Concept White Paper

Reimagining Maps

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Oct 31st, 2020

National Geospatial-Intelligence Polyplexus Incubator: Reimagining Maps

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Contents

Reimagining Maps

Reimagining Maps was written in response to the National Geospatial-Intelligence Incubator of the same name hosted on the platform Polyplexus and was done so with the intent of discussing the questions outlined below.

Driving and Inspiring Questions

- Can emerging knowledge in mathematics, perception, design, and other related disciplines help us make better, more flexible, more understandable maps and governance? What is possible now or soon that was not possible before?
- What if we suddenly found ourselves forced to explain where things are or how to get from A to B without historic maps? How would advances in abstract mathematics, psychology, cognitive neuroscience, art, augmented reality, and other technologies and disciplines be used to inspire cartography if it were a new field?
- Can map systems accommodate various users and facilitate modern action affordances?
- Can maps be dynamically customized using emerging knowledge in mathematics, perception, design, and other related disciplines?
- Can best practices in computer science fuse with insights from phenomenology and ecological psychology to make human-computer interactions healthy and meaningful?
- Can governance of datasets and map generators be transparent, effective, and secure?
- Can responses to disasters be rapid, contextual, and human-in-the-loop?
- What is possible now or soon due to changes in the use and availability of geospatial hardware and software technologies?

Introduction

The field of cartography sits at the intersection of applied mathematics, engineering, geology, geography, user experience, and graphic design. Methodologies and concepts from cartography have been creatively applied in a variety of fields, such as the application of spatial mapping techniques to information in knowledge management, or the use of itinerary visualization methods in non-spatial journeys such as learning maps in learning management systems. These fields have been subjected to their own forms of development and evolution leading to new methodologies and concepts somewhat removed from their origins [1]. Cartography itself has undergone a great deal of technology-driven development [2] but would look very different today had it been developed as a new field through the creative application of methodologies and concepts from those it inspired. As the modern information and logistical context presents new challenges and thus new demands for maps, we propose a "reimagining of maps" through an interdisciplinary synthesis inspired by the interdisciplinary origins of maps themselves.

While geospatial mapping has traditionally fallen solely within the scope of cartography, this relationship is subject to a number of common misunderstandings. The most general of these misunderstandings may be the assumption that cartography is a field which is solely concerned with the preparation of geospatial maps. Modern cartography is indeed concerned with geospatial representation but the origins of the practice are primarily found in the production of maps that were non-geographic, such as maps of the stars, maps that informed cultural and religious practice, and maps that stressed relationship and categorization over precision in spatial representation [3–5]. Further, there is a misunderstanding that, historically, maps were in regular use for navigational purposes in transit, which was rarely the case [1,6]. In actuality, medieval and ancient maps were considered "precious" artifacts [5] often used for archival purposes and interdisciplinary (military, geopolitical, scientific, and commercial) reference but most parties traveled by itineraries that were informed by maps or by those with knowledge of them [1,6]. Histories of cartography indicate reasonable efforts taken by their authors to ensure clarity when discussing the subject, regularly using terms like "geographical", "maritime", and "terrestrial" [7,8] to indicate what kind of map is being spoken about, as each came with its own quirks and utility [1,7–9]. The objectives of spatial mapping are not always about explicit representations of territory, instead, the contemporary and historical focus is often more aligned with the connection of data to the missions and needs of other disciplines, in order to accomplish goals through primarily static, graphic representations of space and time.

In this paper we define the key dimensions of the Geospatial Problem Space before drawing associations between the traditional foci of cartography (the production of maps and archival sets) and fields such as abstract mathematics, complexity science, and information governance. The objectives of this paper are to first consider the key dimensions of the Geospatial Problem Space and the limitations of the field of cartography in its current state and at its cutting edge, and then to consider the objectives, strengths, and limitations of diverse fields adjacent to cartography such as applied mathematics, engineering, and digital pedagogy. These adjacent fields are intended to serve as a basis for exploration of the potential future of cartography. Finally, direction is provided for future research activities, specifically concerning the development of integrative frameworks for geospatial intelligence production and user experiences involving:

- Rapid generation and customization of user-aware maps
- Signal processing techniques
- Role-based access systems for collaborative production of artifacts
- Open Source Intelligence (OSINT)
- Next Generation Analytics
- Artificial Intelligence (AI) in the Loop with Humans & Humans in the Loop with AI
- Action-oriented usage of geospatial artifacts

Part I

Current State of Geospatial Maps

Recent changes in medium, mobility, data availability, and infrastructure have greatly impacted the field of cartography. These technological evolutions have accordingly changed the strengths, limitations and objectives of maps, reflected by developments in the affordances that cartographers are able offer to users through their map products. Here, we consider the strengths, limitations, and objectives of modern Cartography in the context of ongoing technological changes, before exploring areas of non-geospatial mapping to understand where insights for geospatial maps may be gleaned. First, we reflect on the current state of maps, with focus on ecological, social, and COVID-19-related use cases and challenges of 2020 (Figure 1).

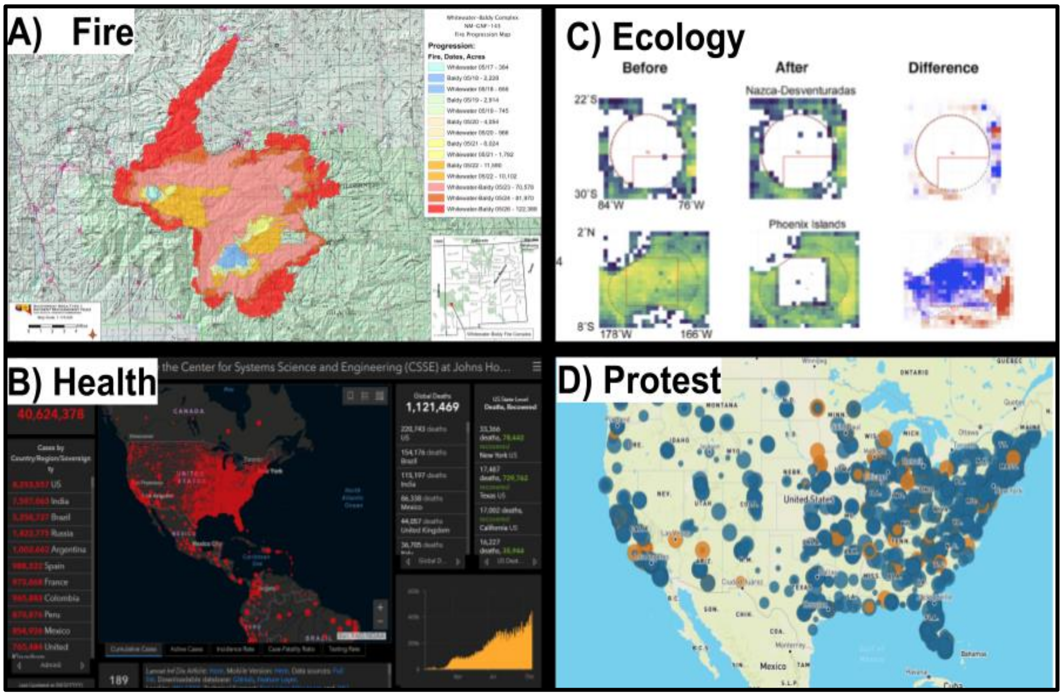

Figure 1. Use cases for maps in 2020. A) Fire map image from [10] . B) COVID-19 case map from [11] (10/20/2020). C) Marine conservation maps From Figure 2 of [12]. D) Map of protests around the United States from [13], last updated June 16th, 2020.

Interoperability

The availability of spatial data online is increasing rapidly, largely through catalogs or standalone APIs. These data catalogs fit into traditional map production workflows: beginning with the sourcing, cleaning, and organization of data, followed by careful cartographic manipulations and stylings, resulting in an end product that is a static or standalone interactive map (see Figure 2) [14]. The specifics of how this pipeline is carried out, depend on the specific features of the situation such as the volume of data, update frequency, security model, end user platform specifications. At best, the data manipulation processes are shared and documented within a code repository like GitHub. This transparency and reproducibility help make tools and datasets more useful across situations, and thus more interoperable. Large, complex datasets often need custom pipelines in order to be transformed into useful and interoperable formats. With limited standards for aggregation of data prepared without Geospatial consideration (flexible attachment to grid, locations, or boundaries) or assessment frameworks for geographic coverage, consistency, and change in value over time (related to user dynamics of different source mobile apps), the potential power of heterogeneous datasets has not been realized or leveraged. If the work is collaborative or intended to be auditable, it is essential that data manipulation processes are shared and documented within a code repository framework such as GitHub.

The global COVID-19 response in 2020 has accelerated several trends related to the processing and sharing of private sector aggregated location data. Governments and companies such as Facebook, Mapbox, Simtable and SafeGraph are involved in map products that summarize population movement, and data from these efforts have been leveraged by researchers to study various outcomes, including relating epidemiological outcomes with compliance with movement restrictions, with an eye towards developing a leading edge prediction of viral resurgence. This urgency and heterogeneous uptake across different areas has led to significant challenges related to interoperability as well as privacy. COVID-19 has revealed both problems and opportunities regarding institutional trust and data sharing. The value of individual health data in helping governments and civilians plan for and react to the spread of disease is inarguable, but the lack of a standardized framework for individual governance of personal data has led to mixed sentiments regarding sharing, which is potentially related to the success of national governance in combating the pandemic [15–21].

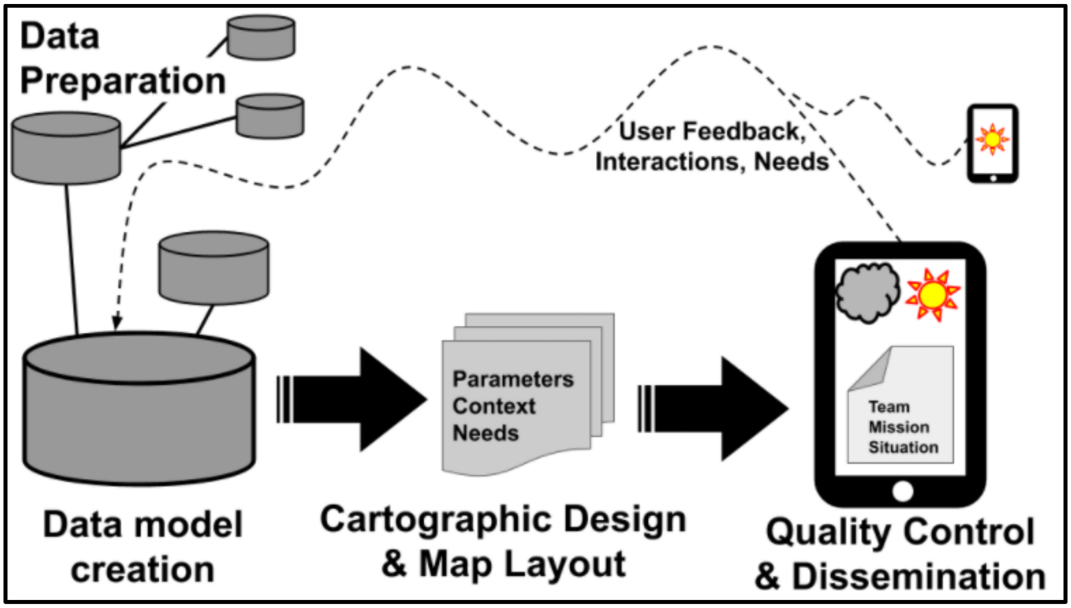

Figure 2. Map Production Pipeline

Skill Gaps

The computer science and artificial intelligence communities are often concerned with best practices for "mapping" data from one structure to another to take advantage of efficiencies or advantages of one representation of the data versus another, but the GIS trained workforce is broadly unprepared to implement these best practices or work with code, databases, or Artificial Intelligence (AI) [22]. Due to the specialization silos and changing hiring practices that emphasize machine learning, computer, and data science backgrounds, the GIS workforce may be in danger of simply being displaced by software developers. For example, common general questions facing developers using tools by the company Mapbox are: "how is our data loaded into the client side for manipulation?" and "how will we pre-process this data on our platform into vector[1] tiles?". Expertise in cartographic methodologies and practice are rare to find in the aforementioned communities [24–27]. The resulting lack of synthesis in the best practices among the domains of computer science, data science, and GIS, as well as those between these domains and graphic design and user experience engineering (UX), has notable impacts on the consumers of maps, who are liable to

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[1] A data standard for terrain and traffic data [23]

be overwhelmed with volume of data or misled by its presentation. Existing processes and complicated delineations of responsibility may, at the least, cause general misunderstandings about course of action analysis, and, at the worst, lead to tragic failures such as those caused by errors in emergency (US 911, UK 999) dispatch orders or motorists being left stranded in deserts [28–31]. The skills needed for modern cartography are those that facilitate the answering of these questions.

User Awareness

Overly prescriptive, robotic guidance systems are among the worst signal-to-noise ratio offenders in everyday life (e.g. frequent and salient "false positive" notifications reduce user vigilance and thus impair navigation). At this point, navigational guidance has limited intimations of human-level experience and understanding, for example providing ambiguous guidance during complicated maneuvers, or being disconnected from obvious surrounding phenomena in situations encountered on a daily basis. These systems have a limited ability to incorporate users' cognitive awareness, and any introduction of existing knowledge as a filter would vastly reduce the cognitive load for navigation. Further, likely due to a lack of trust in both intent and capability of users [32], there are limited affordances for users to update details about their environment in order to improve the experiences of others and where these affordances exist they often don't implement best practices on crowd sourcing [33], consequently generating a variety of complex threat surfaces for the purposeful and accidental introduction of uncertainty [34].

Mapping Uncertainty

There is the eternal challenge of determining whether blank spots on the map represent absence of presence or lack of knowledge. In OpenStreetMap, an empty place may have already been surveyed for structures and none were found, or it is possible that it was never evaluated before or recently (and thus may actually have or not have a structure at that location). During the 2014-2015 Ebola response, West African communities that expanded rapidly in recent decades were found to be unmapped, a challenging situation for public health and resource allocation. The urban edge and new settlements are ever expanding, particularly in newer cities of Global South. We need to track the meaning of blank spots globally, perhaps through the use of generative models that take uncertainty into account. Some techniques do exist that allow for inference in unmapped or poorly-mapped areas, for example approaches that soften the boundaries of point and vector data [35]. However, the approaches for mapping uncertainty thus far have not lent themselves to meaningful to action facilitation in challenging situations [36].

Existing infrastructure is rapidly overturning as well in response to crisis from climate, conflict, and public health emergencies. The impact of COVID-19 lockdowns on business closures means that wide parts of our existing maps are suddenly out of date. It should be feasible to identify entire districts that have overall less certainty of continued function. The inability to handle uncertainty, combined with larger volume of diversified source data, in rapid production, makes maps more vulnerable to unintentional or maliciously injected noise.

Threat Actors

In a global world, the security, governance, and trust of maps and data becomes even more important. Fundamental data such as GPS is vulnerable to spoofing [37]. Intentional map data spoofing has occurred in augmented reality games such as Pokémon Go and games which use real-world spatial data to generate their environments, such as Microsoft Flight Simulator, both have been known to show distorted segments of OpenStreetMap [38,39]. An increasing fraction of real-life is enacted online in “social media”, in the gray-zone between games and reality. The Ukraine/Russia conflict presents a (possibly apocryphal) story about the introduction of intentional changes in OpenStreetMap to divert forces into less strategic points on the landscape. More well-known are the security risks of wearable GPS-enabled trackers, which can leak information about sensitive assets [40]. In cities and military operations, where maps are in constant use to facilitate decision making, the consequences of inaccurate maps can be dire. As user-input influenced maps become spaces for conflict themselves, there is a critical need for map quality assurance, based upon data and pipeline trustworthiness.

Volume of Data

Implementation of user-informed systems that account for quality assurance and trustworthiness means leveraging huge volumes of data in a manner that is sufficiently responsive to on the ground situations (e.g. within the expected timescale of interacting with a smartphone app, less than seconds). The need for fast decisions means that analysis of data must also in part migrate to the edge of the computing network, away from centralized server farms and towards the end-user's networks and devices. Increasing power of devices and geospatial processing libraries means less round-trip travel for gathering insights. Some projects are beginning to explicitly address these challenges, for example the US Wind Turbine Database [41] calculates power capacity using Turfjs [42,43].

As the data environment becomes more complex, along with a growing necessity to leverage new open sources, the ability to communicate data certainty and chain-of-custody to the end product is paramount. The pursuit of these goals has led to problems in data analysis as an ever-increasing number of sensors and information-producing devices is making data volumes expensive or untenable to store in totality. This necessitates action-oriented, privacy-preserving, and flexible low-dimensional representations of data, a topic returned to later in the paper. In 2020, location and environmental sensors are becoming embedded into our devices, vehicles, infrastructure and objects in the logistics flow. These sensors are proliferating in number, reporting time-tagged location data to multiple aggregators. In 2019, hundreds of millions of GPS chips were in use, most commonly attached to a networked device, reflecting a market of around $100 Billion USD. New geo-positioning systems are coming online in all of the major powers. Nearly all new vehicles ship with GPS and network components. With a vehicle fleet turnover of 15-20 years [44], it is safe to predict that a majority of vehicles will be generating location data by the end of the 2020s, either through onboard sensors, or smart devices carried by passengers.

Accessibility

As technological platforms increase in scale and intricacy, accessibility for users and institutions is a key concern. Many contemporary projects are making significant strides in spatial mapping reach and accessibility however there is still a long way to go. To provide a few examples: the NOAA Big Data Program makes very large and ever-growing imagery and analysis projects accessible directly in networked cloud computing environments [45,46]. Other maritime use-cases of large geospatial datasets are also becoming increasingly important for global ecological and legal governance [47–49]. Leveraging specifications like Cloud Optimized GeoTIFF (Geospatial Tagged Image File Format) [50] enables the efficient utilization of large data stores by offering the ability to share select views of raster data available over the network. Simple specifications like Spatio Temporal Asset Catalogs [51] can solve the problem of manually searching for needed geography, time and quality over many different holders of satellite imagery, both commercial and government.

These developments in software and database technology are all occurring within the landscape of proliferation of government and corporate sensor platforms, in particular, large constellations of small satellites like Planet [52]. CARTO's BigQuery Tiler [53] eases the flow from massive data storage and analysis to map production through automated transformation of results into efficient network centric formats like Vector Tiles [23]. ML enabler [54] reuses the common distribution format of web maps (spherical Mercator tiles) to standardize and scale ML processing and integration into collaborative mapping tools. Edge data capture and processing. "Pixel8.earth" uses commodity mobile phone hardware to capture 3d point cloud models [55]. The Mapbox VisionSDK allows for on-device image segmentation and extraction of real time street level view [56]. These projects and others are pointing the way towards accessible and powerful geospatial platforms for use by citizens, researchers, and policy-makers.

Key Challenge Areas

Here we distill the challenges listed above into three key contemporary challenge areas for geospatial mapping, where significant technological advances would not only be plausible and provide remedy for current limitations, but may also offer opportunity for a transformative reimagining of the potential for the capabilities and generation of maps in the future:

Rapid Generation of Relevant Maps

The challenge of generating relevant maps is linked to the difficulty of integrating user-specific analytics with multidimensional, real-time information about the world, local ecosystem, mission, and team. Maps are used for missions, but when map information is outdated or is inaccurate when compared with reality, the use of the map can become counterproductive. The wider the gap between the map and the territory (due to outdated or otherwise incorrect information), the more risk there is for missions. The purpose of maps is not just to provide information about a user's environment, but instead to provide relevant information to facilitate action—if each user or team involved in a mission has different roles to perform, then maps need to be rapidly rescoped and regenerated in order to properly to optimize communication of information, uncertainty, and affordances relevant to each of their respective tasks.

Informational Compression and User Experience

The users of maps are humans—spatiotemporal technologies reflect a case of human-in-the-loop augmented collective intelligence systems. Even the "right map at the right time" needs to have the correct informational compression for the appropriate user (e.g. an evacuating family, a grocery delivery driver, a recreational gamer). Too much information presented to the user at once, or unintentional noise in the representation of the data, can be cognitively expensive or distracting, thus contributing to risk of misinterpretation, analysis paralysis, or mission failure. The fundamental challenges of sensemaking and semantics are fused with the unique strengths and weaknesses of large datasets in the spatial mapping paradigms of today and tomorrow. Additionally, maps are geopolitical conflict spaces, which means they are often influenced by threat actors engaged in the strategic generation of deliberate noise and perturbations.

Security, Governance, and Trust of Maps and Data

> The increasing reach and accessibility of maps is highlighting problems related to governance, privacy, and security. In some cases, the tension between user-annotated and automatically-annotated features can decrease trust in the entirety of the mapping processes and data sets. At the same time, generative algorithms are being used to create novel data, to extrapolate what street level view is like from satellite imagery [57], or intentionally deep fake landscapes and infrastructure [58]. Google's Kartta Labs is looking to recreate historic street scenes employing a combination of crowdsourced historic maps and deep learning [59]. Research in the domain of computer vision is yielding frameworks that are becoming more competent at extracting meaning from imagery. Notably Facebook produced global population data sets [60], and road networks for integration into OpenStreetMap [61]. Despite this increase in reach of automated annotated map products, in an internal Mapbox study, it was found that within a package of over 100 million Machine Learning derived building objects released by Microsoft for geospatial use cases within the US, there were notable cases of natural features, such as boulders and ponds, being incorrectly labeled as human structures. In all these cases in others, questions about the security, privacy, and governance of data are front and center. Without reliable and authenticated data, stored in well-governed repository frameworks, complex mapping projects will be difficult to collaborate on and potentially untenable or insecure.

Spatial maps aren't just geospatial. We can "Reimagine Maps" and find cartographic insight by understanding various types of maps outside the traditional reach of map-making.

Part II
Maps in other Fields

In order to understand where we can go with maps, we need to consider the state of progress in various fields. Here we review disparate areas in which "maps" are applied, and consider examples, objectives, and limitations of each area. Across fields and use cases, the map is a tool that facilitates rapid reduction of uncertainty, often by conveying narratives, objectives, constraints, and threats [9]. We can consider an abstract map as a relation between data, information, and goals. In this light, similarities between geospatial maps of various kinds (archival and reference or itinerary) and non-geospatial maps can become apparent and provide actionable intelligence for reimagining the future of maps. For each section, we discuss the goal of the mapping system in focus, in relation to stakeholder requirements, and then inadequacies are addressed or identified.

Process Mapping

Process mapping is the application of spatial metaphors to the design of models of "relationships between activities, people, data, and objects" [62]. Where geospatial maps intend to inform the optimization of movement of objects in literal space, process maps intend to optimize organizational outcomes by helping to navigate the process of the production of a deliverable [63,64]. Process mapping has been applied inward, to the development of process maps themselves, resulting in a variety of methodologies [62], such as the Cobra six-stage method [63], BPR (Business Process Reengineering) project-stage-activity framework [65], and BPI (Business Process Improvement) [66]. Many navigation-oriented artifacts may be described as process maps, such as Operations Orders, which are used in Military, Intelligence, and Civilian teams to navigate toward successful missions [67–69], travel itineraries, communications frameworks, server architecture and distributed computing [70,71], and software. Process mapping has been noted to be of crucial importance to the improvement of the efficiency, reliability, and auditability of business operations [62–64,66,72–76]. The strict mapping of the passing of precursors and products-in-development to end-deliverables has allowed for the development of methodologies that help to clarify to map-readers exact expectations of input and output as well as variability and uncertainty at each stage of the process being described [77,78]. However, process mapping also has strong limitations, such as its linearity and inability to rigorously deal with complex systems beyond the scale of the process mapper's scope. The value of the process map has an inverse relationship with the complexity of the process and the potential for novelty, and may contribute to a false sense of knowing about the nature of the business processes they intend to represent [62], leaving organizations vulnerable due to the lack of preparation for novelty.

Software and Software Development

This potential for novelty in process mapping is not so much a limitation in the description of software and business logic, where process maps are composed of algorithms and strict data structures for the reliable exchange and manipulation of data with expectations for linearity and reproducibility at each stage of the process [79]. In these domains, process mapping languages such as UML can be incredibly expressive [80]. This has resulted in wide adoption in the computer and data science communities to express software in development and have been adapted in the SCRUM and AGILE frameworks to express the workflow of developing the software as well as the software itself [81,82]. These communities are not immune from all of the limitations associated with process mapping languages however, such as the notoriously steep learning curves, strict standardizations, and lack of interoperability between not just the standards themselves but between models produced by them. This is exacerbated by the lack of codified or interoperable ontologies for the state and mechanisms of the systems they wish to model [83–85]. A common comment is that it can be more difficult to code the representation of abstract objects in process languages than it is to code the abstract objects themselves [83]. The standard in common use for UML is hundreds of pages long [86] and interpretations of the standard are often debated, making it inexpressive to individuals who are not already familiar with the standard.

As software projects become larger and include components beyond the scope of the development team (e.g. open-source libraries used as dependencies), process maps can create more burden then they relieve. Where process maps for business processes leak value proportional to the complexity and potential for novelty within a process, process maps for software see diminishing returns and, after some threshold, negative returns. This reduction in value is related to the level of complication of the process being described. In the engineering of complicated systems, it is best practice to institute a separation of concerns regarding the various mechanisms within the system [87]. In order to meet this demand, many UML maps would have to be generated in order to maintain low signal-to-noise ratios for developers working on their sections of a project. At the cutting edge of process mapping are solutions to these limitations, embedded in frameworks like cadCAD [88]. In cadCAD, the entire modeling process can be mapped and simulated, and maps can be generated rapidly with scope defined to any particular mechanism or the flow of state between them. The cadCAD package was developed in the interest of providing a generalizable framework for the modeling of Complex Systems but can apply to other systems as well.

Complex Systems

In Complexity Science, the “map” is a nomadic metaphor that relates actors and actions of various kinds [89]. The idea of a map is applied across systems and scales, in order to highlight analogies [90–94]. Some shared methodologies across these use cases include Bayesian modeling, network science, and predictive/counterfactual approaches [95,96]. The objective of these maps are to enable understanding, control, and design of large emergent or autopoietic systems [97,98]. These kinds of maps are used qualitatively as metaphors or homologous structures that suggest system leverage points for control. These maps can variously take the form of system engineering diagrams [99,100], complex system modeling platforms [88,101], or causal “world modelers” as per several recent projects, but also can be used as quantitative tools. Causal diagrams are often used in complex systems maps because these kinds of models can lead to reduced uncertainty about key leverage points for action. Similar to the geospatial problem space, interoperable encoding of complex ontologies and pipelines for transformation of data seem to be key limiting factors within these domains.

Communications

In the gray-zone between Geospatial and process maps lie the applications of mapping metaphors and methodologies to represent communications. Communications maps which intend to represent connectivity in physical locations have had to overcome key limitations of two- and even three-dimensional Geospatial representations in order to include non-terrestrial entities such as satellites which are never static in position and are not fixed in position to the Earth. Methods to remedy this have included three-dimensional colored overlays, re-rendering the map based on timestamp, and including supplementary non-spatial maps [49,102,103]. These accompanying non-spatial maps are especially important to understanding the flow of maritime communications, where most of the communication is being done between a series of objects which are in motion and communicating information which needs to be routed to a variety of destinations over a variety of channels. Some of these destinations are spatial, such as a Port Authority, but many destinations can be abstract, such as the set of all servers within a company which can parse some kind of incoming sensor data from a vessel. Key challenges of this mapping are a lack of data standardization and a pileup of low-integrity data from the introduction of Internet of Things (IoT) sensor-technology producing billions of data points per vessel annually [49].

Communications maps are being implemented as a part of workflow maps in other domains which also have abstract, non-spatial paradigms, such as in server architecture, distributed computing tasks [70,71], and in the embodied and remote information processes that are increasingly enacted in the small-group online settings (research, education, innovation, etc.), where novel individual and collective affordances are available [34,104]. In such situations, team communication maps are network representations of the channels of information flow among teammates [100]. Team communication maps can be reflected visually as a graphical layout, or using other visualization techniques from topology, network analysis, and big data analytics. The objectives of team communication maps are several-fold: to clarify how collaborators are informationally connected, to design improved paradigms for teamwork, and to reduce redundant or spurious links within a group. Team communication maps are specifically designed to deal with the challenges of many interacting agents, some aligned and some adversarial/external teammates. Modern team communication protocols are primarily through the internet, though can also be through other electromagnetic spectrums or physical objects. Current limitations of team communication mapping tools include the scarcity of usable yet flexible tools, and friction with integrating such tools into current team tech stacks and behavioral repertoires.

Knowledge Management and Information Systems

Knowledge mapping has a variety of definitions, but all reference common objectives, which include the facilitation of exploration, discovery, navigation, and recovery of information [105–107]. Knowledge maps help to connect ideas and observations within a framework that allows for disciplinary (e.g. accounting, legal) or interdisciplinary teams (e.g. research, military) to make sense of the relationships between topics and concepts. Knowledge mapping is generally a qualitative, visual task composed of adding and arranging different ideas on a canvas to suggest new associations to make, or analyses to perform. Knowledge mapping of this kind has become popularized as a note-taking tool under the name “mind-mapping” for individuals who are looking to improve their work-flow in business, research, and education contexts [108,109]. Enterprise Knowledge Management Systems (KMS), such as those employed by Palantir and similar companies, include the generation of maps that can be extremely quantitative and formalized, especially in specific subfields or where extensive semantic data already exist [104,110]. The creators and users of these maps generally face the same challenges as those found in cartography and software development: learning curves, generalizability of data, requirements for versioning, access control, and the need for rapid generation of new maps in order to allow for separation of concerns or scope for mission by the reader. Enterprise KMS have overcome some of these challenges by creating mechanisms for interoperability and versioning, and by creating query systems which regenerate maps based on stated objectives of the user and the information they’re already aware of, but these systems require a great deal of work in initial set-up and data integration in order to become feasible.

In the relatively new domain of Open-Source Intelligence (OSINT), knowledge mapping is being implemented in order to facilitate the opening of the intelligence production cycle to include both members of the public and sources of information which are available to the public [111]. The “eyes and ears” model which dominated most domestic and foreign intelligence operations prior to the 20th century was successfully implemented at global scale by the city state of Ragusa around the 15th & 16th centuries [112], but the style of implementation is not amenable today given the number of individuals and amount of information sources available. While OSINT is often noted to be solely concerned with the inclusion of public resources in the intelligence production cycle, its focus on aggregation and interdisciplinary collaboration has led the domain to create a set of methods which help to fuse a variety of traditional intelligence gathering methods (see Figure 3) into a generalized framework for organizational sensemaking at a scale that traditional implementations of the eyes and ears model cannot [112,113]. Knowledge mapping in OSINT faces many of the same challenges as those found in enterprise KMS with the added difficulties from lack of affiliation and pre-existing trust between collaborators, as well as concerns with the inclusion of sensitive and highly technical materials in workspaces and individuals who have various levels of clearance and disparate domain expertise. It has been recommended that challenges of this kind may be overcome through the use of role-based access, user-aware work-spaces, better data standards, and gamification of tasks [100,104,114].

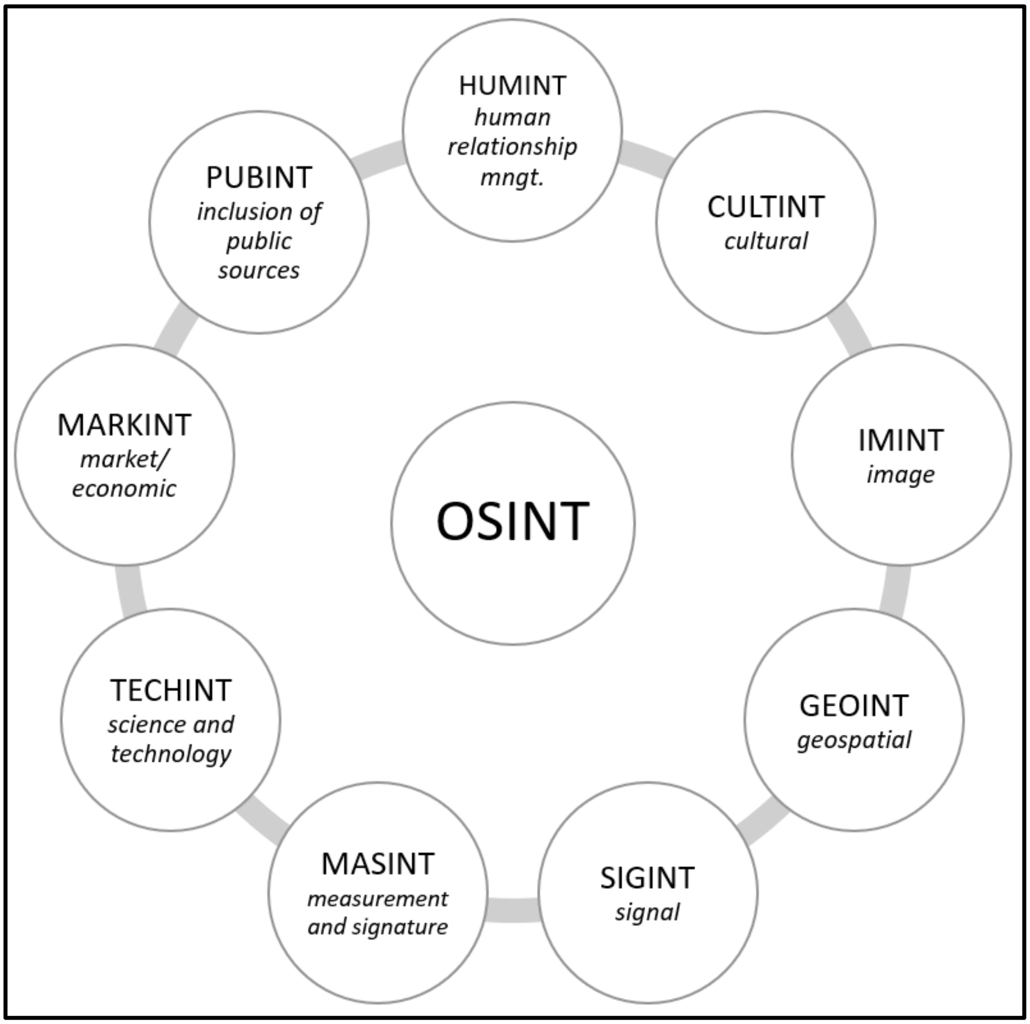

Figure 3. OSINT Fusion

Education, Curriculum, and Learning

At the intersection of process mapping and information mapping are mapping metaphors in the domains of education, continuing professional development, and human resources. The ability to communicate competencies and knowledge attained and mapping them to the requirements of roles and continuing education has been becoming increasingly difficult as fields of study, roles, and credentials become more specialized, which is consistent with early 20th century predictions [24–26,115]. The effects of this increasing granularization of specialization are exacerbated by two major factors. First, learning has become more personalized and decentralized, often being done online and outside the context of the traditional classroom. Second, deeply tied to the problem of specialization silos themselves, is that the communities concerned with the development of education and personnel data standards are generally composed of individuals who have a strong background in computer science with limited understanding of pedagogy or vice versa. As a consequence, many competency standards such as xAPI [116,117], SCORM [118], and LOM [119] are highly linear and inflexible. Attempts to update these standards have generally caused the standards ecosystem to become only more byzantine, causing problems with adoption.

The objectives of many of these efforts was either to optimize competency development by rapidly generating and monitoring personalized learning pathways in order to identify and overcome skill and knowledge gaps, or to integrate approaches found in research from outside the realm of traditional organizational psychology in order to develop organization-level competencies and performance [120] such "serious games" [104,120] and collaborative creative work [121]. In order to overcome current limitations to achieve these objectives, it has been suggested that research be directed toward developing mechanisms for crowd-sourcing the cataloging of learning resources and relationships between learning resources and competencies, managing incentivization of crowd-sourcing through microtransactions, managing trust within crowd-sourced networks, and better understanding self-forming human networks, rapid optimization of collaborative work, and rapid formation of virtual organizations [120,122,123].

Ecology and Biology

The natural world, and the study of it, can inform the study of maps. Maps are used in Ecology to map species distributions [124], ecosystem services [125], and regulated areas for human use through space and time. In basic or theoretical ecology, maps exist as abstract or idealized spaces in which processes like succession, gene flow, and guild formation occur. For applied or conservation ecologists, maps are essential in providing information on corridors for animal movement, information on the location of genetic diversity, and potential sensitivity of different populations to projected climate changes. The objectives in ecological studies of maps are to determine how features or aspects of ecosystems such as their patchiness or resource distribution, influence biodiversity, system resilience, and organismal behavior [126,127]. Other goals of ecosystem mapping include characterizing the dynamics and (informational, geospatial, ecological) components of the niche. Modeling of ecological niches can assist in sampling for conservation or utilization. Ecological analyses are often at the regional or global scale, and increasingly being used in conjunction with sensor or GPS data, to regulate maritime and terrestrial activity [48]. Machine learning schemes based upon biogeography are transferable into other domains, perhaps because biogeographic maps integrate multiscale spatial and temporal phenomena, and can integrate predictive and Bayesian methods. [128].

Some limitations of ecological modeling include microheterogeneity of the niche (e.g. temperature at one level of the rainforest different from temperature on the ground), and accurate historical/future prediction of climatic trends. Microheterogeneity of the niche can confound regional-level predictions, for example in the case where local temperature highs/lows can be outside the confidence interval of the larger area, it is unclear whether the confidence interval of the larger area should be expanded, or how to otherwise include this information on variability. The challenge of past and future projections of climate, used in niche occupancy prediction models [124,129], are similar to issues arising in large-scale climate modeling [130]. At the cutting-edge of addressing these challenges in ecology, are large consortium projects, globally-replicated long-term experiments, and spatiotemporal analytics algorithms borrowed from other fields [131]. In behavioral ecology, dynamic network representations are mapping out the interaction patterns of agents in systems like ant colonies and schools of fish [132,133]. Beyond ecological cases, there is a long history of “map” metaphors in developmental and evolutionary biology, such as the case of Waddington's epigenetic landscape [134], the genotype-phenotype map [135,136], and fitness landscapes [137–139]. Map metaphors for biological systems are linked to causal analyses (e.g. mapping between cause and effect) and therefore influence policy and culture [9,140,141].

Mathematics

Maps in mathematics often take the form of metaphors for projections of data or the results of functions onto visual planes, but these metaphors are tied to a generalizable ontology and set of methods for managing transformations of data between planes [142,143]. Functions are kinds of maps that connect inputs to outputs, for example, the function y=2x maps values of y onto values of x that are twice as large. Metaphor, ontology, and methods alike provide helpful lenses for application and understanding the nature of functions and their domain (the objects and values which can be acted on) and range (the objects and values which can be produced) [143]. The ontology within the mathematics mapping domain diverges a great deal from other mapping domains described, most notably in the definition of the term "map" itself. The "map" does not refer to the visual projection of data on "Plane Y" from data sourced from "Plane X", instead, the "map" is the function through which "Plane X" data are passed in order to generate or locate the data which sit on "Plane Y".

Mathematical mapping methods have been well generalized to work outside the realm of theoretical math and abstraction in physics and applied engineering. For example, in the gray-zone of computer science and mechanical engineering, these methods allow the "map" to be an algorithm, enabling the mapping of complex, n-dimensional objects, an example being the mapping of stress-tensors[2] to any other measure of strain [145]. These kinds of maps enable interoperability between standards without the addition of new standards or frameworks as well as enable the rapid generation of visualizations and models [145]. These mathematical intimations regarding maps overcome the limitations found within other map domains described, as maps become "generators" of visualizations rather than the visualizations

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[2] Tensors are high-dimensional objects that are increasingly being used in machine learning across different domains, through transferable algorithms such as TensorFlow [144]

themselves. Freed from focus on fixed products, mathematical maps can be linear, non-linear, chaotic, stochastic, or whole computer programs with humans in the loop, such as AI, and can contain multiple layers of maps contained within Markov blankets [146,147]. This is akin to modern paradigms in cartography where "maps" are increasingly becoming user-informed and user-aware, and being presented in terms of dynamical connectors, rather than simply being low-dimensional projections of higher-dimensional data.

The application of mathematical maps represents the cutting edge of a number of fields. For example, underpinning the field of cryptology, which is concerned with the security and encoding of data, is the ontology and methodology associated with maps [148,149]. The "hashing" of an object, or the reproducible, algorithmic conversion of data into a string of a specified length of random characters is a type of "non-homotopic" data transformation or mapping. Non-homotopic transformations are those which occur using a map for which there is no defined inverse or reciprocal (we can transform the data from plane XY onto plane WZ, but there is no defined map that will project the resulting WZ data back into its original position on the XY plane). Where reverse transformations are implausible or computationally intractable, non-homotopic mappings can be used as a one-way encryption, or hashing, technique. On the other hand, the encryption of data is an explicitly "homotopic" transformation in which there is one map for encoding data into cipher-data and another for conversion from cipher-data back to its original state. Underneath the business logic of advanced data manipulation and integration frameworks, such as those used by Palantir, are transformations described as "isomorphisms", which are structure- and order-preserving maps [150,151], and transformations over special kinds of maps like "functors", which allow for the coherent transformation of objects from one set or category to another [152,153]. In cases where mapping transformation is able to convey some knowledge about the strategies available for a specific the starting state and action (e.g. "this account has enough money to pay the bill") while strongly protecting other dimensions of the data (such as specific amounts or previous transactions), the relationship is known as "zero knowledge". Zero knowledge cryptographic proofs are increasingly relevant for Internet of Things (IoT) [154] and cryptocurrency uses [155,156].

Part III
"Reimagining Maps"

The application of mapping metaphor and methodology in many of the domains and subdomains described have converged on some combination of the three key areas of limitations of modern spatial maps raised in the Introduction. However, each domain has approached the development of next-generation solutions to their shared limitations in unique ways, and these advanced approaches will be considered in the reimagining of maps with respect to each key area of limitations.

The Map is Not the Territory

Many of the domains described faced similar requirements for the necessity of rapidly generated maps for managing detail and scope, producing maps for a variety of users and stakeholders, viewing maps at a variety of scales, and managing the integration of changing parameters, user input, and constant flows of real time data. Mapping paradigms in mathematics and at the cutting edge of the mapping of complex systems and workflow, are potentially helpful conceptions and methodologies for the rapid generation of relevant Geospatial maps.

The application of static reference maps in many tasks is now outdated, as reference data living in databases can simply be projected on command to any number of visualizations or directed to analysis frameworks. Now that the data can more easily live at their source or in accessible collections, they are frequently used or updated through transformations into a more fit for purpose data structure. This fundamental turn in cartography towards dynamic data structures moves beyond the practice of the mapmaker as collecting data to their workspace for human evaluation, to the mapmaker applying cartographic transformations to ever updating sources outside their control. The static map no longer serves a single arbiter of truth. Rather, mapping can now primarily consist of sculpting the processes by which user- and mission-specific maps are generated and delivered. This shift toward holding the map in the data allows for the interactive visual representations of complex or mechanistically complicated systems where no single static representation could possibly communicate all of the meaningful components or processes without overwhelming the user.

Using conceptions of maps from within mathematics, where maps are generators of the projection rather than the projection itself, paired with the gamification and temporary, Instantaneous Remote Teams (IRTs) of experts found at the cutting edge of OSINT practice [34,100,104]. The traditional mapping procedure of data preparation, model creation, cartographic design, layout, quality control, print, and dissemination [14] could be greatly expedited and more easily delegated to a variety of teams of collaborators and contributors. For each encountered map request, temporary teams could be formed from domain experts and relevant stakeholders to produce generators for the transformations and projections necessary at various stages of the procedure [104]. Prioritizing the production of generators rather than the production of visualizations has already led to a great deal of progress in the enterprise mapping community, converting more organizations to this prioritization and creating non-proprietary standards for generators and the data which they use could yield a great deal of value. In addition, the use of Instantaneous Remote Teams (IRTs) helps to overcome previously stated problems regarding the difficult to attain skill combinations required for successful navigation of the entire procedure by a single team or individual. Select data scientists and domain experts can be enlisted to focus on case-specific generators for the often non-routine data preparation and model generation or be considered the generators themselves, and cartographers and graphic designers can focus temporarily enlist the help of software developers or data scientists in generators of layout and projections without these skill-sets dominating these areas of the procedure.

User/Role/Actor-Centric and Mission-Aware Maps

With the correct generators, systems can have a model of the end-user built-in and use a map production procedure that not only takes end user characteristics into account, but also their objectives and feedback through the use of gamification. This gamification, through playful mechanisms found in Pokémon Go can be used to incentivize crowd-sourced development of features and notable improvement of mapping products. In the domain of linguistics, Duolingo, a language learning platform, has mechanisms to allow expert users to help adapt and add to curriculum as a part of their own language learning. However, these user-contributed additions are slowly adapted for larger populations by more trustworthy users and staff—these mechanisms could be used to help inform trust management in crowd-sourced development of catalogs and map products as well.

A key generalized objective across all mapping domains is hodological facilitation: they need to facilitate pathfinding and sensemaking for users intending to orient themselves or their assets toward action. Within the domain of this generalized objective are benign use-cases, such as finding a place to buy an iced coffee or trying to circumvent traffic where failures are measured in minutes wasted, alongside far more serious use-cases, such as evacuation during forest-fires, avoiding riots and roadblocks during civil unrest, and ambulances circumventing traffic, where failure is measured in human bodies and success in lives saved. In critical modern use-cases, maps must be generated just in time, not with just a visual layout, but rather with a mission-aware interface providing a sculpted set of representations and options that will either have outsized impacts on mission-success or quickly incorporate feedback from failures to do so.

BOLTS

Across nearly every mapping domain reviewed, there were limitations at the cutting edge concerning, not the availability of data, but the ability to rapidly integrate it. At the cutting edge of each of these domains, there appears to be an overwhelming consensus that standardization of data is prerequisite to the rapid generation of maps. Synthesizing the requirements from each domain indicates a need for data specifications which are reasonable for Business, Operational, Legal, Technical, and Social (BOLTS, see Figure 4) use-cases.

One of the primary obstacles to developing such standards in the past has been adoption and the inflexibility that, axiomatically, accompanies the introduction of hard-coded standards. Universal standards for the exact schemas of all data objects that could be of use is unachievable, however, borrowing from concepts regarding transformations within mathematics may provide interesting insights. It is not necessary that all data be universally fit to specific schematics in order to be BOLTS reasonable, instead, all that is necessary is that the objects referenced within a data object (maritime vessels, individuals, documents), the instantiated data object itself, and the schematic which is used are accompanied by metadata in order to inform transformations. Standards regarding this type of meta-data would allow for greatly increased data sharing and cross-platform compatibility while also enabling the highest standards of privacy and governance if the standards were paired with encryption and decentralized consensus protocols.

Just as mathematics defines maps as the functions which project the data, rather than the projection itself, BOLTS standards have the potential to provide an infralanguage by providing the standards for metadata to inform access and rapid transformation of data across frameworks. The presence of such an infralanguage and clear metadata would also allow for easier integration of AI into workflows to facilitate cross-referencing, discovery, and production, and transformations into varied, lower-dimensional forms while maintaining sourcing and context.

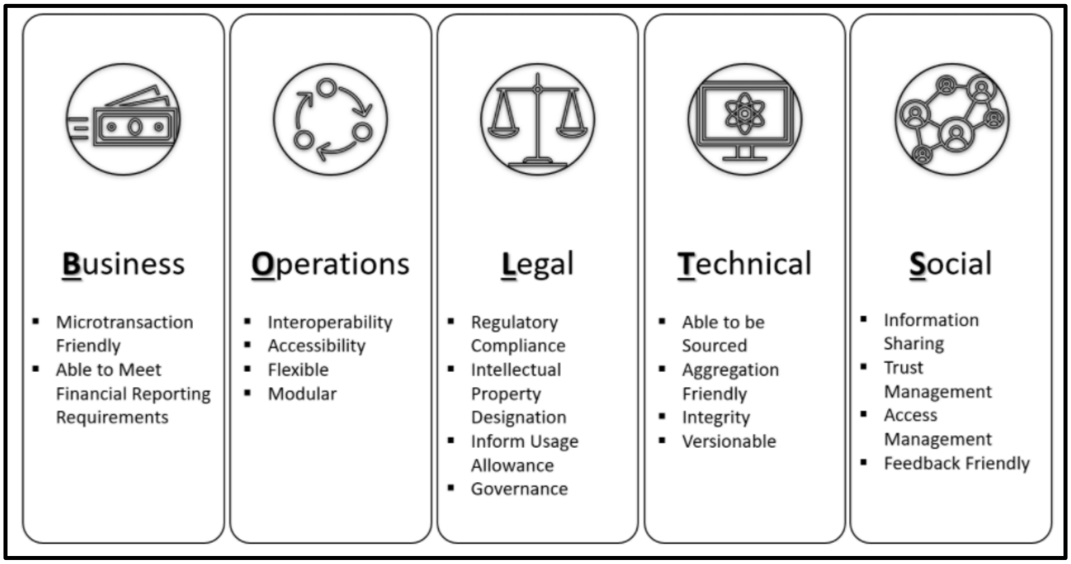

Figure 4. BOLTS

Fuzzy and Incomplete Data

One of the great challenges to universal data catalogs is the presence of disagreement over not only what should be present in the schema, but also on how to handle disagreements and uncertainty within the data itself. This extends from somewhat benign cases of “what version of the book are we referring to in this library?” to “where is this national border?”, the practical impacts of these disagreements can range from dangerous to meaningless. Future data and metadata standards should incorporate the potential for disagreement and heresy within collections and acknowledge sourcing. Further, user-informed maps have already become conflict spaces and subject to threat-actors. It is possible that the future of maps doesn’t prioritize crowd-sourcing, but instead “network-sourcing”. Based on the actual practice of data collaboration in OpenStreetMap and Wikipedia: reputation is foremost in the level of scrutiny any contribution receives. The anonymous crowd is treated with suspicion. Social networks, both in online and real spaces, are useful for assessment of the utility or validity of a contribution to a network-sourced map product. This requires the development of tools that offer algorithms or affordances to users to assess and assign the reputation needed for certain actions or visualizations to be accessible.

Case study for Future Maps

We now consider the potential impacts of a future of maps which includes these priorities and findings through the use of a narrative use-case based on a scenario offered by the United Kingdom’s Defence and Security Accelerator (DASA) “Map the Gap” competition [157,158].

In the “Map the Gap” competition, teams were tasked with surmounting realistic in-field challenges. The context is as follows: when expeditionary forces navigate within enemy territory, it is critical to mission success that physical boundaries be overcome, not just in the short term by advance units (e.g. reconnaissance and special forces which operate at the operational reach of the field army), but also in the long term by units which have trouble navigating physical boundaries such as mechanized support and logistics units [159,160]. In the case of logistics and support units, these physical boundaries cannot just be overcome once, but must be reliably overcome many times with efficiency and robustness [161]. Some of the most notably difficult terrain features to overcome are known as “wet gaps”, such as streams, rivers, and bogs [157].

Rivers in particular offer a great number of unique challenges to expeditionary forces. From an engineering perspective, rapid construction of bridges requires knowing a number of difficult to ascertain variables which include but are not limited to, the profile, depth, and other characteristics of the river bed and riparian banks, the ground bearing capacity on both the near and far bank, the gradients and material compositions of the banks, and the logistics of material and equipment access. From a military perspective, bridge building requires allocation of equipment which immediately alerts the enemy to intent and location of potential river crossings. In addition, all current methods of bridge construction in the field place reconnaissance engineers and their equipment in vulnerable positions and take a large amount of time with a high probability of having to abandon the site. At the intersection of military, engineering, and joint operations contexts is the inclusion of numerous stakeholders and domain experts: reconnaissance engineers to identify and choose potential sites, expeditionary and joint operations command staff who select sites based on current unit positions as well as intent and threats after crossing, logistics staff who are involved in this process helping to define requirements, and field intelligence who inform stakeholders with intelligence products such as briefs and maps.

In a reimagining of maps informed by BOLTS data specifications, allowances for fuzzy data, user/role-centric and mission aware maps, and IRTs, this procedure could be greatly expedited and far less dangerous. When the obstacle is identified (e.g. a “wet gap needs to get mapped”), two discrete calls might be made. The first call would go out to a number of individuals from the relevant organizations who have the appropriate clearance and domain expertise to form an Instantaneous Remote Team (IRT) with the purpose of choosing a bridge site, given what is known from remote sensing data and eyes on the ground. The second call goes out to create a digital workspace which can integrate data and coordinate work between the individuals and liaisons of units which are involved in the choosing the site. This workspace includes a variety of geospatial data-sets which offer the ability to project uncertainty over the structures and details they intend to represent.

When field intelligence liaisons access the project-specific workspace, they select a role-based view which offers them data-sets, interactive dashboards, and situation reports from various reconnaissance teams and unmanned aerial vehicles in the area of operations. Local video and satellite reconnaissance data are blended with public source data to provide catalogs to users of the workspace to generate two and three-dimensional renderings of the terrain and relevant objects in the area of operations. Situation reports and intelligence data are processed to present interactive views that create high-sensitivity and high-specificity warnings regarding the potential for enemy activity. Reconnaissance engineers accessing the workspace see none of the detection alerts, situation reports, or positions of unmanned vehicles, but they do see warnings reflecting the potential for enemy activity and probability of detection. If involved engineers want to understand further, and have the clearance to obtain this information, they may change their role and see additional information. Otherwise, engineers weigh the warnings while making decisions regarding where to order the deployment of a variety of semi-autonomous, amphibious vehicles which carry combinations of sensors and sampling tools for the mapping of the variables associated with grading locations for site selection. Remote vehicle operators accessing the space, only see deployment orders, the positions of other remote vehicles, and warnings regarding enemy activity. When operators spot suspicious activity, they can submit situation reports which will be seen by field intelligence, their command, and other operators.

Throughout this process support, communications, logistics, and command elements are in the loop watching for distress calls and requests. Cartographers, graphic designers, and domain experts work in concert to respond to requests for information and develop models and visualizations that are not available via extant generators. They document and enact their process and procedure for developing these artifacts in versioned repositories where new after-action IRTs can be formed with software developers and domain experts around creating generators for them in future operations. The workspace is an extension of a Knowledge Management and Command and Control System (C2) which allows for the integration of data-streams from other related operations and creates special work views for liaisons who need to be aware of the overlap between operations, preventing friendly fire and other silo-related errors. Command and staff elements, related and unrelated to the operation can watch over the area of operations and take the view of any user or role to see what they see in order to intervene or redirect effectively.

While this example is from the military domain, the approach applies as well to similar use in domains of city planning, where joint operations command, field intelligence, and military engineers are replaced by their civilian counterparts, such as local governing bodies, community planners, concerned citizens, and civil engineers. Both domains are often caught in a protracted process fraught with non-productive cycles of arguments exacerbated by hardened interests and conflicting goals. In the city planning domain, there may be a large amount of existing and acquirable data, such as traffic studies, service and infrastructure impact studies, zoning regulations, and legal processes to synthesize and evaluate for accuracy and relevance, but the planning process itself is necessarily speculative. An IRT model that incorporates city officials, developers, residents, and land owners in a role-based workspace design that allows them to iteratively comment on, evaluate, and develop compromises regarding the possible cityscape increases the likelihood of results that are consistently beneficial to all stakeholders.

Each role has overlap with every other, no two maps are the same as each map is curating the information required for sensemaking within each role's information niche. Engineers hot-swap generators for projecting different sets of data over the map, allowing them to dial in to specific factors at different times without the need to request laborious production of multiple maps. Given a clear separation between datasets and map generators, information can be shared in a compartmentalized and secure fashion with trusted and untrusted actors on the ground. Joint operations command and city planners alike could have full access to add experimental generators for projections built from agent-based models and recommendation engines. Maps intended for human understanding should be personalized and tailored towards role-specific reduction of uncertainty. Map generation can be iterated—if the maps presented are not useful, the generators can adapt and adjust to that feedback either automatically or with human preferences in the loop. Maps intended for use by autonomous vehicles are action-oriented reduced representations of local or regional conditions and would be customized to run on minimal hardware or in offline settings. Running through the entirety of these systems are some of the pillars of the future of maps: advanced analytical capacity, action-orientation, flexibility, modularity, accessibility, and interoperability.

Conclusion

In this paper we have surveyed the current state of cartography, with consideration for the pressures applied by COVID-19 as well as the changes in cartographic affordances for areas such as movement data, and addressed recent advances in technology are rapidly shaping the landscape of maps. We then reviewed a variety of fields adjacent to cartography where "maps" play a key role, such as mathematics, ecology, project management, and complex adaptive systems. Across fields and through history, maps and mappers are beset by similar challenges such as: integration of multimodal data, representation of uncertainty, user customization, and designing for action rather than archiving. We synthesized insights and practices from disparate areas in order to provide direction for research to realize a reimagining of maps and offered a use-case related to bridge construction in adversarial settings to convey what that reimagining might look like.

Funding and Acknowledgements

Daniel A. Friedman is funded by the NSF program Postdoctoral Research Fellowships in Biology (NSF 20-077), under award ID #2010290.

Richard J. Cordes is supported in research efforts through a Nonresident Fellowship with the Atlantic Council on appointment to the GeoTech Center.

The paper was written as a result of participation in an incubator named “Reimagining Maps”, hosted by the National Geospatial-Intelligence Agency on the platform Polyplexus.

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