This is an excerpt from Frank Elavsky's dissertation on *Tool-making as an Intervention on the Accessibility of Interactive Data Experiences*, which can be accessed in full at this archival link:

http://reports-archive.adm.cs.cmu.edu/anon/hcii/CMU-HCII-26-103.pdf

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- Chapter 7: *Cross-perception*: Rethinking Input Design Towards Blind Analytical Interaction
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Abstract

In this dissertation, we contribute practical advancements in tool-making as an intervention on the accessibility of interactive data experiences. The thesis of this dissertation is as follows: *This dissertation argues that the tools practitioners use to build interactive data experiences are themselves sites where accessibility barriers are produced, prevented, or alleviated for both end users and authors. This work contributes five tools—Chartability, Data Navigator, Softerware, Cross-perception, and Skeleton—that collectively center accessibility work on the empowerment of disabled and non-disabled practitioners across the full arc of evaluation, data navigation, analytical interaction, and personalization.*

Rather than framing accessibility research solely around ideal experiences for end users with disabilities, this thesis investigates why accessibility work is so difficult for the practitioners who build interactive data experiences and what tool-making can reveal about those difficulties. We organize this investigation around four domains where practitioners face the most persistent challenges: evaluation, navigation, interaction, and personalization. *Chartability*, a heuristic framework contributed first and maps the full landscape of accessibility barriers and identified these three latter domains (navigation, interaction, and personalization) as the areas where the most severe gaps remain. *Data Navigator* and *Skeleton* then investigate navigation, finding that practitioners struggle because navigation structure has no visible, manipulable representation in their workflows. *Cross-perception* engages interaction, demonstrating that blind data analysis has been constrained by existing tools and that a new interaction design framework can reshape what analytical work is possible. *Softerware* addresses personalization, revealing that access needs genuinely conflict across users and that meaningful personalization requires system-level infrastructure that does not yet exist in practitioner tooling ecosytems.

Combined, these contributions provide empirical insights and practical advancements in the state of the art for tooling that bridges gaps in current accessibility practices in visualization and data science. Our work ultimately enables people with and without disabilities to better evaluate barriers in, analyze with, design for, develop, and personalize interactive data experiences. We demonstrate that tool-making is a productive intervention that both engages accessibility barriers and elucidates why those gaps exist in practitioner work.

Part I

Introduction

Chapter 1
Introduction

This thesis is a body of research situated within the existing research area focused on making interactive data representations more accessible for people with disabilities. Much of the work in this existing area is situated within the context of making interactive data *visualizations* accessible, particularly (but not exclusively) for people who are blind. My work, contributed here in this thesis, is focused on using *tools* as a specific intervention and sub-area of study for making interactive data *representations* accessible for people with disabilities, broadly speaking. ("Representations" here is an intentionally broader term than "visualizations," which are exclusively visual representations of data.)

Before we begin, two things must be understood up front, or else the rest of this thesis could be interpreted with disruptive assumptions: we must interrogate the phrase "making visualizations accessible" and unpack why *tools* are a meaningful area of study.

1.1 Is "accessible visualization" really an oxymoron?

The first assumption that must be disrupted is perhaps the motivating cornerstone of this research, which is that the phrase "making visualizations accessible," while a noble goal, is not the semantically correct phrasing nor precisely what describes my work. This can be misleading. I do use the phrase "accessible visualization" but will admit that this seems to confuse certain people with very particular opinions about things. We will clear this up.

Villains of our field's past have written incendiary and ableist perspectives on why "no forms of data visualization, not just dashboards jam-packed with graphics, can be made fully accessible to someone who is blind," and that "[a blind man] will never be able to analyze data as I do visually, because many aspects of vision cannot be duplicated by his other senses" [24]. However, this position misunderstands what the goal of accessibility is, and arguably even what the goal of visualization itself is.

Making visualizations accessible *isn't* about the visualization, it's about making the outcomes of the visualization accessible.

Visualizations are ubiquitous and paramount for decision-making. However, the *artifact* that is a visualization is not even the goal of the act of visualizing: developing understanding, insight, confidence, and communication among and between human beings are the goals of visualization. Visualization is about making data easier to use for all kinds of things. Yes, our visual system enables us more than any other form of sensory cognition that we have [10, 29, 103]. But we aren't trying to make sight itself accessible. We are trying to make it possible for people to make meaningful decisions, gain valuable information, build conjectures, and effectively communicate with others.

Many, many people who I've spoken to over the course of my career, even before embarking on this thesis journey, misunderstand this simple fact: making a "visualization" accessible *isn't* about the visualization itself but rather making what the visualization is meant to *accomplish*

accessible. It's about equal outcomes, not equal interactions with an artifact.

People with disabilities are no small portion of the world's population. In the United States, 27% of people self-report living with at least one disability that affects their daily lives [79] and all of us will eventually age into disability (if we are lucky to live a long life).

People with disabilities (again, that will be all of us *eventually*) deserve to participate fully in life. They deserve financial independence. They also deserve loving care and interdependence. People with disabilities have a right to make informed decisions, to know about the status of a global pandemic, and to have an understanding of local and national politics [23]. While we use visualizations to navigate all of these domains, the goal is not to make the charts and graphs themselves somehow equally useful to all people. That would be a false measurement of success.

Our goal then, is measured by the success of lives led by people with disabilities [108]. Many other measurements are just metrics along the journey towards that goal. We then ask: Can people with disabilities also use data to live full lives? Can they make *fast* decisions based on data? Meaningful, careful, *slow* decisions? Communicate complex ideas? Crunch and clean data, develop models, find errors, and build hypotheses? Can they have memorable, immersive, beautiful, aesthetic experiences with data too [48]? Making "visualizations" accessible really is a misnomer. We are ultimately trying to make everything about what interactive data experiences *accomplish* for people equitable and accessible.

Again, if the goal of accessible visualization were about visualizations themselves, then the correct course of action would be one framed by the medical model [71]: that there is a normative state of behavior and capability (in this case, it would be "normal" to be able to read a visualization and make a decision) and any deviation from that norm must be corrected. This framing first assumes that the visualization should not be altered or improved. And then this framing puts the burden on the bodies of people with disabilities: that they must be "fixed" and given sight or brought to some equivalent state as someone who is "healthy," normal, and sighted. Plenty of scholars have already discussed why this framing is a problem, not only because it places undue burden on people with disabilities, produces pathologies and hierarchies of disability, but also because it is fundamentally not economically or ethically feasible.

So we then turn to other models of disability, such as the social model. The social model is heavily discussed by disability scholars and is not the end-game or last and total way of thinking about disability [71, 83, 84, 101, 126]. But the core motivation is that society, not medicine, is also a path towards solving problems that people with disabilities face. A few important concepts and concretely actionable things come from the social model that can help motivate the work of this thesis.

First, we look to the historical birth of the social model of disability: in the 504 sit-ins that took place in the United States in 1977. Cities had curbs and curbs are a barrier for people who use wheelchairs. So protests happened because decisions were being made without people with disabilities at the table. In this instance, people acknowledged that political power was an exclusive club and fought to ensure their cry "nothing about us, without us!" materialized.

And this leads us to the first and most-foundational philosophical framing for this thesis: that our *artifacts*, these things we've created from curbs to data visualizations, can become *barriers* for people with disabilities. And it is then the artifact, not the body of the person with a disability, where disability is produced in this model. Rather than a comparison to a normative state as a way to frame disability (the medical model), we instead must observe and evaluate material

outcomes based on human-made problems.

So, the social model is framed around society "solving" inequities: we get involved and make political and legal change tangible. But a second model also emerges from within the social model: one where we can now frame *who is first responsible* for repair: the curb designers and implementers.

And knowing who is first responsible for access leads us into the moral and ethical imperative that motivates this thesis: the builders and makers of visualizations are ultimately the ones who provide exclusive value for only a subset of people: those *without* disabilities. **We must first change how builders and makers do their work.**

So the phrase "accessible visualization" is really about recognizing that visualizations produce barriers for people. That means that it is our ethical imperative, as builders and makers, to fix them. And that act of fixing barriers leads us away from mere visual representations of data into a wide variety of other senses and interaction modalities. There are many paths forward towards fuller and more-equitable lives led by people with disabilities.

1.2 On *tools*, *tool-making*, and *human-tool* interaction

Then the act of making becomes immensely important: we, the builders and makers of our world, need to get things right; there is a risk involved when making things that we will exclude people with disabilities. We need to make sure that we build a better world than the one we have now. We must care for new things we create and tend to the repair and maintenance of what we've already made. And this ethical imperative leads us to the topic of *tools* and *tool-making*.

So the second thing that must be understood before we embark on this thesis is that *tools* are not the same as *solutions* or *applications*. Sometimes tools can be used to *solve* things and are certainly, in ideal circumstances, *applied* in various contexts. But understanding the role of the "tool" in human-tool interaction is paramount for engaging in the work of making anything accessible for people with disabilities.

We use tools to shape our world, break old things, and make new things. But a tool, like the hammer (as an example), does not inherently *solve* something like homelessness. But a hammer can be used to build homes if there are social policies in place and proper resources allocated. This means that for the success of tooling, there is often a larger material, social, legal, and policy reality that supports and necessitates those tools. This thesis will not be focusing on changing the upstream dependencies, but optimistically operating as if they were true (or will be true in time).

However, in some cases, tools can *destroy*. The hammer has a claw and can easily pry apart boards and tear down homes. So tools carry potential to do all kinds of things, both good and bad, and how a tool is used is often open-ended, variable, and heavily dependent on socio-technical realities. Tools participate in personal and political agendas [120] and are sometimes, for this reason, regulated or made proprietary and controlled by powerful entities [32, 115].

So tools are not without any sort of ethics. We cannot just blame tool-users for outcomes when much of a tool depends on these larger systems and structures. Technologies (tools included) encode the assumptions and biases of their *creators* as much as, if not more than, their users. Tools that build things for others to use can be loaded with assumptions about what peo-

ple are *able* to do [121] and also rules and guardrails about what anyone downstream from that tool's design *should* do [32, 114]. These assumptions, biases, and rules *limit*, *enforce*, *magnify*, *exclude*, and *enable* what a tool-user is capable of.

Tools for visualizing data are a perfect case study in this problem: virtually every major data visualization library, application, or software ever made was made entirely with the assumption that data should be transformed into visual representations. This is a reasonable assumption, since virtually all of the tool-makers are sighted and visualization is incredibly helpful to our cognition of and communication with data [26].

So data visualization, as a field, has focused its tool-making efforts on reducing the difficulty involved in visualizing data. Some visualization tools are concise [89], others are lower level but much more expressive [8]. Tool-making in visualization has focused on making it easier to scaffold a wide variety of interactions both with the visualizations as well as with their underlying data models [41].

However, as time has moved on, people began to speak out about color-vision deficiency in data visualization. Some people, primarily those with X/Y chromosomes (largely men) who are of European ancestry, have a deficiency in their ability to perceive certain colors. Then a plethora of research arose that began to look into the barriers that folks who are colorblind face in data visualization. As a result, our practices and tools improved. We began to educate practitioners, develop new color palettes, researched new methods for testing our designs, and built new systems for handling automatic color encoding. Our tools evolved.

But now data visualizations have arguably become ubiquitous in daily life. By comparison, we have far more tools now for making visualizations quickly and easily than we do for representing data in non-visual ways. We also have far more research, relatively speaking, into how sighted end users interact with visualizations.

So this thesis engages gaps that arise in this space: Practitioners face immense challenges when crafting accessible data experiences. We first need to educate practitioners on what accessibility barriers actually are in interactive visualizations. Then, we must help them engage the hardest barriers in this work and create building blocks that help them to construct navigable data experiences, build design frameworks that can inform entirely new kinds of data interaction, and develop software systems for end-user personalization and agency. Our research seeks to advance the state of the art in tools that assist in accessible data interaction while also using tool-making as an intervention that helps us to better understand and characterize *why* and *how* data practitioners face barriers themselves in this work.

Chapter 2
Background & Related Work

2.1 Practitioners and Tools

2.1.1 Understanding Builders, Makers, Designers, and Developers

Research investigating the practices and experiences of individuals who create with computers employs a range of high-level methods. Ethnographic studies, case studies, and design ethnographies are common approaches, allowing researchers to immerse themselves in communities such as the DIY/maker and assistive technology spaces [47, 50]. These methods capture the nuanced challenges practitioners face when engaging in new and unfamiliar work, including the transition from traditional to digital fabrication, coding, and tool creation [49]. By observing and interviewing practitioners in naturalistic settings, researchers uncover the social, cultural, and technical factors that shape how makers adapt and evolve their work practices.

Participatory design and co-creation are also central to this field [102]. These approaches encourage collaboration between researchers and practitioners or end-users, enabling a deeper understanding of the cognitive and creative processes behind design and development [36]. Such collaborative sessions reveal how designers shift their thinking when encountering novel challenges, embracing iterative processes that blend experimentation with reflection. Similarly, developers often modify their applications, tools, and even programming languages through feedback loops and community-driven innovation, highlighting a dynamic interplay between individual creativity and collective knowledge.

Additionally, design-based and case-study research methods explore how new practices can augment the existing work of practitioners [14, 53]. This involves not merely filling gaps or solving isolated problems but reimagining the possibilities for creative and technical expression. Researchers in this space envision systems that support continuous learning, adaptation, and innovation [34]. The focus is on enabling practitioners to extend their capabilities—providing scaffolds for experimentation, fostering environments where unconventional approaches are encouraged, and integrating new technologies in ways that amplify creativity and intelligence rather than simply addressing deficits [57, 109, 121].

Overall, the research methods used in this area are multidisciplinary, combining qualitative insights with iterative design practices to offer a holistic picture of the challenges and opportunities of builders, makers, designers, developers.

2.1.2 Approaches to Tool-making in Human-Computer Interaction

In human-computer interaction, tool-making research spans both the creation of entirely new capabilities and the enhancement of existing systems. One prominent approach involves piggybacking on current systems—leveraging their established functionalities to introduce improvements that streamline workflow or unlock new interactions [33]. This method often focuses on integrating with widely used platforms to amplify their usability, enabling users to perform

tasks in more intuitive or efficient ways. By building on existing infrastructures, researchers can demonstrate how small, targeted modifications have the potential to transform user experiences.

Another significant approach centers on the notion of appropriation [17, 18, 87, 107]. Here, research examines how users adapt tools for uses beyond their original intent. Studies in this vein explore the creative processes behind such re-purposing, uncovering the latent functionalities and opportunities that emerge when practitioners modify systems to suit their unique needs. This perspective often leads to the development of modular, extensible tools that encourage experimentation and user customization, fostering a more personalized interaction with technology. In some cases, theory has been developed from the study of emergent and generative tool-use [2, 5], broadly informing future tooling projects as well as general theories of creative human interaction with technology.

Beyond these, tool-making in HCI also includes the development of systems designed to empower users by providing entirely new capabilities, sometimes explicitly named "toolkits" and other times generally just referred to for their ability to enable novel interaction and outcomes [61, 81, 88, 97, 97]. These projects may range from novel software environments that facilitate rapid prototyping and live programming to innovative hardware devices that bridge the gap between digital and physical interactions [43, 45, 81]. The emphasis is not solely on problem-solving but on enabling creative exploration, new possibilties, and even hacking the potential of technologies towards new ends [44]. Such projects often present their contributions through demonstrative prototypes and case studies that reveal potential applications, even if they are accompanied by minimal formal evaluations [21].

This body of work reflects a balance between novelty and practicality. While some projects aim to introduce groundbreaking new ways to interact with data and systems, others refine existing practices to improve efficiency and accessibility. Together, these approaches underscore a commitment to enhancing human capabilities, allowing users to not only solve problems more effectively but also to unlock new avenues for creativity and innovation.

2.2 Data, Accessibility, and Data *and* Accessibility

2.2.1 Advancements in Interactive Data Visualization and Data Science

Recent years have witnessed significant advancements in interactive data science and visualization, driven by innovations that enhance both the performance and usability of data tools. Cross-filtering, as a subtype of cross-linked interaction, has emerged as a powerful technique, enabling users to interact with multiple data dimensions simultaneously [3, 40, 63, 112]. By linking various filters, analysts can quickly build hypotheses and isolate patterns, trends, and anomalies in complex datasets, leading to more informed decision-making. Stress has been placed in recent years on developing fast systems that are optimized showing more and more data at once while reducing latency in user interaction as much as possible [41, 63, 123].

Automated data processing and cleaning have revolutionized workflows by reducing the time spent on manual data wrangling [22]. Sophisticated algorithms now automatically detect inconsistencies, fill missing values, and transform raw data into usable formats. These improvements enable researchers and practitioners to focus more on analysis rather than preparation.

Faster tooling has further accelerated data exploration. Enhanced computational frameworks and optimized libraries allow for real-time data manipulation, making interactive visualization more responsive [41]. Coupled with easier-to-use grammars and scripting languages, these tools lower the barrier to entry, empowering users with limited visualization, geometry, trigonometry, data, and graphics coding experience to generate complex, interactive, visual representations of data [89]. New visualization types and techniques—ranging from dynamic dashboards, faceting, to immersive 3D visualizations—offer novel ways to explore and interpret data [123].

Despite significant breakthroughs, current advancements have largely neglected the needs of people with disabilities. Innovations in data science and visualization have focused on sighted user populations, prioritizing visual clarity and interaction speed using direct pointer techniques (such as with touch or a mouse) [72]. This focus often overlooks accessibility requirements for individuals who are blind, have low vision, experience cognitive or vestibular challenges, or possess motor disabilities that limit traditional pointer use [119].

2.2.2 Accessibility and Assistive Technology in Research versus Practice

2.2.2.1 Research: Focus on Blindness and Computer Output

Research and standards are both somewhat limited by a strong bias towards visual disabilities. In *Chartability*, 36 of the 50 criteria related to accessible visualization considerations involve visual disabilities [20, 23]. Marriott et al. also found that visual disability considerations are the primary focus of data visualization literature [72], leaving the barriers that many other demographics face unstudied. Accessibility research broadly has traditionally concentrated on the experiences of individuals who are blind, investigating how they perceive and interpret computational output [66]. Studies in this area explore alternative modalities for conveying data, such as auditory representations (through synthesized speech), tactile interfaces, and sonification techniques. Researchers focus on identifying effective methods for transforming visual data into formats that blind users can easily comprehend. This body of work not only examines the perceptual challenges but also delves into cognitive processing differences, aiming to optimize the accessibility of complex information and interactive systems for users with visual impairments.

While research has made strides in converting visual outputs into auditory or tactile forms for blind users, interactive input methods remain underdeveloped. Most efforts have concentrated on optimizing screen reader navigation and information retrieval, leaving text entry and command execution cumbersome. Screen readers, as they currently exist, offer limited support for efficient input, making it challenging for users to perform complex interactions. Although tactile interfaces hold promise for providing more intuitive input methods, they are still in the experimental stage and have not been fully integrated into mainstream accessible computing solutions, perpetuating a critical gap in effective user interaction.

2.2.2.2 Practice: Focus on Standards and Specialization

In contrast, practical accessibility efforts are often centered on the implementation and adherence to established standards and guidelines, such as WCAG [110]. There has been a growing interest in developing guidelines for practitioners [19, 20] and even applying guidelines as a method of

validation alongside human studies evaluations and co-design [23, 64, 65, 128]. Existing accessibility standards bodies like the Web Content Accessibility Guidelines do stress the importance of accurate, functional semantics in order for screen reader users to know how to interact with elements [111]. For interactive visualizations this means that button-like or link-like behavior should expressly be made using elements that are semantically buttons and links.

Accessibility professionals, who typically possess specialized expertise, act as intermediaries between the design and development of digital products and the strict requirements of accessibility standards. Their role involves translating abstract guidelines into concrete design solutions, ensuring that websites, applications, and services meet regulatory benchmarks. By focusing on a standards-based approach, practitioners help organizations navigate the complexities of legal and technical requirements, thus ensuring that accessible design principles are integrated into mainstream technology development. This dual focus on rigorous standards and specialized expertise ensures that accessibility is both technically sound and legally compliant across diverse digital environments.

However, accessibility standards are inherently reactive, often lagging behind rapid technological advancements by five, ten, or even twenty years (or more). This delay occurs because developing, vetting, and formalizing standards requires consensus among diverse stakeholders and extensive testing to ensure compatibility and compliance. In contrast, cutting-edge interfaces and computational capabilities evolve swiftly, driven by dynamic market forces and user innovations. Consequently, accessibility guidelines tend to reflect outdated technologies, creating a persistent gap between modern interactive systems and current best practices in accessibility.

2.2.3 Data and Accessibility

In parallel to Mack et al.'s "What do we mean by Accessibility Research?" [66] nearly all topics of study at the intersection of accessibility and data are focused on visualization and vision-related disabilities [119]. Largely, access issues other than vision that affect data visualization (such as cognitive/neurological, vestibular, and motor concerns) are almost entirely unserved in this research space. Kim et al. found that 56 papers have been published between 1999 and 2020 that focus on vision-related accessibility (not including color vision deficiency), with only 3 being published at a visualization venue (and only recently since 2018) [60]. Marriott et al. found that there is no research at all that engages motor accessibility [72]. We have found 2 papers that engage cognitive/neurological disability in visualization and 1 student poster from IEEE Vis, which are all recent (specifically intellectual developmental disabilities [125] and seizure risk [99, 100]). We found no papers that engage vestibular accessibility, such as motion and animation-related accessibility. We also found that there is no research specific to low vision disabilities (not blindness or color vision deficiency) unless conflated with screen reader usage in data visualization. Blind and low vision people are often researched together, but in practice may use different assistive technologies (such as magnifiers and contrast enhancers) and have different interaction practices (such as a combination of sight, magnification, and screen reader use) [106].

Since the 1990s, the most prominent and active accessibility topic in data has been color vision deficiency in data visualization [12, 62, 73, 78, 80]. Research projects that explore tactile sensory substitutions to charts have been a topic in computational sciences dating back to the

1983 [92], with tactile sensory substitutions being used for maps and charts as far back as the 1830s [35]. Sonification used both in comparison to and alongside visualization and tactile methods for accessibility dates as far back as 1985 [9, 15, 25, 70, 74, 127]. Some more recent work has explored robust screen reader data interaction techniques [30, 98], screen reader user experiences with digital, 2-D spatial representations, including data visualizations [90, 95], dug deeper into the semantic layers of effective chart descriptions [64], and investigated how to better understand the role of sensory substitution [13]. Jung et al. offer guidance that expands beyond commonly cited literature that chart descriptions are preferably between 2 and 8 sentences long, written in plain language, and with consideration for the order of information and navigation [56].

A wide array of emerging research projects investigate screen reader users needs, barriers, and preferences, and offer guidelines, models, and considerations for creating accessible data visualizations [13, 23, 64, 95]. Jung et al. offer guidance to consider the order of information in textual descriptions and during navigation [56]. Kim et al. collected screen reader users' questions when interacting with data visualizations, which could open the door for more natural language data interaction [59].

Data visualization accessibility has come far in recent years. But little work has been done to explore what disability scholars call "access friction" - a tension that arises when access must be negotiated [37, 48]. This friction is often a result of static barriers in shared spaces: one artifact or approach designed to include some people may end up excluding others.

Yet despite these resources, making data visualizations more accessible remains a difficult task for practitioners [55, 96]. Some accessibility guidelines even conflict, for example on the topic of patterns and textures used in charts. One side stresses that patterns are harmful to cognitive and visual accessibility [91] while another stresses that redundant encoding strategies are necessary [20].

These difficulties point to a deeper problem: the tools practitioners use to build data experiences were not designed with accessibility in mind, and the resulting gaps are not evenly distributed. Even in an ideal state where guidelines agree, the hardest remaining challenges cluster in three domains: navigation, interaction, and personalization. In these, practitioners lack the structural, technical, and infrastructural means to reason about accessible design and act on those considerations.

Chapter 3
Overview of Contributions

In this dissertation, we contribute practical advancements in tool-making as an intervention on the accessibility of interactive data experiences. The thesis of this dissertation is as follows: *This dissertation argues that the tools practitioners use to build interactive data experiences are themselves sites where accessibility barriers are produced, prevented, or alleviated for both end users and authors. This work contributes five tools—Chartability, Data Navigator, Softerware, Cross-perception, and Skeleton—that collectively center accessibility work on the empowerment of disabled and non-disabled practitioners across the full arc of evaluation, data navigation, analytical interaction, and personalization.*

Rather than framing accessibility research solely around ideal experiences for end users with disabilities, this thesis investigates why accessibility work is so difficult for the practitioners who build interactive data experiences and what tool-making can reveal about those difficulties. We organize this investigation around four domains where practitioners face the most persistent challenges: evaluation, navigation, interaction, and personalization. *Chartability*, a heuristic framework contributed first and maps the full landscape of accessibility barriers and identified these three latter domains (navigation, interaction, and personalization) as the areas where the most severe gaps remain. *Data Navigator* and *Skeleton* then investigate navigation, finding that practitioners struggle because navigation structure has no visible, manipulable representation in their workflows. *Cross-perception* engages interaction, demonstrating that blind data analysis has been constrained by existing tools and that a new interaction design framework can reshape what analytical work is possible. *Softerware* addresses personalization, revealing that access needs genuinely conflict across users and that meaningful personalization requires system-level infrastructure that does not yet exist in practitioner tooling ecosytems.

We engage each domain below with the questions: "Why does this work matter?", "Why is it hard?", and "What has tool-making within this domain showed us?"

The 4 domains of work that I engage in this thesis start first with **evaluation**. In work contexts where someone is designing and developing interactive data experiences, the practitioner must have the knowledge, tools, and resources available to systematically identify how their interfaces produce barriers for people with disabilities. A significant portion of professional accessibility work (arguably most, if not all) is founded on auditing and evaluating barriers to access. This work is pre-dominantly done through a standards-based approach [110], although in more robust evaluation work, people with disabilities are actively involved in the process [82].

Evaluation is difficult work because much of it is contextually defined by the author themselves, and most tasks at this intersection require careful, non-automated processes and methods [16, 82]. To make matters more difficult, no comprehensive guidelines, tests, and tools exist in any singular location. Practitioners often must gather these resources themselves, which tend to be situated towards accessibility in general or are high-level and provide minimal usefulness in practice. Additionally, practitioners themselves often have little knowledge about the veracity or quality of any given bit of information they gather [55, 96], and often do the work themselves to synthesize this disparate space of information into a usable format they can apply to their own

evaluation work.

To engage this, our first main chapter focuses on *Chartability*, a heuristic framework that enables designers, developers, and auditors to systematically evaluate data visualizations and interfaces for a wide range of accessibility barriers, considering people with visual, motor, vestibular, neurological, and cognitive disabilities. In this project, we did the hard work for other practitioners and contributed our collection of synthesized accessibility resources in a single workbook. We had practitioners try out our resource in real environments, in-situ, in order to learn more about the challenges and barriers they themselves faced in evaluation work. With *Chartability*, practitioners, especially those with limited accessibility expertise, gained more confidence and clarity in assessing and improving their work. Additionally, *Chartability* has since become widely applied as a framework that isn't just used for evaluation but also as design guidance in many contexts, internationally, including policy organizations, governmental groups, and more than 100 companies and businesses.

Chartability then opened up a significant landscape of new projects and research directions. From a combination of my existing expertise as a visualization designer and engineer, in addition to continued application of *Chartability* in the wild, we began to identify the trickiest and most-difficult domains of work for practitioners. Chartability has 50 total heuristics, or tests, each organized under one of 7 principles. But 3 larger domains began to emerge as the areas where the most severe and dramatic accessibility barriers remained unaddressed: on data *navigation*, analytical *interaction*, and interface *personalization*.

So the next section of this thesis engages the first of these three: **navigation**. Navigation is a fundamental type of interaction that is leveraged by modern software-based assistive technologies. Screen readers, the primary tool used by people who are blind to interact with computers, navigate content. Additionally, many other assistive technologies, such as a sip and puff device (like the "POSSUM" from as far back as '63 [68]) also navigate. Navigational technologies are leveraged by people with a significant array of disabilities, yet tend to be entirely ignored by existing data visualization tools, which are pre-dominantly built to support direct input (using a computer mouse).

Empirical work has already demonstrated that structural navigation is actually good [128], even when regular alternative text (image descriptions) exist. This is both because people who are blind can gain both a high level understanding (from the description) as well as lower-level sense of the data's structure and arrangement, in addition to the fact that discrete, structural navigation exposes interactivity that may exist on any visualization elements (such as they can be hovered or clicked with a mouse in order to perform some action). So, if good empirical work exists: *why haven't practitioners put this research into action? What makes this work hard to do?*

We first built *Data Navigator* to provide the building blocks we needed in order to address the technical and conceptual gaps that were required to make any visualization or visualization tool provide a navigable, interactive structure. *Data Navigator* is a low-level toolkit which can be used to construct accessible navigation structures such as lists, trees, and diagrams from an underlying graph structure. We leveraged graph theory for an applied HCI problem: nodes and edges represent any relationships within the data as a structure, which then supports rich expressiveness of data navigation experiences. Users can navigate discrete marks in a visualization, clusters, groupings, and more. In addition to its structural scaffolding, *Data Navigator* also supports a wide array of input modalities leveraged by people with disabilities (screen readers,

keyboards, speech, and gestures).

Data Navigator provided a substrate, but this contribution alone wasn't enough to engage the question *why is navigation so hard, in practice?*. So the chapter following *Data Navigator* introduces *Skeleton*, a data navigation authoring tool built on top of *Data Navigator*. Our novel approach in *Skeleton* involves visualizing and making manipulable the nodes, edges, and textual data that comprise non-visual end user experiences. *Skeleton* visualizes the building blocks that comprise *Data Navigator*. Additionally, *Skeleton* provides expressive, rapid scaffolding capabilities that leverage data visualization rendering engines. This scaffolding engine helps practitioners quickly create common configurations for non-visual data navigation structures that retain visual congruence to the underlying structure.

But most importantly, *Skeleton* serves as a framework that shapes designerly consideration. Our conjecture was that because sighted practitioners cannot *see* navigation building blocks, they will not treat those elements as iterable design materials. We conjectured: Navigation is hard in practice because sighted designers face barriers to iteration and understanding. We conducted an empirical study with sighted practitioners and found that making non-visual elements visual helped practitioners shift from treating accessibility as a compliance task to treating it as a design problem, re-iterating on the visual aspects of their design, and engaging in the complex and nuanced components that comprise data navigation experiences.

Now, **interaction** becomes the next area we wanted to engage. Existing accessible data interaction for people who are blind, including our previous work on navigation (which is a form of interaction), predominantly seeks to expose information. This is what we call *access-oriented interaction*. In terms of low-level analytical tasks, most are then made feasible through navigation, sonification, or summarization-based and question-answering approaches: retrieving values, filtering, computing derived values, sorting, determining ranges, clustering, and finding outliers. What remains are analytical tasks that, despite being "low level" (understood as *unable to be reduced into more fundamental tasks*), are cognitively highly complex: finding correlations and characterizing distributions [1]. These tasks require complex hypothesization and exploration, rather than a system that simply encourages surfacing what is known or what is already present in the data: it requires combining, remixing, restructuring, and dividing data.

But blind *analytical interaction* isn't just important to engage because it is understudied, it is important to engage because many of interactive information visualization's most impactful tools for data science enable it [25, 41, 77, 112]. In visualization, *cross-filtering* is one example of an interaction that enables a user to filter one visual space while seeing a coordinated change in another visual space simultaneously and near-instantaneously. The speed of input interaction and perception of output also matters: even a small bit of latency changes the quality of a user's data exploration activities [63]. We conjectured that a screen reader, the most-used tool leveraged by blind people when interacting with computers, may be insufficient for engaging this task.

To engage this, this thesis introduces *Cross-perception*, an approach for building analytical interactions that support perception in one space of input interaction with simultaneous, non-competing perception of output in another space of data representation. We first formalized a design framework for producing *cross-perception* experiences and then built a novel prototype device, the *cross-feelter*, that enables blind *cross-perception* of a cross-filtering data exploration interface. In an empirical study with blind users (with and without existing data expertise), we found *cross-perception* speeds up analytical exploration by 90% and helps blind users consider

vastly more questions of their dataset (+188% computational queries, +54% spoken aloud) compared to a screen reader-driven interaction.

Beyond performance, we found that our input modality itself shaped the character of analytical engagement: participants didn't just work faster, they considered more dimensions of their data and asked qualitatively different questions. The *cross-feelter* also reduced anxiety and substantially increased enjoyment, particularly for participants without prior data expertise, suggesting that the barriers blind practitioners face in data work are not only functional but affective. Additionally, we had our blind practitioners imagine new interaction possibilities that *cross-perception* could enable including and beyond our *cross-feelter* device.

Our final domain of work is the most difficult for visualization practitioners to engage: **personalization**. While *navigation* demanded better software tooling and visual support and *interaction* required new hardware, *personalization* completely re-orients how software authoring takes place. Personalization matters because of *access friction*, which is a design challenge where one design or interface configuration that might be accessible for one person or group of people turns out to create barriers for someone else [37, 48]. In existing work on personalization and accessibility, studies have demonstrated that end-user control is great to have and can alleviate friction [54, 124], but little work has been done to explore what personalization looks like for an existing data visualization library and how practitioners should build and maintain their existing systems to support it.

Our final chapter introduces *Softerware* to address the tension between standardized accessible design and the diverse needs of real users with disabilities. In the wild, *access friction* exists in every design that reaches a public audience; it is inevitable. This tension ultimately means that some users have a worse experience, and may even face exclusion, with any particular design configuration. So for this work, we conducted our research in-situ with visualization software engineers and designers and worked to build a scalable, flexible software system dubbed "softerware" that enables end users to manipulate the appearance and functionality of the charts and graphs they encounter according to their own preferences. We conducted empirical research to inform our collaborators, as well as other visualization system authors, with guidelines and considerations for building *softerware* systems. In our study, no two participants chose the same preference configuration and participants with the same diagnosed condition sometimes needed opposite design treatments. Practitioners, meanwhile, immediately raised ethical concerns about whether personalization would let designers off the hook for poor defaults. These findings revealed that the real barriers to personalization are not at the level of any individual chart but at the level of system infrastructure: without persistence, cross-system interoperability, and shared standards, the effort required of end users exceeds the value they receive.

Combined, these contributions provide empirical insights and practical advancements in the state of the art for tooling that bridges gaps in current accessibility practices in visualization and data science. Our work ultimately enables people with and without disabilities to better evaluate barriers in, analyze with, design for, develop, and personalize interactive data experiences. We demonstrate that tool-making is a productive intervention that both engages accessibility barriers and elucidates why those gaps exist in practitioner work.

Part VI

Conclusion

Chapter 9
Discussion & Future Work

9.1 What is a "tool?" A reflection on the social and material identity of tools

In the introduction of this dissertation, I use the example of a hammer: a hammer can destroy and it can construct. So is the *use* of a technology what constitutes it? Do we understand the hammer as the *thing we swing, to destroy and to build*? Should we?

This thesis engages domains of tools and tool-making for accessibility: evaluation, navigation, interaction, and personalization. But these categories for work do not fully characterize the upstream conditions that our software systems and data interfaces inherit.

In my work specifically on accessibility, a larger social reality becomes apparent that shapes the question, "what is a tool?" far more than how an individual might use one, or the domains of work that our tool-making inhabits. My research journey has navigated multiple social and political thresholds, from changes to law in the European Union, to the enactment of Title II as part of the update to the Americans with Disabilities Act. These laws have motivated a significant interest in accessibility research, solutions, guidelines, and technologies. In the midst of this, we have seen the rise of overlays and generative AI solutionism [38] and subsequent lawsuits and grass-roots resistance.

For my work, this is mostly good news. Legal change produces motivation, and even with predatory technology attempting to address real problems, pushback is widespread and active. But this paints a picture of the reality that my work inherits: many tools cannot even be used, or cease to be used, if there is not a social, political, and material set of conditions in place motivating those tools, providing resources for their construction, regulating their use, and examining the outcomes of what they accomplish. Tools and technologies are often a response to social, cultural, political, and legal realities that we first negotiate.

I recently spoke on this at a keynote in Australia, on how a hammer isn't *just* a tool and that the idea that "the only thing that matters is how a tool is used" limits how we really understand tools. Instead, I spoke about how a standard, household hammer requires iron and wood. That alone leads to a whole universe of different questions. Western Australia's conservation efforts were disrupted when a significant amount of natural iron was discovered in a wildlife preserve. So laws were passed and now iron is mined there. That iron is largely exported. And Australia then, whether with Australian iron or not, mostly imports their small tools. Iron is sent out, and through a complex network of trade (likely indirectly related to the iron), hammers are brought in. A "hammer," to even exist at all, relies on multiple levels of human governance, international relations, and complex infrastructures of trade.

And while my metaphor is largely motivated to encourage younger practitioners to consider the "iron mines" in the technologies they use, such as modern generative AI, it is also an area that is not adequately explored and addressed in terms of accessibility research.

Research on accessibility is dependent on funding, which is often dependent on political

priorities and action. Depending on the current social and political state of the world at large, accessibility research itself may never gain the opportunities required in order to innovate and produce new tools at all. And as the US's 2025 federal cuts to research demonstrated, millions of dollars devoted to accessibility research can be lost to political agendas. It is for this reason that engagement with policy recommendation and guidance is essential. Personal political activity and involvement is also essential. Researchers who genuinely believe in accessibility as a human right or as a dignity that all people deserve should work with policymakers to ensure that there are material and structural resources in place for this work to continue. We cannot naively believe that technology, divorced from the realm of social and political forces, is capable of solving accessibility barriers [101]. Without enforcement and threat of litigation, very little accessibility work has been accomplished in the past by technology companies alone.

Not featured in these chapters (as they were merely stapled in research papers from previous publications) is the policy and outreach work involved in seeing that work like *Chartability* and *Data Navigator* are used in real contexts, including by organizations that govern and influence the lives of many people. Immediate incentives to produce novelty may not be enough to sustain the larger socio-cultural and political ecosystems that our work participates in and is downstream from. We must also get involved.

9.2 "Applied" accessibility work and *low research*

I came into an academic research environment already as an engineer. I had questions to big problems, especially about how tools might shape human behavior and how we can use that towards ethically good outcomes. But *Chartability* was a project I made first for myself, to engage the problems I, personally, was facing.

And *Data Navigator* was motivated by my existing experience making visualizations navigable. I knew we had to build better tools, because continually trying to make a hierarchical substrate like HTML work for complex, non-hierarchical relationships simply limited what was possible and easy to do.

These two projects then led to many opportunities to test them in applied contexts. Our CZI grant was motivated towards the application of both, Adobe was interested in *Data Navigator*, and the University of Wisconsin's GIS folks wanted to figure out how to make a complex map navigable, *Data Navigator* or not. Yet, as a researcher I wasn't incentivized to pursue these projects. In fact, they all proved to have no immediately apparent novelty. It was a risk to spend my time in these spaces.

Applied work is structurally and socially devalued in academic research environments, seen often as a lower form of research and design compared to more "pure" forms of knowledge production. (I conjecture that in part this is due to the scope of knowledge that practitioners produce: they work to take broad knowledge and apply it to specific, small problem spaces. Foundational research tends to assume that broad knowledge does not then bubble up from this work, that it is a one-way flow.)

In my first year as a PhD student I was given the advice by a senior researcher not to hold my experience as a practitioner too highly because, "practitioners often don't know what they are doing." But I did, of course, to some degree. Yet, this attitude is pervasive in some spaces and is

a problem because it limits what kinds of knowledge we care to attend to.

Initially, I felt that with *Chartability* I had lucked out. But after 4 more collaborations which resulted in funding and 2 research publications, I can now argue that this method has been reliable. In *Softerware* and *Skeleton*, pursing practical problems in applied environments *did* serve as a fruitful source of generalizable knowledge and advancements in the state of the art. But these projects, in addition to *Chartability*, were all motivated by immediate, non-novel problems: people knew their charts were inaccessible and wanted some design guidance or engineering solutions.

So perhaps "low research" works.

Yet some research communities, especially *ASSETS*, have yet to reckon with "applied" work like this. If you trace the lineage of *action research* from Hayes [39] (which is how we frame our applied work in *Skeleton*), it leads into fantastic areas of participatory and community-based work, often with or by marginalized people and people with disabilities [4, 48, 65, 69, 101, 104, 105, 109, 118]. I would even argue that this lineage of work, which prioritizes and centers the lived experience of a person, is also why we have seen so many successful auto-biographical and auto-innovation styles of research as well recently [7, 27, 28, 46, 93, 116, 117].

And yet, action research largely does not touch on how practitioners (particularly those without disabilities) do applied work in accessibility [55, 96]. I believe that significant gaps exist in the space between traditional "high" knowledge production and applied, "lowly" spaces. Researchers tend to pursue novelty and the lifecycle of research production is highly risk adverse. And yet, relatively little work has been done within the accessibility research community to intellectually address the actual social and cultural risks involved producing decades of useless, lost, and forgotten prototypes and design guidelines [49, 51]. I would conjecture that research-producing academics are overly concerned with academic readership relative to the myriad of ways that their knowledge production actually is used by the rest of the world [75]. I would challenge *ASSETS* and the AT/accessibility communities of *CHI* in particular to take seriously the lack of applied (industry, government, and non-academic) work it produces as a community.

9.3 Who is responsible for repair?

Lastly, I want to revisit one of my opening points, where I argue that the *tool-makers* are first responsible for repair. This is true. However, the most pressing issue I have faced in recent years is mostly unmentioned across these research projects: tool-makers might be responsible, but this is because they are the only ones who have the *power* to make things accessible. Does this always need to be the case? Can we imagine an artifact's authority over the user's ability to access being designed towards self-subversion [31] or de-centralized agency [11, 58, 76], instead? What might that look like, concretely?

In *Softerware*, we begin to engage this larger problem in terms of an idealized state where a user can repair or re-design their own experiences. But to me, this self-repair is like laying down train tracks for yourself as you move a locomotive, but then lifting up your own tracks behind you as you go. You're the only one helping yourself. This is not ideal, for you or others.

What we need are broad, lasting, infrastructural changes. On the web, this problem becomes quite difficult to solve. A personal computer or device? Again, someone can auto-design their

interfaces into a better state. But back when I started *Chartability*, the WebAim Million's report showed more than 95% of the top one million website home pages contain at least one critical accessibility error. And now, more than 6 years later, that proportion is unchanged [113].

Some had imagined that generative AI would solve the massive infrastructural repair problems we face. But unfortunately, the latest WebAim Million report shows that since 2020, ARIA usage has increased and correlates to more errors, while use of tabindex on a page has increased nearly 300% and also correlates to more errors on a page. If anything, during the age of generative AI, we have seen existing bad patterns worsen in prevalence and complexity.

I firmly believe that a tools-based approach is not enough on its own. Tool-making cannot be the *only* intervention on inaccessibility. Tools and tool-making, as our thesis argues, have a powerful role to play. But we simply can't tool our way out of failed infrastructure and inadequate policy when someone else *owns* the tools and tool-making. Visiting a website is like going into someone else's home: arranged according to their effort, tastes, and so on. If you can't access their home, you essentially need to request that they let you in personally. Website repair always falls to the owner and maintainer of a website, and they largely don't take any meaningful action.

Sidewalks outside of homes are a good parallel to this problem. Sidewalk accessibility is a massive infrastructural problem [86], and yet localities treat sidewalk maintenance in different ways: some, like where I presently live in the south hills of Pittsburgh, put the onus on the homeowner whose house and property the sidewalk touches. In other places, sidewalks are considered a public path, similar to a roadway, and are maintained through public tax and resource management. To no surprise, privately-maintained, public-access sidewalks are worse for people in pretty much every way than publicly-maintained ones [122]. This is because private homeowners don't care about sidewalk maintenance unless the city manages to fine them or they get sued.

And the web is a collection of private spaces that you visit privately. There is no truly shared, universally democratic, public space on the web. Centralization is partly to blame: sharing space while scaling leads to consolidation.

So my future work will continue to wrestle with the same tensions of scale, repair, and anti-consolidation of power, motivated by the same WebAim Million report. But now I look to questions of *democratic* and *radical* access to accessibility repair. The barriers I hope to tackle in the future are political and infrastructural. Perhaps tool-making will participate in this work, but it seems clear now from my work that the upstream technical problems and socio-political conditions that tools inherit, will likely not be addressed by tools alone.

What does "democratic" and "radical" infrastructure work look like? It will probably be an extension of *Softerware*, to some degree. I imagine future research that explores public-first spaces, ones where access is socially negotiated and repair belongs to all of us. Is this an autonomous space, like an autonomous zone [6] separate from the web? Above it, looking down into it, like shared annotation tools but capable of sharing the manipulation of websites [85]? A space with ambient co-repair, modeled after projects that bring people together [94] or that allow community "fixing" of misinformation [52]? Perhaps feminist thought on the ethics of care can help us [42, 67]? Or maybe it will be something else entirely; I'm not yet sure. But what made the web fantastic years ago is long gone; most of it has been hedged into corporate spaces that are controlled, maintained, and repaired by corporate power. And these entities are notoriously bad at repair. What I imagine in the future involves reclaiming a sense that the web is *ours*, belongs to *us*, and that ultimately *we* are responsible for making it accessible.

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