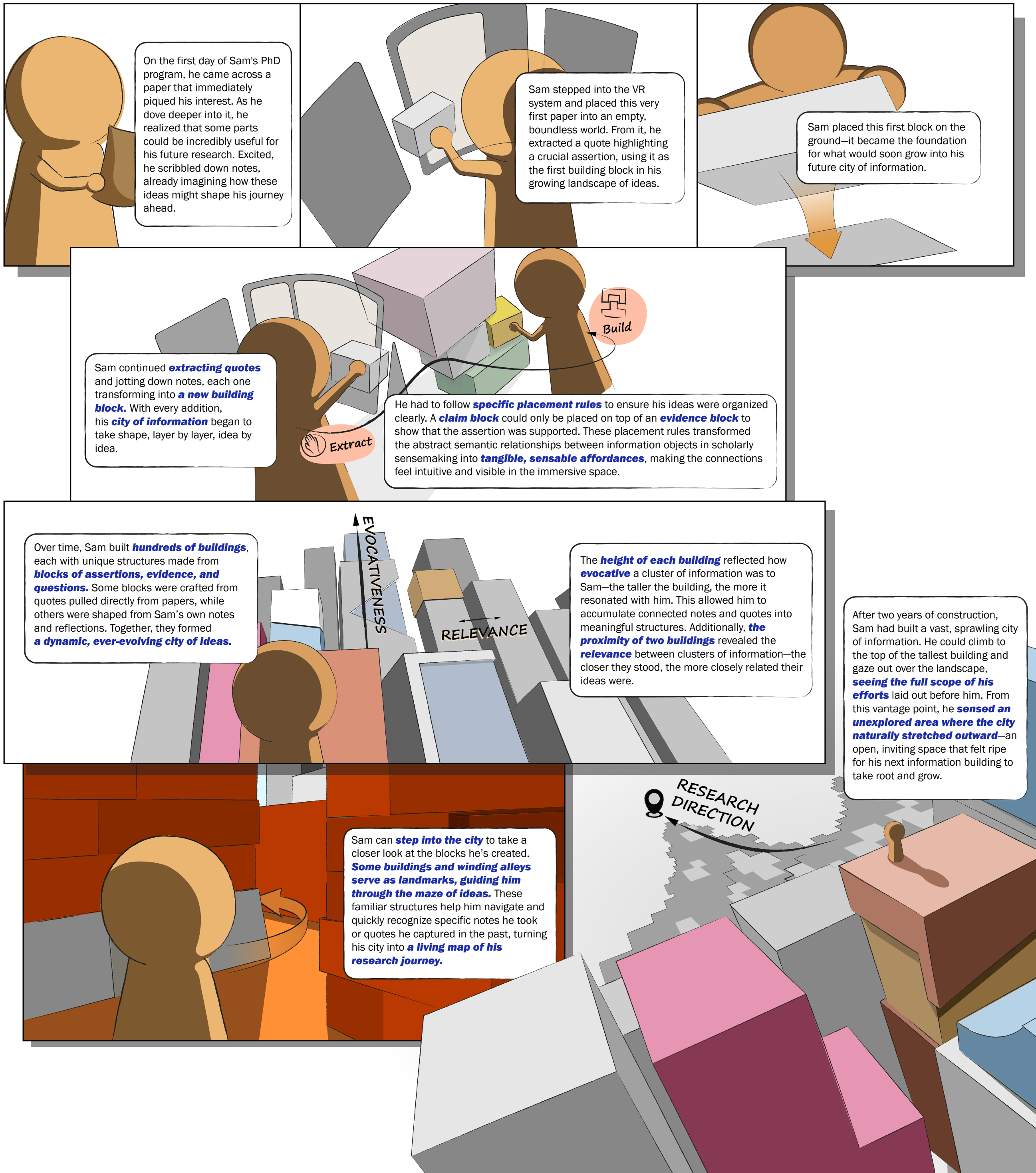
Cross-section refers to a technique used to reveal the internal structure of a design. Artists create cross-sectional images to convey hidden emotions and underlying narratives. For example, The artwork Night [33] by Kiki Kogelnik depicts two figures lying beneath a gleaming disco ball, with the cross-section revealing the bones of one arm while the legs remain unaltered. We hypothesized that the use of cross-section could help convey properties such as structure. Using cross-section might be helpful for scholars to better sense the hidden logic structure behind an information object.

Repetition refers to the repeating pattern of certain items in a design or an artwork. Artists used repetitions to add rhythm into their work. For instance, in *Album of a Mat Queen* [70], Andy Warhol layered red over cyan in the five patterns at the upper left, creating a dynamic interplay of colors. We hypothesized that the use of *repetition* in design for scholarly sensemaking could help convey properties such as quantity and similarity. Repetition can help scholars quickly sense the subtle difference between similar information objects and understand the amount of them.

Prototype Design Toolkit and Conceptual Designs

We combine the objects and properties from our review, and the visual design patterns synthesized from modern arts, into a prototype design *toolkit* that can be used to develop new conceptual designs for immersive sense making systems (Fig. 7). We envision the elements of this toolkit being used like "design cards" [42]: designers can choose properties and design patterns based on a combination of intuition, experimentation, and curiosity (or in randomized pairings for inspiration, if desired), and use the combinations to brainstorm conceptual designs. To illustrate the generative power of this toolkit, we used it to develop three conceptual designs, and marked (in Fig. 7) the specific combinations of properties and visual design patterns we found fruitful for developing these designs. The first design, City of Information, focuses on supporting incremental knowledge synthesis over time. In contrast, the second design, Rusted Text, emphasizes the gradual decline or decay of collected information objects. The third design, Unshaped Matter, proposes a solution for provoking discussion in collaborative sensemaking settings, whereas the first two are more oriented toward individual sensemaking scenarios.

We anchor these conceptual designs in the sample scenario of Sam, a second-year Ph.D. student. Having recently completed his two-year coursework, Sam is now preparing to write a critical synthesis of literature for a chosen research direction for his comprehensive exam, which will also serve as a gateway to his dissertation. These storyboards help visualize how the concepts might function in real-world contexts.

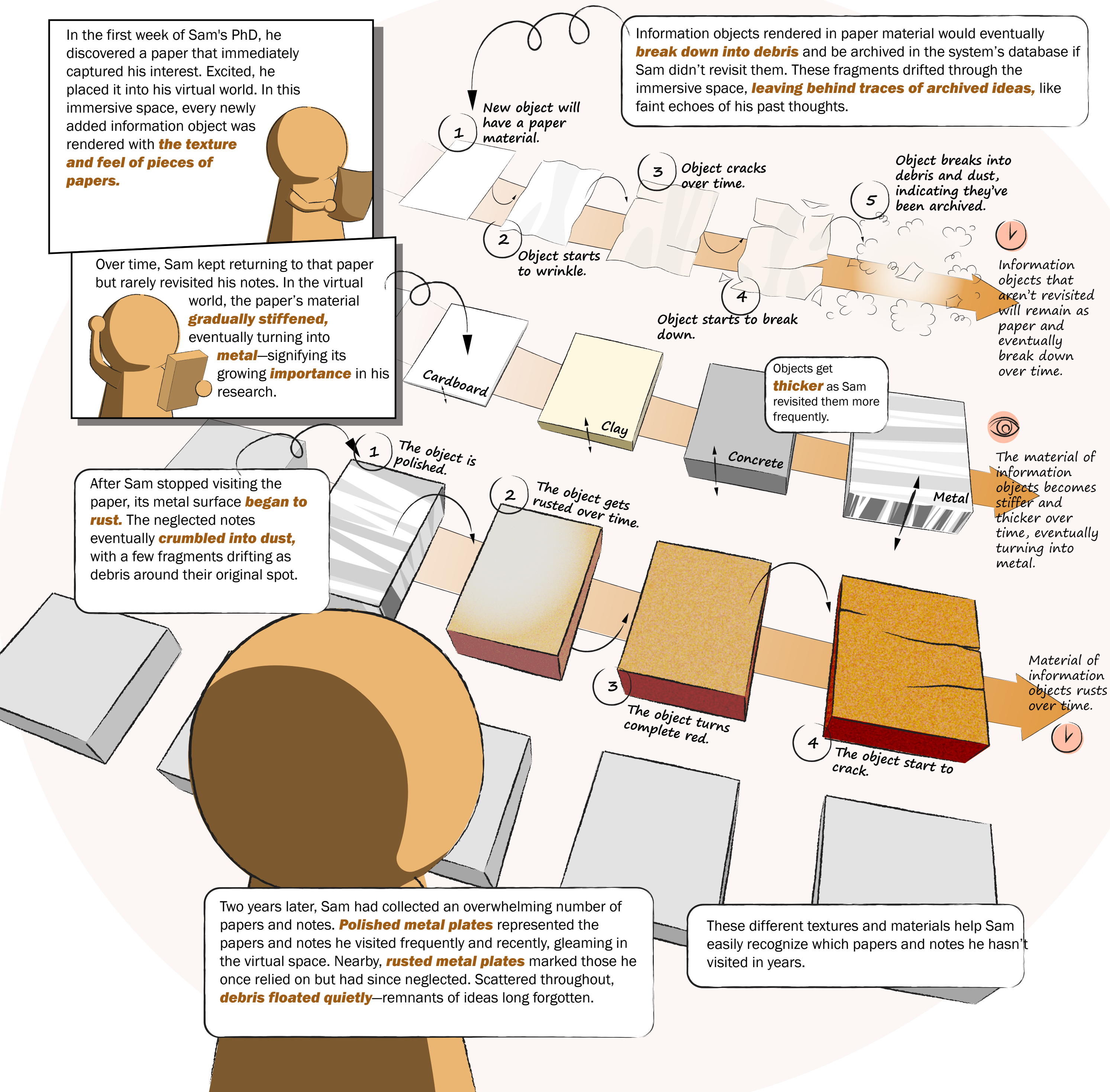


City of Information

It is difficult for a scholar to gain a comprehensive overview of their knowledge. However, having this full view is essential for understanding the frontiers of their research and what has already been fully explored. Current tools provide some forms of this overview, but they often overwhelm sensemakers by presenting an excessive number of connections, leading to cognitive overload.

The City of information provides a solution to this situation. It is a conceptual design that allows scholars to log information in three-dimensional constructions, primarily using visual elements, **Space**, **Repitition**, and **Composition**. This design enhances scholarly sensemaking by providing a set of visual constraints and affordances to aid the synthesis of information. It transforms intangible properties—such as connections and the structure of immaterial information objects (e.g., questions, assertions, evidence)—into a visually perceivable format that supports the crafting of theories and papers.

In this design, a sensemaker begins by building their own City of Information in an empty world, gradually constructing the city from building to building. They extract content from the literature and take notes to create building blocks while immersed in this virtual world. These building blocks have explicit types, and each type has a specific shape that determines which other types can be placed on it. The design encourages a more permanent construction of information buildings, compelling sensemakers to build high-quality structures and be thoughtful when planning the city's layout. Because locations in the City of Information are absolute, modifying the city comes with a cost, reinforcing the importance of careful organization and deliberate synthesis. Over time, the City of Information can expand support for sensemaking towards more marco levels: a sensemaker can intuitively sense research directions by observing where the information buildings are repeating and how the City of Information stretches outward.

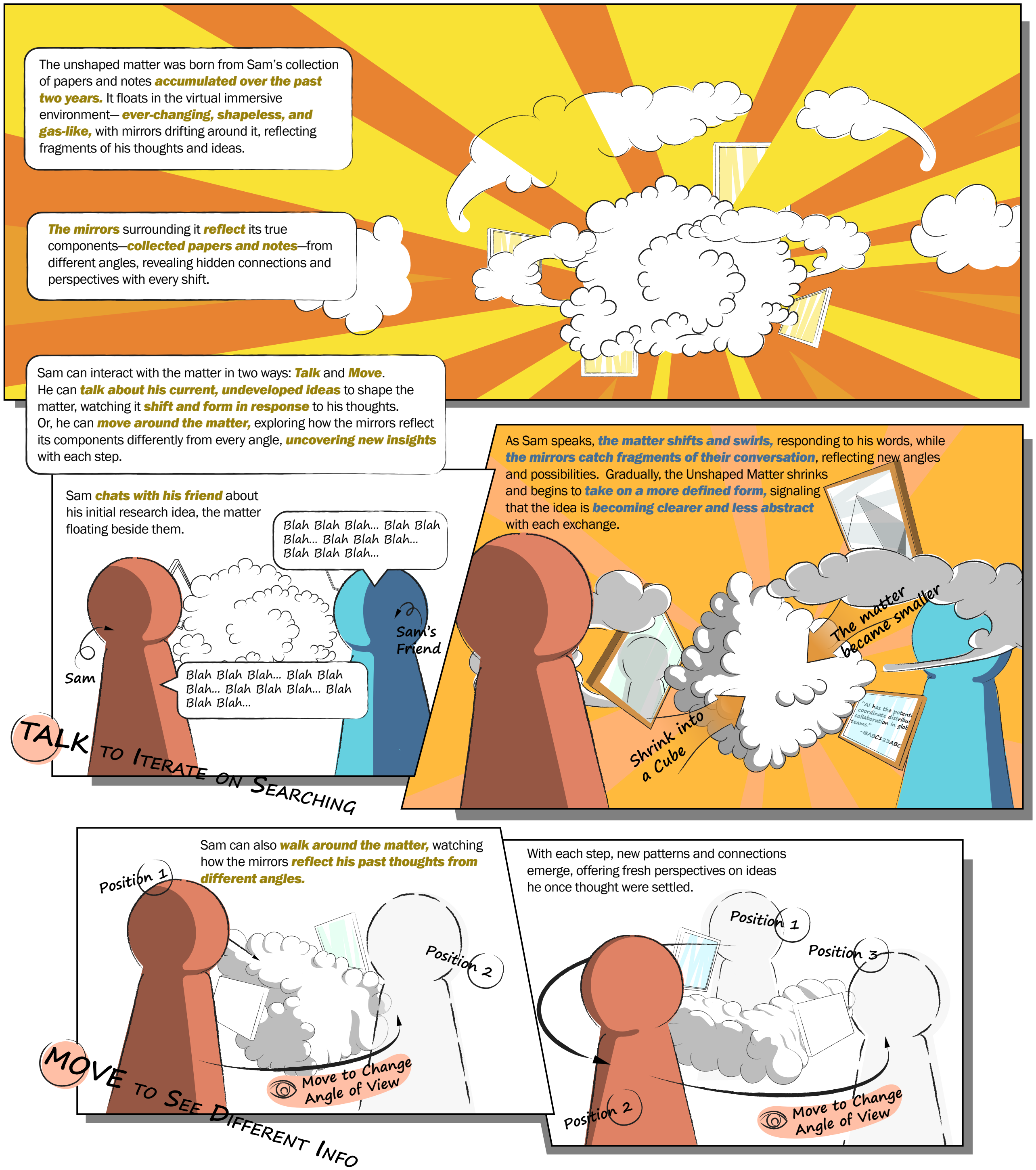


Rusted Text

Integrating texture and material into the design of immersive environments for scholarly sensemaking, the conceptual design Rusted Text tries to convey the property Timeliness to sensemakers. For example, Sam can use this design to quickly understand what information objects have been recently visited.

Rusted text gives scholarly information a metal-like material and **Texture**, enabling information objects to rust like real metals. The degree of rustiness of the material helps old and less visited information objects stands out visually, which is different traditional folder structure. Like digital patinas [36], adding texture and material to information objects can evoke rich emotional sensations that might lower sensemakers' cognitive load when facing a large body of information.

In the scenario of Sam, he had collected hundreds and thousands of information objects in his personal information management system. But it is hard for him to understand how one information object relates to others and determine which particular information object should be visited. In the conceptual design Rusted Text, Sam can quickly identified those information objects that haven't been visited in a long time by perceiving the rust.



Unshaped Matter

Identifying a feasible research question or idea requires extensive iteration and refinement. It often involves revisiting and comparing past ideas with current potential ones. However, finding relevant ideas from past notes and prior research, as well as navigating between them to generate new insights, is challenging with current tools.

We proposed the Unshaped Matter to resolve this issue. It is a conceptual design that supports scholars' sensemaking processes in ideating and refining research questions by leveraging the visual elements of **Fidelity**, and reflection. This design enhances scholarly sensemaking for two key reasons. First, the Unshaped Matter employs a blurry shape to help scholars perceive the level of completeness or explicitness of their research question or idea. Second, the system continuously records scholars' input as new notes and searches for relevant stored information objects (e.g., papers, quotes, notes about assertions, research ideas, and research questions). These retrieved information objects are then displayed to scholars, providing broader inspiration from past notes.

In this design, an AI-powered system has access to the sensemaker's note-taking system and learns from it to form an Unshaped Matter. This Unshaped Matter is a gas-like, floating shape in midair, surrounded by several floating mirrors. This formless matter represents the implicitness and abstractness of a sensemaker's entire body of knowledge. A user has two ways to interact with this Unshaped Matter: they can either engage in a conversation via voice or text, or they can walk around it to perceive it from different angles. This design enables an intuitive foraging and sensemaking loop, with the system iterating search results as sensemakers provide more information about their current ideas, and the changing dynamics of the unshaped matter providing direct, senseable feedback on the evolving explicitness and completeness of their ideas as they explore.

DISCUSSION

In this pictorial, we explored how we might augment scholarly sensemaking by making the full range of scholarly information more senseable. We advanced knowledge on this question in three ways. First, from our systematic review of systems for scholarly sensemaking across 38 HCI papers, we enumerated key types of scholarly information and their properties, ranging from familiar materialized information objects like formal academic documents, quotes, and notes, to more immaterial information objects like research questions, assertions, concepts, and research directions. These objects in turn were associated with a wide range of properties, ranging from tangible properties like position and quantity, to less sense-able properties like quality, evocativeness, and relevance. Next, we synthesized a rich palette of visual design patterns for materializing abstract information in modern artworks, including patterns like fidelity, repetition, composition, and use of space, among others. Finally, we constructed a visual toolkit with these design patterns and our enumerated scholarly information and properties, and used the toolkit to develop three novel conceptual designs for senseable scholarly sensemaking in immersive environments: a city of information, rusted text, and unshaped matter.

Altogether, our design explorations map out a fruitful new design space for immersive environments for scholarly sensemaking that take the body seriously.

Limitations and Future Work

Expanding the Design Toolkit

Our systematic review drew from the ACM Digital Library only; this might limit the comprehensiveness of the review, since sensemaking support systems are studied in other venues, such as visualization conferences and journals that are indexed in IEEE Xplore. Our review also specifically focused on prior work that directly addressed human sensemaking: thus, we excluded papers that proposed computational ranking systems based solely on metadata, such as citation counts, which may introduce properties like “impact”. These properties were not directly observed in our sample of HCI-focused papers, but may be useful to explore to expand the range of properties that scholars engage with during the sensemaking process. Yet, our enumerated information objects and properties proved rich enough to inspire novel conceptual designs. Further, as we discuss in the following sections, the enumerated objects and properties both align with and enrich prior models of scholarly sensemaking.

Our synthesis of design patterns from modern artworks was also heavily visual, leaving the other senses of the body unexplored. While this modality still proved sufficient to illuminate a fertile design space, we are eager to systematically explore ways to make abstract scholarly information senseable beyond the eyes: for example, inhaling warm air can create a sensation of breathlessness, which can evoke tacit emotions such as nervousness or simulate an immersive dangerous scenario [9]; and shape-changing displays and haptics might also be leveraged to provide more immersive “digital patinas” [36] for scholarly information than the visual rusted text designs we have outlined here. Exploring this wider array of senses might enable richer, more direct perception of properties like quality or evocativeness, and perhaps also inspire more accessible systems for scholarly sensemaking.

Finally, we proposed that our design toolkit could be used as a set of design cards, with the logic of choosing combinations of properties and visual design patterns left to the intuition, expertise, and creativity of designers. Over time, we envision that community usage of, or additional conceptual reflection on, this toolkit might yield repeatable logics that could provide more guidance to individual designers who wish to use the toolkit, to mature the toolkit into a design *framework* for senseable immersive scholarly sensemaking.

Evaluating the Efficacy of Conceptual Designs

The question of efficacy for our conceptual designs remains unanswered. Here, we used a design fiction approach to try to illuminate novel affordances and possibilities. We intentionally anchored our conceptual designs in a scholarly sensemaking scenario that embodies key properties of real-world sensemaking scenarios where difficulties with sensemaking have been observed, such as complexity and scale of the synthesis task (generating novel research directions vs. simple summarizations of a few papers), as well as temporal and spatial fragmentation of sensemaking over time [7, 24, 43, 48, 78]. Our eventual conceptual designs also resonate with some key desire paths observed in prior observational studies of scholarly sensemaking. For instance, the City of Information’s compositionality resonates with observations of scholars making formal typed distinctions between different types of notes [7, 78], and building overview structures to facilitate revisiting and sensemaking of prior notes, such as tables and indices [24, 78]; and Rusted Text’s dynamics resemble scholars’ expressed desire and prototyped practices for elaborating and/or archiving previously written notes over time [78]. This grounding of our scenarios and designs gives us reason to believe that our conceptual designs have the potential to augment scholarly sensemaking in real-world scenarios.

In subsequent work, we aim to refine these designs (and more) into concrete prototypes that we can deploy in user studies to better understand how and to what extent senseability support can augment scholarly sensemaking. Our initial hypotheses is that increasing senseability will enable faster, more iterative sensemaking, by reducing the “cost structure” of sensemaking [49, 54]: we expect that scholars will be able to construct richer, more complex and insightful theories, literature reviews, and research proposals, with less time cost and effort. We expect to be especially likely to observe this in sensemaking scenarios that, like our conceptual design scenarios, exhibit key characteristics of complexity and temporal and spatial fragmentation of scholarly information.

A richer material ecology of scholarly sensemaking

The information objects from our systematic review partially align with prior models of sensemaking. For instance, materialized information objects, such as formal academic documents, correspond to “evidence files” and “presentations”, while data correspond to "evidence files", in Pirolli and Card's [50] Notional Sensemaking Model. Immaterial information objects can also be mapped to the model, with research directions aligning with "schema," as they guide the future actions of researchers; and contributions, theories, and assertions mapping to "hypotheses" in the Notional Model. In Blake and Pratt's Collaborative Information Synthesis (CIS) Model [7], key constructs like "hypothesis projections" map to our assertions, and "context information" can be mapped to our intangible property of "context" and its associated information objects (e.g, community context of research ideas [44], organizational and societal context of contributions [57]).

But other information objects like contents, summaries, notes, reviews, research directions, research works, concepts are not so easily mapped to existing models; and our enumeration of key properties of scholarly information objects are also an extension over previous models. Thus, our results enrich our understanding of the material ecology of scholarly sensemaking, expanding our capacity to design material interactions for supporting scholarly sensemaking.

Towards a material "physics" of scholarly information
Our conceptual designs illuminate an exciting research opportunity to develop a "material physics" of scholarly information, such as compositional rules in material space, "decay" of materials over time, and transformations between various degrees/forms of fidelity.

As we outlined, these dynamics can be conceptually mapped to key properties of scholarly information and interactions between information objects, such as changes in evocativeness or quality, or supporting relationships between assertions and evidence. But to enable actual interactions based on these "physics" in an immersive environment, we need to develop ways to computationally reify them. We wonder how careful integration of a range of AI technologies might enable technical research along this line: for instance, might argument mining [61] and claim verification [12, 68, 69] models enable "extraction" of key information objects like claims and ideas and evidence from their messy context, along with key connecting relationships between them? With these new "raw materials", might users then "program" material physics using more natural programming paradigms like visual prompt engineering [4] or programming-by-example [75]? Might users also define classifier models — based on models like Bayesian reasoning [63], or even by inspiration from models of forgetting in human memory [6] — that can help define "rusting" properties over time, or predict the "quality" of ideas in one's database? These material physics could be developed communally, in conversation with community norms around scholarly sensemaking, which are sometimes instantiated in community standards like the GRADE framework for evaluating quality of evidence [22]; they could also be defined locally, on a per-user or sub-community basis. We wonder what impact this might have on the development and maintenance of epistemic culture in scholarly communities.

We see resonance between these ideas and recent calls for closer attention to metadata for enabling the future of text in immersive environments [25].

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