Entanglements for Visualization: Changing Research Outcomes through Feminist Theory

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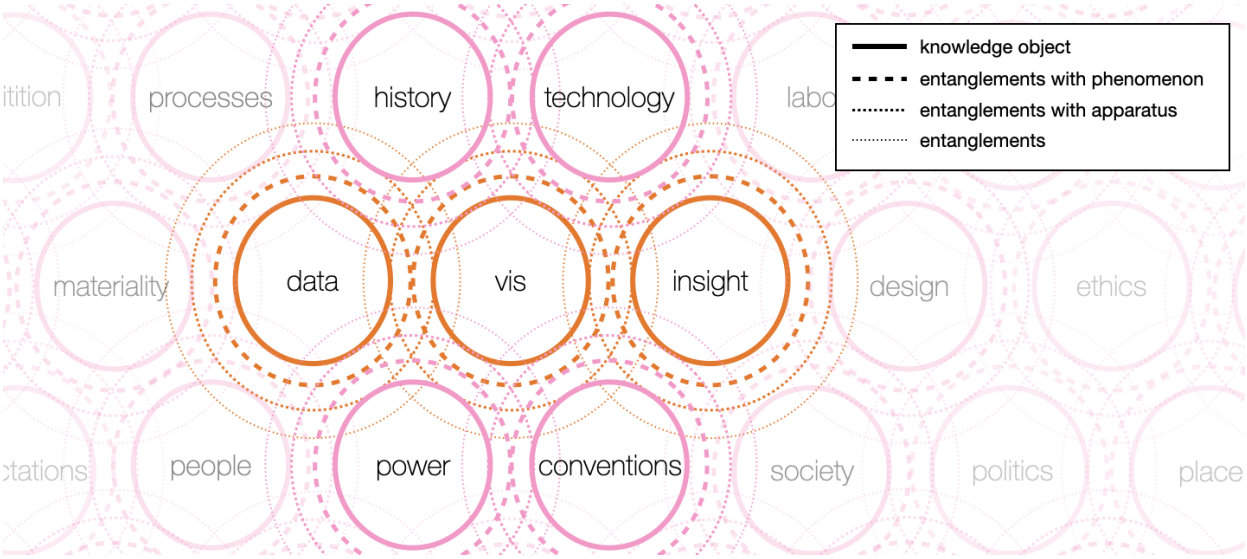

Fig. 1: A core contribution of this paper is a transposition of the feminist theory of entanglement into a visualization context, and specifically to reimagine how data, visualizations, and insights come to be. Entanglement theory centers the role of relationships within visualization research practices. Knowledge artifacts — like data, visualizations, and insights — are shaped by and representative of the phenomena and apparatuses that create them. Phenomena are the things in the world that we wish study and are dynamic and unbounded. Apparatuses are how we come to learn, measure, and understand phenomena: they, too, are dynamic and entangled. An entangled perspective on visualization draws attention to how we know what we know about visualizations as entangled with society, power, processes, and ourselves as researchers.

Abstract—
A growing body of work draws on feminist thinking to challenge assumptions about how people engage with and use visualizations. This work draws on feminist values, driving design and research guidelines that account for the influences of power and neglect. This prior work is largely prescriptive, however, forgoing articulation of how feminist theories of knowledge — or feminist epistemology — can alter research design and outcomes. At the core of our work is an engagement with feminist epistemology, drawing attention to how a new framework for how we know what we know enabled us to overcome intellectual tensions in our research. Specifically, we focus on the theoretical concept of entanglement, central to recent feminist scholarship, and contribute: a history of entanglement in the broader scope of feminist theory; an articulation of the main points of entanglement theory for a visualization context; and a case study of research outcomes as evidence of the potential of feminist epistemology to impact visualization research. This work answers a call in the community to embrace a broader set of theoretical and epistemic foundations and provides a starting point for bringing feminist theories into visualization research.

Index Terms—Epistemology, feminism, entanglement, theory

1 Introduction

A spate of recent work has begun to challenge the normative assumptions of foundational visualization research, including the ideas that people are perceptual machines, visualizations are neutral, and data are objective representations of reality. Studies show that the strength of people's beliefs measurably impacts how they perform visual analysis tasks [101]; that the visual rhetoric of science can be co-opted for anti-science activism [65]; that visualization professionals continue to omit uncertainty despite strong beliefs of its critical role in the accurate representation of data [58]; and that text visualizations are complicit in replicating systems of power within civic discourse settings [11]. Researchers are now acknowledging the role of design considerations beyond purely perceptual ones [12] and advocating for the acceptance of emotive goals in visualization design [64, 67]. In short, the visualization community is increasingly recognizing how the ways we design and read visualizations are entangled and influenced by factors beyond the screen.

Early acknowledgement of the non-neutrality of visualizations comes from Dörk et al.'s conceptualization of *critical infovis*, which promotes a set of principles that support researchers in confronting the situatedness and context-dependent nature of visualization practices [36].

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Critical infovis — and the more recent ideas of data feminism [35, 40] and the ethical dimensions of visualization [27] — pulls from feminist theory and scholarship that, broadly considered, draws our attention to how systems of power and privilege shape experiences and phenomena in the world. This work supports designers and researchers in understanding the ways visualization practices are non-neutral and offers productive and pragmatic guidance for countering power and neglect in those practices.

In this paper we argue that there is more work that feminist theory can do for visualization research. We call attention to the generative potential of feminist epistemological theories that explain how people come to know about and shape the world. These theories of knowledge production, including the production of scientific research, take history and context, people and processes, into account. When applied to visualization research, these theories point us to how data and visualizations, and the people who produce them, are all interdependent. This view diverges from the normative assumptions of visualization research that embrace the objective, neutral position of science, and that see people as separate from the visualizations that they produce or read. This paper stems from our engagement with feminist theory, both as an intellectual exercise and within our design practices, and puts forward evidence to show how feminist theories of knowledge production — in other words, feminist epistemologies — can change research outcomes.

In particular, this project team sustained a long-term collaboration across disciplinary boundaries and practices to interpret the theoretical concept of *entanglement*, as formulated by Karen Barad [6], as an alternative epistemology for visualization. Entanglement theory considers knowledge production practices as inextricably connected to history, society, and the material world. In this work, we articulate how entanglement theory brings forward new ways to view the relationships among data, visualization, and people in our own research practices. In the case of this project team, the idea of entanglement changed the way we thought about data analysts bringing their own knowledge into analysis pipelines, a research topic we first investigated as *implicit error* [76]. By grounding our research in entanglement theory, we overcame many of the lingering contradictions of the implicit error concept and developed a new and more capacious concept we called *data hunches* [71]. Here, we reflect on our movement from implicit error to data hunches to illustrate how entanglement theory — as engaged through our research design and also through interpretive strategies from the humanities — helped us to scale an *epistemic wall*, moving our research in new directions.

Our main contribution consists of three parts: a contextualization of the concept of entanglement within the longer history of feminist epistemological theories; a presentation of entanglement theory for visualization research; and a case study that demonstrates the generative potential of embracing an entanglements epistemology. This work represents an appeal to the visualization community to engage with feminist epistemological theories, and alternative epistemological theories more broadly, answering a call to extend the theoretical foundations of the field [28, 78]. We conclude with a reflection on how our specific experiences with feminist epistemology can inform a broader set of theoretical foundations within visualization.

2 Clarification of Terms

The discussions in this paper rely on the use of several words that are both overloaded and ill-defined in the visualization community. Here, we briefly present our specific use of the words feminist, critical, epistemology, and theory.

Feminism is most broadly known as a socio-political movement that works for equality of the sexes, with current movements extending towards eradicating systemic biases based on gender, sexual orientation, race, and other marginalized identities. Less well known is *feminist theory*, which refers to research that centers the role of power and privilege in scholarly accounts of truth, reality, and knowledge. In this paper, we use feminist theory in reference to the work in this intellectual tradition.

Relatedly, the term *critical* is broadly considered to reflect work that criticizes or challenges existing norms. But here too exists a scholarly foundation, called *critical theory*, that traces societal organization, constraints, and outcomes to enduring cultural, historical, and/or ideological forces. Feminist theory is often considered a type of critical theory: one where the roots of ideas stem specifically from feminist scholars and activists and their emphasis on examining and challenging unequal forces of power. In this paper, our use of the word critical is in reference to critical theory, and we differentiate between feminist and critical ideas when those ideas are specifically grounded in feminist theory, or not.

Finally, *epistemology* is a branch of philosophy that examines the production of knowledge. In other words, it offers theories of how we know what we know. Critical to epistemological thinking is an attention to the set of standards and practices that shape, define, and assess knowledge contributions. Different epistemologies, thus, draw attention to different aspects of knowledge production at the expense of other aspects. Understanding how and why these differences matter are central to epistemology. Within visualization research the predominant epistemology is one called *positivism*, which contends that scientific knowledge can be obtained through the pursuit of objective, empirical evidence. In this work we surface a feminist epistemology — entanglement — as an alternative means of understanding how scientific knowledge is produced. When discussing specific theories that researchers have proposed for describing and detailing how knowledge is produced, we use the term *epistemological theories*. When these theories derive from feminist views of how knowledge is produced, we use the narrower term *feminist epistemological theories*.

3 Related Work

In this section we discuss prior visualization research that includes or builds from feminist perspectives. We also briefly cover closely aligned work in feminist HCI research.

3.1 Feminist Visualization

Several prominent projects synthesize critical and feminist theories into actionable guidelines and principles to support researchers in understanding and countering the effects of power and privilege in visualization practices. Dörk et al. put forward design principles that highlight the contextual aspects of visualizations in a framework they call *critical infovis* [36]. The formalization of critical infovis draws from emerging critical perspectives in HCI and articulates arguments for the non-neutrality of visualizations and their design. Building on these ideas, the principles put forward by D'Ignazio & Klein in their *data feminism* framework support designers and researchers in questioning the role of power in the production of data and its subsequent use [35, 40]. Data feminism is grounded in feminist theory and is the first work to specifically advocate for a feminist approach to visualization design. In complementary work, Correll investigates the role of power and responsibility in visualization design to press for ethical considerations in visualization practices [27]. His arguments are partly grounded in critical and feminist theories that entangle ethical obligations with the production of scientific knowledge.

Reinforcing this work, a number of papers more specifically critique normative visualization design sensibilities through critical and feminist perspectives. Kennedy et al. emphasize the rhetorical power of minimalist visualization design conventions that give visualizations the aura of objectivity and neutrality [53]. Akbaba et al. critique Tufte's minimalist design standards through a surfacing of their roots in a politically charged history [4]. And Hill et al. bring forward the ways that judgements on what makes for good and bad visualization design is unconsciously shaped by socio-cultural phenomena like racism and sexism [54]. All of these critiques emphasize the situatedness of visualization(s), a central idea in feminist theory that views knowledge as inseparable from its context [49].

A string of recent projects take a feminist lens in the design and study of visualizations, though not always explicitly so. Elli et al. design a visualization of sexual harassment in academia, taking care to respect the victims of assault through practices that humanize the individual experiences present in the datasets [41]. In another example, Wood et

al. connect their *literate visualization* framework for documenting design processes with feminist principles from data feminism to scaffold the externalization of design decisions and make labor visible [100]. Another set of studies upend normative assumptions about how people use and read visualizations: showing that people read visualizations based on personal relationships to the topics and authors of the visual [86]; that the same visualizations are used in different ways by groups of opposing political views [65]; and that the receptiveness of an individual to new information affects their willingness to engage with visualizations [52]. Other recent studies explicitly frame research questions to lift up overlooked and neglected views, including: Burns et al.'s study that interrogates the visualization community's prevalent but overloaded and dismissive use of the term novice [18]; He et al.'s study that complicates the community's characterization of the general public [52]; White et al.'s call to consider the unique visualization needs of older adults [98]; as well as Akbaba et al.'s study that surfaces power asymmetries and neglect in design study collaborations [3].

This previous work makes strides in applying feminist theories to visualization research outcomes. It does not, however, directly engage with the underlying epistemology of how we, as visualization researchers, come to know, study, and design visual representations of data. Several lines of existing theoretical work do bring forward alternative epistemological foundations for the field. Drucker argues that researchers in the digital humanities have broken with their epistemic, constructivist origins in their embrace of empirical data and statistical visualizations [38]. She calls for a new framework of how to design visualizations for humanities research through a rethinking of data as *capta*, treating uncertainty as a given, and collapsing the distance between reader and interpretation. Hinrichs et al. build from Drucker's theories to put forward a provocation of *visualization sandcastles* to emphasize that visualizations have value beyond engineered tools [55]. These constructivist views of data and visualizations echo the theoretical arguments that Meyer & Dykes make in their framing of interpretivist visualization design studies [78]. They use this framing to propose an alternative standard for rigor for conducting collaborative, design-oriented visualization research. We continue these epistemological conversations in this paper, specifically bringing forward entanglement theory as an additional lens for studying the relationships of data, visualizations, people, and insights.

3.2 Feminist HCI

HCI researchers have been using a wide range of feminist theories to question and counteract the role systems of power play in what and how technology is developed. Early work by Bardzell & Bardzell introduced several basic tenets of feminist theory to HCI leading to key contributions including an articulation of a feminist HCI methodology [7,8]. More recently, Danielescu et al. challenge the gender binary in text-to-speech conversational agents by developing a non-binary voice assistant [32]. Howard & Irani demonstrate how interview subjects are not just knowledge resources, but rather, are active participants in the research process, as seen through the subject's care and interest in the research topic [57]. In other work, researchers rely on feminist principles to trouble normative beliefs about data in design processes. Sanches et al. present several case studies where they design technology to experience different types of biodata [91]. Relatedly, Desjardins et al. design and deploy devices across their homes to transform IoT data into different visual and tangible forms [34]. Across all this work, feminist theory guides the research questions to challenge normative design decisions that ignore marginalized perspectives and uphold data as objective and stable sources of truth.

More broadly, HCI researchers have brought in a range of critical theories to their practices. Ogbonnayaogburu et al. build on critical race theory to center and elevate storytelling in HCI as an important method, in the support of anti-racist activism [83]. Indigenous theories, with their focus on relationality and place, expand how researchers can build and relate to artificial intelligence technologies [68] and data practices [22]. And turning to queer theory, researchers highlight the importance of using mischief and play as queer methods that challenge norms and assumptions of technology that reinforce gender binaries or exclude marginalized perspectives on health [70,93]. Across these many and varied critical theories are a set of values and core tenets that shape the intellectual questions researchers ask, as well as tie together historical and social contexts that impact the relationship between researcher and research.

In looking at research trends across time, some HCI researchers have proposed the third (and current) wave of HCI research as one defined by critical and feminist epistemologies: an engagement of plural perspectives, context as situated and emergent, and a focus on values [8,50,51]. Building on these views, Frauenberger puts forward *entanglement HCI* as a new epistemology for the next paradigm shift in HCI [46]. His characterization of entanglement HCI is grounded in a broad range of critical and feminist theories and purposefully de-centers people in the study of technology to make the role of the material world more visible. Although the framing of entanglement HCI is relevant for visualization, it does not address the specific foci of visualization research — data, visualizations, and insights — as the carriers and objects of visualization research knowledge. In this paper, we draw specifically from the feminist theory of entanglement. We relate this theory to data, visualizations, and insight, and provide evidence for how this shift in attention alters visualization research outcomes.

4 Entanglement

In this section we introduce entanglement theory in three parts: a genealogy; an interpretive overview of the theory; and, a specific transposition of the theory to the visualization context. We put forward a genealogy, rather than a history, to present our deliberate threading of ideas, peoples, and places as one possible account of many histories that contextualize the evolution of a concept [43,44]. Following the genealogy, we present an interpretation of the key elements in Karen Barad's theory of entanglements that have resonated with our work and altered our research practices. We end by transposing the abstract concepts onto concrete matters of concern within visualization inquiry — data, visualization, and insight — as grounding examples of how feminist epistemology provides a novel framing to common concepts in visualization research.

4.1 Genealogy of Entanglement

Our genealogy of entanglement begins at the end of the 20th century in a period known as the *science wars*. This period was marked by the rise of postmodernist theories that challenge the scientific values of objectivity and impartiality. Postmodernists surfaced the myriad ways that past scientific endeavors, attentions, methods, and evidence were shaped by socio-cultural issues such as gender, race, and class. Many postmodern theories were grounded in *relativism*, a philosophical position that denies claims of objectivity and asserts that all knowledge is relative to a specific person and context. In response, scientists pushed back and denounced postmodernist theories as anti-intellectual and naive to the workings of the scientific process.

Feminist scholars, studying the history of science and its practices, engaged in the discourse of the science wars, challenging both the scientific and postmodern stances. A key contribution during this period was Donna Haraway's idea of the *god trick*. Developed through direct reference to data visualization, the god trick describes the illusion of objectivity and impartiality that is conveyed through the perspective of *"seeing everything from nowhere"* [49]. Haraway argued that this god's-eye-view gives the data being visualized — and by extension, science — a façade of neutrality, hiding its ties with militarism, capitalism, colonialism, and male supremacy. In addition, this god's-eye-view accords an aura of dominance and singularity to any claims that the visualization or scientific experiment might enable, invalidating additional or alternate claims that might be made since they must necessarily be derived from non-objective and therefore flawed perspectives.

As a corrective, Haraway put forward a feminist epistemology through a theory she called feminist objectivity, or more famously, *situated knowledges* [49]. This theory holds that it is possible to know true things about the world, but that individual knowledge is always partial rather than complete. The *situated* in the idea of situated knowledges describes the specific perspective of the knowledge producer

that determines what is possible for them to know (and show to others) and what is not. It is only by understanding the affordances and the limits of each person's partial perspective, and by bringing those perspectives together in a composite whole, that *"the possibility of sustained, rational, objective inquiry rests"* [49, p.548]. The situated knowledges theory has since prompted scholars from a wide range of disciplines — including visualization [27, 36, 40] — to consider what those situated or partial perspectives might be, how those perspectives impact the production of knowledge, and how multiple perspectives might be brought together to create a more complete picture of the phenomenon at hand [20, 33, 90, 94].

In the 2000s, a new strain of feminist epistemology emerged that supplemented the earlier work of Haraway and others, alternately described as *new materialism* or *feminist materialism*. These theories continued to probe the nature of knowledge production, but they expanded to include a consideration of the objects that we seek to know more about, as well as the relation between those objects of knowledge and those who study them [5, 6, 16, 25, 79]. One of the most influential new materialist scholars was and remains Karen Barad.

Trained as a theoretical physicist, Barad turned to feminist studies of science as a way to pursue the broader implications of the scenarios that they encountered in their scientific work. In their landmark book, *Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning* (2007), they take on the assumptions embedded in Newtonian physics — namely, that material objects in the world exist as discrete entities and act only when acted upon — to question other distinctions in the world. Drawing from Niels Bohr's deeply philosophical interpretations of quantum mechanics, Barad's theory of *entanglement* troubles ideas of the separability of observer and object, matter and meaning. Entanglement theory — what Barad calls agential realism — offers a framework for understanding how *"human and nonhuman, material and discursive, and natural and cultural factors"* are entangled with each other, in scientific practice as in the world [6, p.26]. We describe Barad's theory in Sect. 4.2 and interpret it for visualization in Sect. 4.3.

Humanities researchers, as well as researchers in science and technology studies (STS), have engaged extensively with Barad's theory of entanglement and the ideas of new materialism more broadly. The decade following the publication of Barad's key text saw thousands of applications and extensions of their work. Today, a new generation of feminist researchers are enriching the ideas associated with new materialism with key concepts and conversations from queer theory, animal studies, environmental humanities, Indigenous studies, Black feminism, and Black studies (e.g. [47, 69, 77, 87, 95, 97]). These extensions can be understood in terms of their emphasis on relationality as the primary site of knowledge-making, including: between subjects and objects of science; between humans and non-humans in the world; as well as, between systems of knowledge making. Crucially, the ability to account for multiple ways of producing knowledge and their relationships to each other allows for a consideration of structural forces of power — sexism, racism, colonialism, and more — to reemerge as the forces that determine these relationships.

4.2 Entanglement Theory

Barad's theory of entanglement is rooted in interpretations of a particular thought experiment developed by physicists to better understand counter-intuitive aspects of quantum mechanics. This particular thought experiment considers how to determine the position of an electron by taking a picture of it with a photon. It starts by imagining that a photon with a known trajectory is sent towards an electron; the photon scatters off the electron and hits a rigid photographic plate. The position of the electron is determined based on the photon's original trajectory and its final position on the plate.

However, the act of measuring the electron's position by bouncing a photon off of it inadvertently changes the electron's momentum due the law of conservation of momentum. The thought experiment thus continues: to account for the effects of the measurement (the photon) on the object of measurement (the electron) you just measure the change in the photon's momentum and ascribe that to the change in the electron's due to, again, the law of conservation of momentum. To measure the photon's momentum you instead allow it to scatter to a non-rigid plate on a spring and measure how much the photon displaces the plate. With this measurement you determine the photon's momentum after it has scattered off the electron. But here lies a paradox: by measuring the momentum of the photon via a plate on a spring you can no longer accurately know its position, a measurement that instead requires a *rigid* photographic plate. You cannot accurately determine both its position *and* momentum, and thus you cannot simultaneously know the position and momentum of the electron.

This paradox is the basis of Werner Heisenberg's well-known *uncertainty principle*. The uncertainty principle codifies the mechanics of the experiment as: the more certain we become about the electron's position, the more uncertain we become about its momentum. Barad summarizes Heisenberg's principle as one solely focused on what is knowable, and counters with another interpretation put forward at the same time by Niels Bohr that more deeply probes at the nature of matter itself. In Barad's telling, Bohr interpreted the paradox not as one of uncertainty, but of indeterminacy. Bohr questioned whether the properties of the electron exist *at all* before the moment of measurement. From this view, Bohr proposes that the position of the electron is determined through its interaction with the measuring device — consisting of both the photon *and* the experimental set-up with the rigid plate — leaving its momentum indeterminate. The position and momentum of the electron do not co-exist.

Barad extends Bohr's interpretation into a broader epistemological claim: that measuring attributes creates both the measurement *and* the attribute. Not only do interactions with measurement devices determine which properties matter, they more fundamentally *make* properties matter. Barad extends this view into a whole world in which object and observation, humans and non-humans, matter and meaning, are all mutually constituted. Just as quantum physics offered an alternative framework for understanding matter and measurement over Newtonian theories, we propose that Barad's theory of entanglement can offer an alternative to the positivist and representational epistemologies that are dominant in visualization [78].

The basic unit of Barad's entanglement theory posits that *phenomena* in the world — the things we want to understand, study, or come to know — do not exist as discrete things, but rather as dynamic entanglements of people, things, processes, conventions, history, and power. We gain knowledge about a phenomenon through the enactment of a measuring *apparatus* that determines what we come to know about the phenomenon. Like in the thought experiment where properties of an electron are determined by sensing objects as well as the decisions that define what measurements to make, apparatuses in scientific research more generally consist of not only measuring devices, data collection protocols, and study designs, but also the systems of power and privilege that determine what counts as meaningful to know about in the first place. Apparatuses are themselves dynamic, entangled phenomena with no intrinsic boundaries.

The point of interaction between an apparatus and a phenomenon, however, produces a static, momentary representation that is specific and determinant, and that can be known and studied. This momentary representation encapsulates all the components of the phenomenon that are accounted for by the apparatus, and excludes all those that are not. Thus, *"apparatuses are not mere observing instruments but boundary-drawing practices"* [6, p.140]; they are tools that delineate the borders of what knowledge is made available. In this paper we refer to this static, momentary, bounded representation as a *knowledge artifact* in order to signal that this representation consists not only of measurements, but also of objects, processes, or ideas that capture what we come to know about a phenomenon through its interactions with an apparatus.

It is worth noting that entanglement theory does not just concern epistemology; it also considers questions of how knowledge artifacts come to be (ontology) and our role in their production (ethics). We draw attention to this latter point because it centers ethics in the making of knowledge artifacts and illustrates how research is socially, historically, and spatially specific: when there is a decision to study a phenomenon

in one state, it is also a decision to not study it in another. Entangling knowledge and knowledge-making practices with larger systems of power and privilege is, at its core, a feminist practice of science. We briefly discuss the ethical implications of entanglement theory in Sect. 4.3.4.

4.3 Entanglement for Visualization

Here we argue that entanglement theory can help us productively reimagine the primary foci of visualization research: data, visualizations, and insight. These three concepts serve as the basis for how we describe how visualizations work in the world, as illustrated by the influential visualization reference model [21, p.17] [23]. But in standard accounts, we most often refer to these three concepts as separate, delineated, and stable.

An *entanglement theory for visualization* reinterprets these concepts as knowledge artifacts, produced through the interactions of phenomena and apparatuses, illustrated in Figure 1. Visualization research through an entanglement lens brings forward the ways that knowledge artifacts represent situated, momentary slivers of complex phenomena in the world, along with the ethics entangled in our research practices. In the following subsections, we propose an entanglement theory for visualization that reframes data, visualizations, and insight each as knowledge artifacts, and provide provocations that stem from each to illustrate the generative potential of thinking through visualization research with entanglement theory. We then briefly discuss the implications for ethics when conducting research with an entanglement perspective. We argue that with this reinterpretation comes new opportunities for research and design; we provide a case study in Sect. 5 to illustrate this point.

4.3.1 Data

From an entanglements perspective, we consider data as knowledge artifacts produced through the interaction of a data-generating apparatus and the phenomenon in the world the data are meant to represent. Data are static representations, shaped by the standards, conventions, and thinking at that moment. The phenomena they represent, however, are constantly in flux. For example, census data are intended to represent the phenomenon of a country's population, or who is living within a specific geo-spatial boundary. But people do not sit still: they move, they die, they give birth, and cross borders. The census, as a knowledge artifact, is but a momentary snap-shot of a country's population, removed from the dynamic ways people live.

Moreover, apparatuses for producing data include measuring devices as well as their limitations, whether the limit is of sampling a population or resolving a quantitative value. In considering census data, multiple factors are at play: decisions regarding who is counted as a resident or not, when and for how long the counting happens, and the various ways that the counting is done. Current visualization practices account for some of the ways that apparatuses shape data through metadata [19] or uncertainty metrics [84]. But these practices only account for what is known and considered about *how* data are collected.

Apparatuses for data collection are also entangled with sociotechnical systems, such as the motivations of people and institutions for undertaking the work. For example, census data includes many politically and culturally determined categories that define what characteristics of residents matter for a country's official demographics, some of which can even be weaponized for political gains [14]. Researchers who are responsible for data collection are situated in academic and institutional organizations often dominated by majoritized groups. Consequentially then, the data reflect those groups' interests and particular world views, reinforcing certain social boundaries over others [42]. In the well-worn example of a Word2Vec model trained on Google News, gender bias was encoded in word associations between gender and occupation, such as *woman is to nurse as man is to doctor* [13]. The gender bias reflects how the training data was shaped by the stereotypes and standards of society, language, and the news media of a particular time. In another example, Buolamwini & Gebru illustrate how marginalization is perpetuated in commercial facial recognition systems [17]. In their work, they highlight the scarcity of training sets that are representative of variations in skin-color and race. Notably, the commercial facial recognition systems, built on these datasets, perform the worst in identifying the intersectional group of Black women. Their results echo the words of Black feminists, like Lorde [74], the Combahee River Collective [24], Cooper [26] and Crenshaw [29, 30], who have repeatedly discussed the negative compounding effects of oppression that Black women face.

Considering data as a knowledge artifact, one that is produced by inclusions and exclusions that are in turn defined by dynamic, entangled apparatuses, surfaces a number of provocations for visualization researchers. What is our responsibility to understand, and even account for the boundaries drawn by a data-generating apparatus? How can visualizations do more to expose the entangled nature of data? What might it mean to design visualizations for entangled data — data that is produced by dynamic, unbounded apparatuses interacting with similarly expansive phenomena — rather than for data that is viewed as objective, singular, and complete?

4.3.2 Visualizations

An entanglements perspective also suggests a visualization or visualization system as a knowledge artifact that represents the designer's interpretation of a visual data analysis need in the world. The need could be a domain expert's goal of making sense of their particular data, or it could be a data worker's desire for tools for visualizing data of many forms. In all cases, this need is an entangled phenomenon, shifting and changing based on a whole host of factors, such as: the timeliness of scientific questions, availability of new funding, and advances in available technology, to name a few. The phenomenon is also entangled with how target users change. In a design study, for example, it is not unusual for the needs of domain experts to change as they learn through the design study process and through their use of prototypes [99]. Initial questions can become irrelevant, causing new visualization tools to be quickly out-dated once they are deployed [3]; it isn't that the visualization is unsuccessful, per se, but that the phenomenon under study is dynamic.

Furthermore, the apparatus involved with the production of the visualization tool is also a complex entanglement of the designer's interpretation of a need in the world [78]; the tools and materials they used [89]; the conventions that speak to what is good and bad visualization design [12]; the research ambitions of the visualization designer, as well as those of the target users [3]; and more. As other scholars have demonstrated, visualization design upholds certain principles, while discounting others [4, 53]. Klein argues that 19th century visualizations by Elizabeth Palmer Peabody are perceived as unorthodox and complicated today because they have been excluded from canonical visualization history [63]. The same can be said of W.E.B. Du Bois' data visualizations of Black American life [10] — his visualizations are more akin to modern art in comparison to the minimalist, statistical charts upheld by Tufte [96]. Despite the common assumption, and design intention, that visualizations are windows onto the data, critics point out visualizations are not neutral [27, 36, 38, 78], and are instead designed interfaces that determine the way data are used, providing *"a procedural setting that shapes the roles and ways of knowing available to users"* [75, p.128].

Viewing a visualization as entangled troubles many of our assumptions and beliefs about what it means for a visualization to be effective and good. What is the value of an out-dated visualization system if its existence shifted and changed the very needs it was designed to address? How do standards for evaluating visualizations reflect certain value-systems over others? How might we open ourselves to broader perspectives and values about the role of visualizations in society?

4.3.3 Insight

Insight — a concept at the heart of visualization [21] — is a notoriously difficult concept to isolate or define. In a literature review of insight characterization, Battle & Ottley note that while there are varying and different definitions of insight, *"insights, objectives, and tasks are intertwined"* [9]. An entanglements perspective of insight as a knowledge object representing a visualization user's knowledge about a phenomenon in the world broadens this view by drawing our attention

to *how* insights represent entangled phenomena *and* the apparatuses that produced them. An entangled perspective reminds us that insights do not emerge from the singular user alone, nor can they be separated from the inclusions/exclusions of the data or the affordances of a particular tool. Data and visualization, design and convention, actively participate in the process of insight emergence.

The concept of entangled insights also encompasses the wealth of knowledge and studies in the visualization community that indicate the myriad ways people are more than perceptual machines when interacting with a visualization. For example, studies show that personal beliefs shape how conclusions are drawn from charts [65, 101] and how trust is given (or not) to the data [61, 86, 102]. In addition to beliefs, domain knowledge plays an important role in data analysis. For example, insights are often not replicable by non-experts, even when given the same data view as experts [37]. As part of a dynamic, entangled apparatus, there are a seemingly endless list of personal factors that can impact how and when an insight occurs [73].

This entangled conceptualization of insight as knowledge artifact invites us to reimagine the roles of people, visualizations, data, processes, conventions, history, and power as part of the relationships and dynamics that contribute to it. Embracing the idea of entangled insights, however, upends some of the most basic assumptions of visualization research. How do we evaluate the efficacy of our tools if we cannot untangle and identify their effects on insight emergence? How do we probe into the nature of insight if we are entangled in its emergence? How do we ethically consider our role in the knowledge people acquire through the use of our tools? How might we consider the impact and success of our work that is inherently entangled with the work of others?

These latter two questions highlight the deeply connected topic of ethics with an entanglement perspective of visualization, which we briefly discuss next.

4.3.4 Ethics

Ethics is an urgent and persistent concern that has plagued technology studies for decades. Correll demonstrates the many ways in which visualization researchers can take personal responsibility for their work through collecting data empathically and challenging power structures [27]. While these are reasonable steps toward accountability for our actions as researchers, it leaves space for ethics to fall through the cracks of responsibility. Current ethical frames require that individuals are responsible for how data are created or how visualizations are maintained. But who is responsible when the work to understand the apparatuses that created a dataset are enough to fill a paper — see Lee's work on Zika virus data [66] as an example — or when maintenance of visualizations lies between a complex web of competing interests, agency, and access to resources [3]?

Entanglement theory provides a theoretical and epistemological framing that is an alternative to arguments of ethics as a set of considerations added *ad-hoc* or *post-hoc* onto research. Through entanglement theory, ethics becomes a fundamental part of visualization research, inseparable from questions about the nature of the knowledge, how that knowledge is formed, and who (or what) forms it. This arises from an understanding of entanglement as including all the influences that came before, and all the effects that come after. In other words, the past is entangled with the future.

Through an entanglements lens, ethics shifts from an individual responsibility, located within the confines of one research project, to a relationship between many actors that share a collective responsibility. It centers the role of visualization researchers and designers as supporting (or silencing) certain knowledge over others through the enactment of tools and research. This requires constant reflection and negotiation of practices and relationships. Also, entanglement theory necessitates discussions about ethics that encompass both future-looking impact and historical significance. Such a shift presents historical dimensionality to research beyond citing other researchers, and instead toward the material, labor, and societal aspects of data, visualization, and insight. Furthermore, the concept of ethics expands *beyond* the created technology or the specific actions taken to reduce harm; instead it asks of researchers to be careful, thoughtful, and curious throughout the research process. Conducting research with entanglements as an epistemological lens introduces and reinforces the impact of relationships into research practices.

5 Case Study: The Effects of Entangling Data

We turn to a case study to illustrate the productive nature of engaging with entanglement theory. The case study centers on two of our published research results, *implicit error* [76] and *data hunches* [71]. These ideas emerged from years of design study research and first-hand observations of how experts bring extensive domain knowledge into their analysis of inherently imperfect and incomplete data. The case study is a reflection on how two different epistemological lenses applied to the same phenomenon resulted in different research outcomes. The projects were conducted in collaboration with visualization researchers not involved with *this* paper and so we underline our names for ease of reading.

The case study spans seven years, and begins in 2016 when Meyer and McCurdy began a design study with public health experts who were working to stop the spread of the Zika virus in Latin America. This design study led to the conceptualization of expert knowledge about flaws in the data as *implicit error*, detailed in a paper presented at IEEE InfoVis 2018 [76]. After publishing this result, Meyer and her colleague Lex engaged in discussions around the prevalence of implicit errors in many of their design studies. With Lin and Akbaba, they brainstormed design opportunities for externalizing and visualizing implicit errors in visual analysis tools.

Concurrently, starting in 2020, Meyer and Akbaba began a collaboration with Klein to discuss feminist perspectives for visualization. Klein proposed Barad's writings on entanglement [6] as a potentially resonant theory for reconceptualizing visualization research and design goals. We held frequent meetings to discuss entanglement theory and experiment with mapping key ideas to visualization concepts, specifically to the concept of insight. Klein pointed Meyer and Akbaba to other texts on central and emerging feminist theories, and over time their understanding of feminist epistemology grew beyond the text, shifting their attention in research to new questions and opportunities.

One notable shift was in our attunement to the entanglements of data and more specifically, implicit error. Meyer and Akbaba became aware of the epistemic assumptions built into the concept of implicit error, and to the ways those assumptions created tensions with our experiences and observations of how experts work with data. In other words, entanglements expanded our understanding of the phenomenon for the better. Along with Lex and Lin, we proposed revisiting and redefining implicit error as *data hunches*, detailed in a paper presented at IEEE VIS 2022 [71]. Our shift in thinking was grounded in entangled perspectives of data, visualization, and insight.

We reflect on the epistemic tensions of implicit error, and our shift to data hunches in the case study detailed here. We retell the lines of research motivating both projects, with a focus on the tensions in the implicit error work that stemmed from its epistemology weighing certain aspects of the phenomenon over others. We call this an *epistemic wall*, or a boundary that limits how a phenomenon can be studied. We define epistemic walls as the boundaries of explainability that are possible with a given, single epistemology. Reaching these boundaries results in difficulty explaining phenomena either through insufficient methods or ill-fitting concepts. We discuss the epistemic wall we reached with the concept of implicit error, how entanglements reconfigured our view of data and valuing of expert knowledge, which then allowed us to scale the epistemic wall and arrive at the idea of data hunches.

5.1 Hitting an Epistemic Wall: Implicit Error

In this subsection we use the term 'we' to refer to Meyer and McCurdy, the visualization researchers involved with the implicit error research.

In 2016 we worked with public health experts who were actively trying to quell the spread of the Zika virus in Latin America and the Caribbean. The collaboration was structured as a traditional design study [92], and resulted in the development of a visual analysis tool to support global health experts analyze World Health Organization

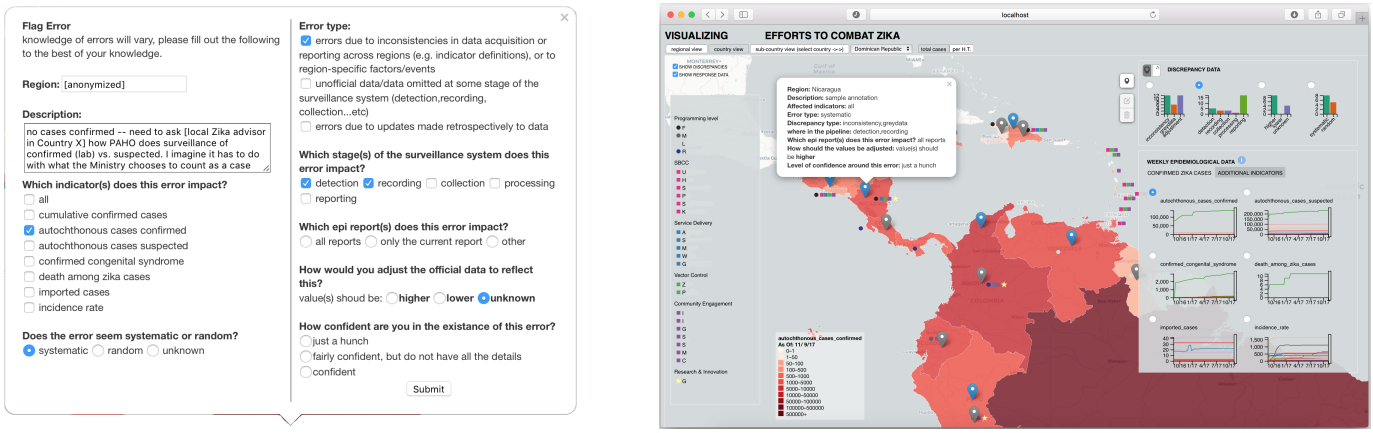

Fig. 2: Our conceptualization of implicit error led to the design of an annotation mechanism to allow experts to record what they knew about flaws in the data (left). We designed an optional layer in the visualization tool for showing recorded implicit errors: pins on the map show where an implicit error was placed, and on click the annotation left by an expert is shown (right).

(WHO) Zika data. The WHO released Zika data on a weekly basis by collating datasets produced by Ministries of Health in individual countries. With this data, the global health experts made decisions about risk and recommended appropriate responses.

Although our visual analysis tool received positive feedback by a range of stakeholders, we struggled to get our immediate collaborators to incorporate it in their daily workflows. In probing this reluctance, we came to understand that even though the tool was effective for visualizing the data, it also brought forward the ways that the data were deeply problematic. For example, when asked to test the tool one expert noted that in order to actually use it they had to *" 'suspend [their] disbelief' around the quality, consistency, and availability of the data"* [76]. In another example, an expert explained that although the visualization showed a higher spread of the disease in one country over the other, the reality was likely the reverse due to the differing standards by which the countries' Ministries of Health decided whether a particular person did indeed have Zika, or not. Put simply: although the visualization accurately represented the data, the data did not accurately represent what the experts knew to be true about the spread and detection of the disease.

Through discussions and workshops with the experts, we discovered that the data was littered with discrepancies. The reasons for the discrepancies were complex and multifaceted, and intricately tied to the collection and disease classification strategies from the places where they originated, as well as their political, cultural, and social contexts. All that complexity was being flattened thousands of kilometers away and presented as a uniform data source in the visualization tool. The scope of issues with the data quality were not anything that we could control or correct, and they troubled our beliefs about the authority of the official data. We became dejected and wondered what good we were doing building a visualization tool that did not accurately reflect reality.

We were, however, encouraged by the extensive and deep knowledge our collaborators had about the ways the data were flawed and why. We wondered: how might we capture this expert knowledge? How might we structure it so that we can use it in the tool? Could we use it to modify the data? To present different visualizations? To model systematic errors? And more importantly: should we?

Our collaborators discouraged our ideas of modifying the data or the visualizations based on their insights, insisting that the official data is the official source. This echoed our own unease with altering the values without clear authority and expertise to do so. Furthermore, the most revealing aspects of their insights were hopelessly unquantifiable. In the end, we designed an annotation mechanism for the experts to externalize what they knew about flaws in the data, shown in Fig. 2. The content of the annotation is hidden at first and marked with a pin, which upon click, reveals the annotation as a text layer on top of the visualization. We termed the discrepancies in the data *implicit errors*.

But we were left with an unresolved tension: the WHO data was official and authoritative but also deeply flawed, while the expert knowledge was partial and subjective but rich with nuance, context, and insight. McCurdy synthesized this persistent tension during the presentation of our work:

> *Supposing down the line we found that [we] could quantify aspects of implicit error, is this really even the answer? Is it valid to assume that expert knowledge is more accurate and trustworthy than the official data? And would we lose important aspects of implicit error through quantification?* [1, slide 20]

It turns out, we had hit an epistemic wall.

5.2 Scaling the Epistemic Wall: Data Hunches

In this subsection we use the term 'we' to refer to Akbaba, Meyer, Lex, and Lin, the visualization researchers involved with the data hunches research.

We noticed flaws in data everywhere: in a design study with surgeons who commented that data about the amount of reuse of patients' blood during surgeries was not always recorded accurately [72]; in another design study with meteorologists who learned to adjust for biases in large weather models to accurately make local weather predictions [88]; and in a project with families who were using air quality sensors in their homes to understand what activities led to poor indoor air quality, insights that were invisible without their intimate, contextual knowledge [80, 81]. Our observations matched the findings of others who had also been documenting the ways that experts bring extensive knowledge to their analysis to overcome the limits of their data [45, 82, 85]. Data as flawed and imperfect is the norm, not the exception.

This conclusion challenges scientific assumptions about data: that with enough sensor calibration, or collection specification, or samples, a dataset can accurately and precisely capture a phenomenon. This view stems from the positivist epistemology permeating science that assumes objects in the world are separate from each other, that properties of objects have inherent values, and that these values are consistent regardless of who or what measures them. A positivist view of data presumes that these values can be recorded through careful observations, resulting in objective measurements that are independent of their context.

Scholars in the field of critical data studies, however, argue that data are always entangled with their context. Bowker [15] and Gitelman [48] have memorably asserted that *"raw data is an oxymoron"*. In their critique of big data, boyd & Crawford describe how data analytics inherently strip data of their context in pursuit of an objective representation of the world, but that this move is an error: *"taken out of context, data lose meaning and value"* [31]. Loukissas makes the point, though, that entangled perspectives on data are at epistemological

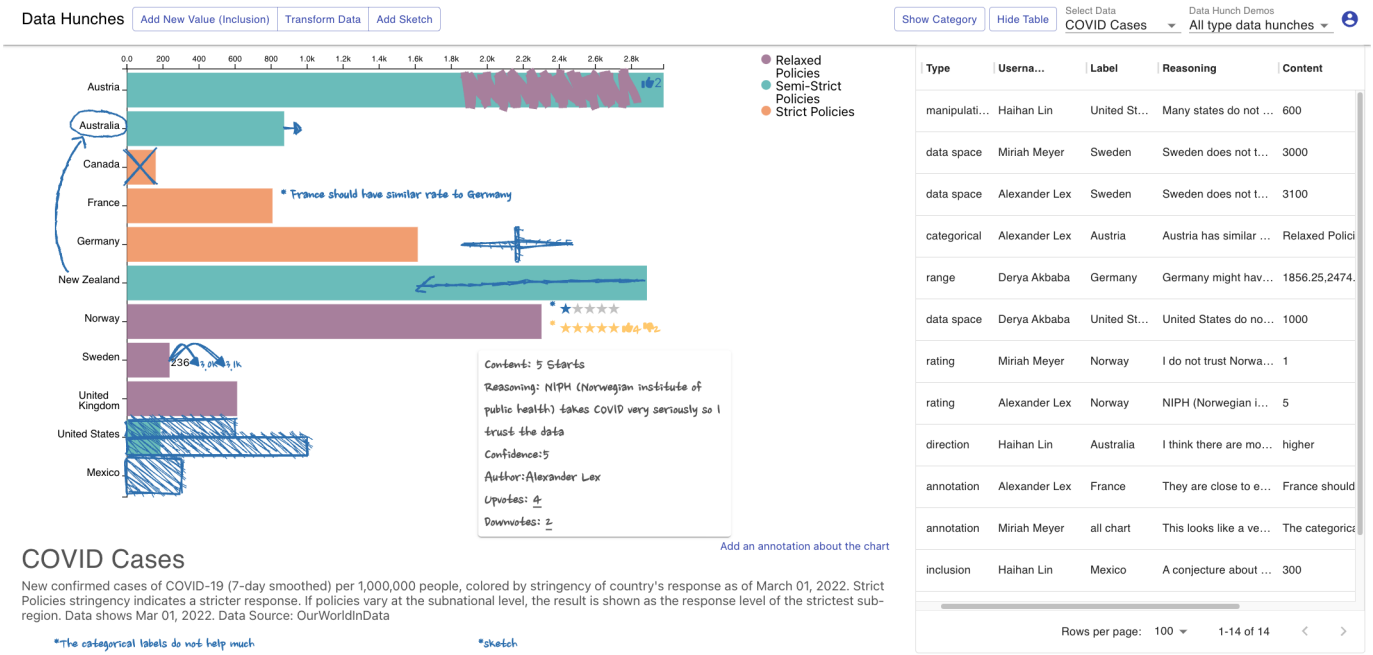

Fig. 3: Our conceptualization of data hunches led to the design of a multi-faceted externalization mechanism that allowed experts to visually record their knowledge about the data (left). We designed the interface to support visual manipulation of the base visualization, to support the affordance of directly manipulating the data. Sketchy rendering was used to visualize the data hunches in-close spatial proximity to the base visual but also to distinguish it. A table (right) recorded the type of hunch, the username of the externalizer, the label, the reasoning, and the particular adjustment made.

odds with how technology was invented, where the latter is embedded with an epistemology that governs *"the digital [as] independent of any substrate"* [75, p.53].

We found the debates in critical data studies compelling as they seemed to articulate the entanglements that we observed in our projects with domain experts. They contributed to our understanding of data as entangled and inseparable from their means of production. With these new concepts and epistemological framing of entanglement we began to view data as a knowledge artifact, bounded by a data generating apparatus that is entangled with a multitude of factors, some that are technical and others that are social, cultural, political, and historical. This perspective allowed us to understand the indispensable role of experts' knowledge about the entanglements of the data and their representational limitations. From a feminist theory perspective, the data combined with experts' knowledge – and here, we specifically mean the situated knowledges from multiple experts, externalized and available to all – *is* what allows for objective sensemaking from data. This perspective enabled us to confidently position expert knowledge as equally valuable and insightful as the data itself.

With this new framing we reconceptualized implicit error as *data hunches*, shifting the focus from imperfections in the data to contextualizing knowledge about why the data is what it is. We explored the design space of interactions for letting experts record their hunches, and we developed design guidelines for visualizing data and data hunches together as shown in Fig. 3. Sketchy rendering marked externalized hunches alongside, near, and sometimes even on top of the base visualization. These guidelines speak to the importance of expert knowledge for making sense of the data, providing more information about how the data are entangled with the apparatuses of their production. Our design experiments with a simple bar chart led to ideas of how to interpret data and hunches (or, entanglements) together.

The significance in the design and conceptualization of data hunches lies beyond subtle word-smithing and a simple bar-chart demo: our understanding of how expert knowledges and data work together was completely altered, as were our visualization design goals. Entanglement theory drew our attention to how our design choices reflected our implicit valuing of knowledge and data, subjectivity and objectivity. With implicit error, we visualized expert knowledge as a side-note marked by pins, intended to explain abnormalities in the data, but easy to ignore at an overview. This design choice supports the collection of implicit error as annotations, clearly maintaining the original visualization for the purpose of objectivity. In contrast, data hunch externalizations are difficult to ignore. The use of sketchy rendering is large and spatially placed next to the data item it is intended to modify. The design for data hunches places expert knowledge as visually salient and equally important as the initial dataset. As more and more expert knowledges are externalized that challenge the representativeness of the data, our design choices ultimately produce a cluttered visualization where it is difficult to read the base visualization, troubling the authority of the data.

This case study illustrates the change in epistemology between implicit error to data hunches, which we describe as hitting, then scaling, an epistemic wall. Addressing epistemic walls are particularly important for visualization research because visualizations instantiate and reinforce the epistemology of the researcher — they are literally visible within the visualizations [39, 53, 55, 63]. While designing for implicit error, the underlying positivist epistemology created a wall that limited the potential of incorporating expert knowledge in a visual system. The expert knowledge was seen as subjective and less important to the official data. This resulted in our feelings of a persistent tension between wanting to incorporate expert knowledge, but also not wanting to change the official data. Later, when we came to understand the phenomenon through the lens of entanglements, the tension dissolved. Entanglements, and feminist epistemology more broadly, enabled us to scale the prior epistemic wall, opening up new possibilities for visualization design and research. Knowledge and data, epistemologically, could be upheld together. Thus, instead of fretting over changing the data or visualizations, this gave space for us to experiment with how to treat expert knowledge as first-class objects in an analysis tool.

6 So, what's the point?

We motivated this paper with a call for engaging more deeply with feminist theory while also fully cognisant that it may not suit every researcher or their research. And so we turn to those currently questioning commonly-held assumptions in visualization — such as the use of the term *novice* [18], or trying new methods for their studies like diffractive reading of interview transcripts [3], or unpacking the role of identity in how people read political visualizations [56] — as our core audience.

The existing current of recent visualization research that challenges visualization norms suggests a generative potential for designing and studying visualizations with increased attention to power and privilege. With this paper we hope to deepen this line of work by providing an introduction to feminist epistemology that rethinks and reframes how knowledge artifacts come to be. More broadly, though, our case study is meant to persuade you that it is worth the time and effort to develop new epistemic perspectives.

We acknowledge that it took us several years of engagement with feminist theory to produce the kind of shift we describe in the case study here. A significant hurdle was in loosening our readings of feminist theory from a prescriptive, engineering lens that sought to crisply define and understand concepts, to a more interpretive one that invited re-imagining of ideas. Our ideas of entanglements for visualization in Sect. 4.3 are meant to be read in the looser, imaginative, feminist theory tradition.

In addition to our difficulties parsing feminist theory, we also struggled with its historical, social, and intellectual situatedness. Foundational theories and the subsequent interpretations which build on them change over time and in relevance, making it difficult to derive meaning using *only* the printed text. To shorten the interpretation gap for the visualization community we include a brief genealogy and condensed interpretation of entanglement theory in Sections 4.1 and 4.2 to bring together the seminal concepts from feminist theory that have, and that we speculate could, influence visualization research. In our own work we found that our theoretical engagements benefited greatly from collaborating with a humanities researcher who provided the historical and interpretive context vital for engaging with feminist theories. As the authors of this paper, we attest to the rich potential of collaborating across engineering and the humanities with the explicit goal of bringing new theories to visualization research.

As a step forward, we propose the idea that multiple epistemologies can provide an intellectual toolbox for visualization research: every epistemology comes equipped with a different set of tools and methods, drawing attention to some things and away from others. Engaging with new epistemological theories, then, not only becomes a pragmatic solution to epistemic walls in research, but also has the potential to inspire wholly new research directions. This view reflects the recent work of other visualization researchers who are also engaging with epistemologies beyond positivism. One such example is the ongoing line of research that advocates for Bayesian statistics, and Bayesian epistemology more broadly [59, 60, 62]. This work is motivated by the lack of visualization guidelines that acknowledge the importance of personal knowledge, experience, and bias in how visualizations are read, and brings in theories from psychology, cognitive science, and economics, for models and methods that can offer new explanations for visualization comprehension, thus challenging normative models of perception. In another line of research, Lee-Robins & Adar draw on epistemological theories from learning sciences to structure cognitive and affective learning objectives in visualizations [2, 67]. Their work draws on these theories to reframe the relationship between visualization designer and viewer as communicative and pedagogical. A final example is the work of Meyer & Dykes [78] that draws on interpretivist and design epistemologies to rework the notion of rigor for visualization design studies. We speculate that these lines of research and the examples we open with in the very first paragraph of this paper are interesting *because* they reveal walls at the boundaries of the visualization community's current and predominate positivist epistemology.

We acknowledge that it is beyond the scope of this paper to enumerate all possible epistemologies, and also likely beyond the scope of visualization researchers to become philosophers of science. Instead, we put forward a few ideas of what epistemological diversity within the visualization community could pragmatically look like. This may include collaborating with humanities researchers to learn about new theories. It may look like turning to other fields, like HCI and STS, for examples of different epistemologies in use. Perhaps though, most critical to our field, is a constant questioning of norms within our research practices. Instead of pushing for uniformity of methods, values, and ideas of what it means to do *good* visualization research, we instead offer this work as an example of the generative capacity of diversity over uniformity in visualization research practices and perspectives.

7 Conclusion

Feminist theory offers novel avenues to critique the non-neutrality of visualizations and understand their impact. Yet there is more work that feminist theory can do. Because feminist theory extends the critiques of feminism to epistemological claims on knowledge production and truth in the world, it can also guide research practices and theoretical groundings of our work. In this paper, we argue for the capaciousness of feminist theory in expanding the possibilities of visualization research. We present *entanglement theory*, contextualized within a genealogy of feminist theory; *entanglement theory for visualization*, a specific interpretation of abstract theory onto specific visualization matters of concern; and, a *case study*, to illustrate the impact of engaging with feminist epistemology in a visualization context. The case study doubly serves to demonstrate the pitfalls of a lack of awareness of epistemology — the potential to hit an epistemic wall without realizing it. Epistemic walls signal the opportunity to reframe research problems with different epistemological lenses.

Epistemology is part of the foundation for any research discipline. While visualization has predominantly been guided by positivism and similar epistemological theories, we demonstrate that there is room for more to co-exist and to strengthen the theoretical foundations of our field.

And, by the way, an embrace of plurality is intrinsically feminist.

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