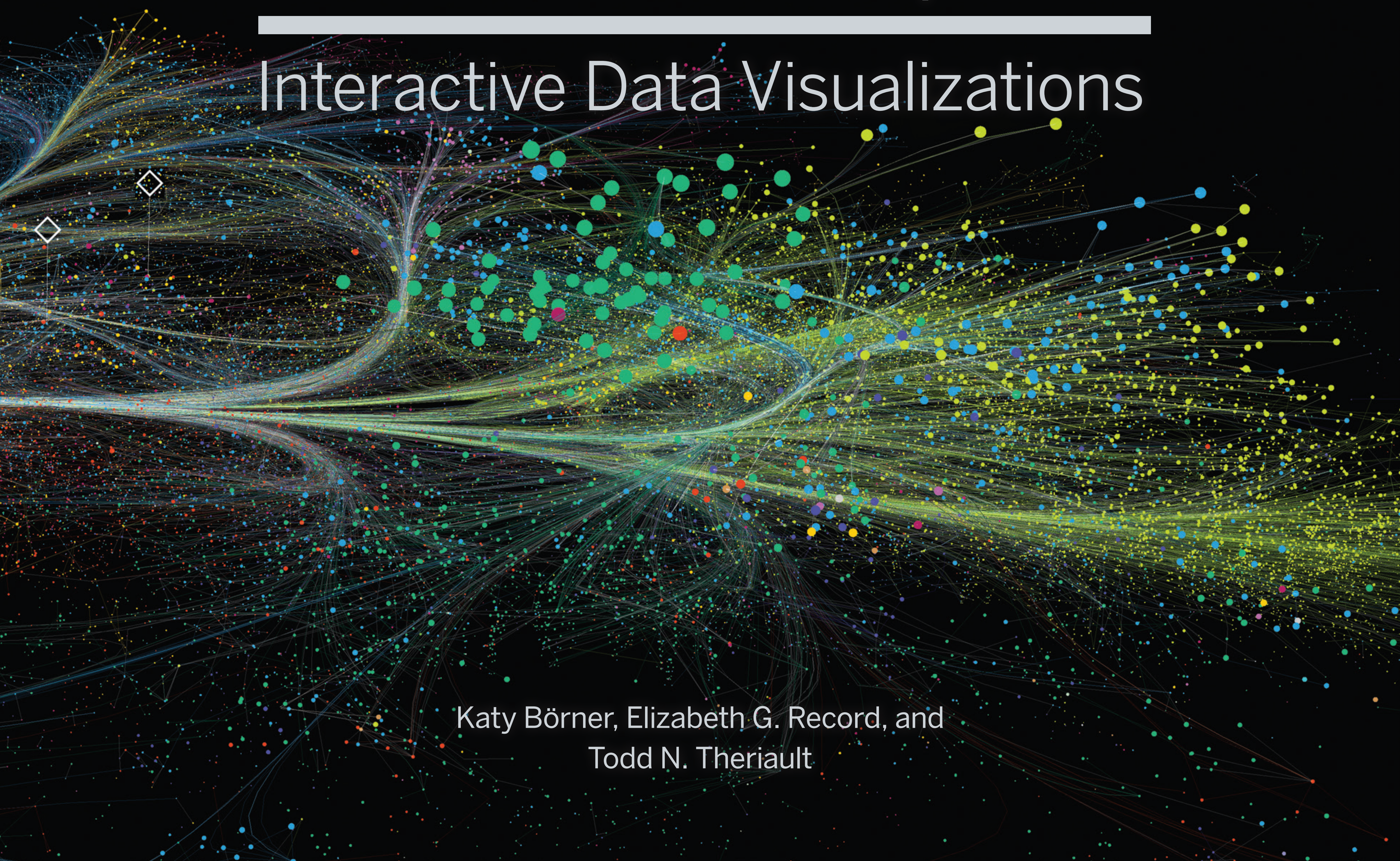
# ATLAS OF Macroscopes

## Interactive Data Visualizations



Katy Börner, Elizabeth G. Record, and
Todd N. Theriault

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# Preface

People are attracted to maps. Once they have found themselves on a map, they want to understand who is nearby, who is far away, and how to get to the next place. Interactive macroscopes make it possible to explore static maps and visualizations in a dynamic way. They allow users to navigate and manipulate streams of (often real-time) data, convert that data into knowledge, combine knowledge with experience to create wisdom, and communicate this wisdom to others. All of this can occur in the context of teaching, engaging, counseling—any situation in which people embark on shared data adventures.

After 25 years of interactive data visualization research, teaching, and engagement at Indiana University Bloomington and internationally, it has become crystal clear that merely providing access to data does not suffice. People need to get emotionally engaged to change their behavior. But how to best engage people to cause positive change? What can we learn from visualizations that have impacted many and initiated change? How can we tell effective stories with data? Or even better, how can readers and users create their own stories and navigate their own data adventures?

The *Atlas of Macroscopes: Interactive Data Visualizations* aims to answer these questions. It is organized into three parts.

**Part 1** introduces the reader to the power of interactive data visualizations and their utility in understanding the world in which we live.

**Part 2** provides a year-by-year overview of the macroscopes selected and displayed between 2015 and 2024, making it possible to see enormous progress in data availability (quality and scope), algorithm performance, and interface usability. Linked videos feature interviews with leading macroscope makers and other experts that help communicate why and how data is being rendered into interactive visualizations to improve human decision-making.

**Part 3** presents challenges and opportunities for deriving meaningful, actionable insights from complex datasets and starts answering questions such as: How can data visualization literacy be improved through formal and informal education and training? How can macroscopes be accessed and utilized by people 50 years from now? How can artificial intelligence augment human intelligence? What might future macroscopes look like, and what problems will they help us solve?

The *Atlas of Macroscopes* builds on the *Atlas* trilogy, also published by the MIT Press. First, the *Atlas of Science: Visualizing What We Know* (2010) introduced the power of science maps to guide our search for knowledge, help us navigate and communicate the dynamic and changing structure of science and technology, and make sense of the avalanche of data generated by scientific research. Next, the *Atlas of Knowledge: Anyone Can Map* (2015) introduced a “timeless” theoretical data visualization framework meant to empower anyone to systematically render data into insights while referring to an extensive set of references and examples for “timely” advice on what tools and workflows are best for answering a specific question. Finally, the *Atlas of Forecasts: Modeling and Mapping Desirable Futures* (2021) introduced the power of computational models for personal and professional decision-making so we can collectively identify pathways toward desirable futures. While this new *Atlas* shares many of the same concerns and objectives as the *Atlas* trilogy, it distinguishes itself through a much more hands-on, interactive, and playful approach to data exploration in public, professional, and personal spaces.

The online website at **scimaps.org** features all 40 interactive macroscopes together with video recordings, event information, and press coverage. The *Places & Spaces* Zenodo community at **zenodo.org/communities/macroscopes** features macroscope-maker interviews, demos, and presentations. We welcome everyone to visit these sites to become data explorers, teachers, and ambassadors who embrace data-driven decision-making that ensures a future filled with productive and rewarding human and machine collaboration, deep insights about the world we live in, and equal opportunities for all.

Katy Börner, Elizabeth G. Record, and Todd N. Theriault

Curators of the *Places & Spaces: Mapping Science* exhibit, **scimaps.org**
Cyberinfrastructure for Network Science Center
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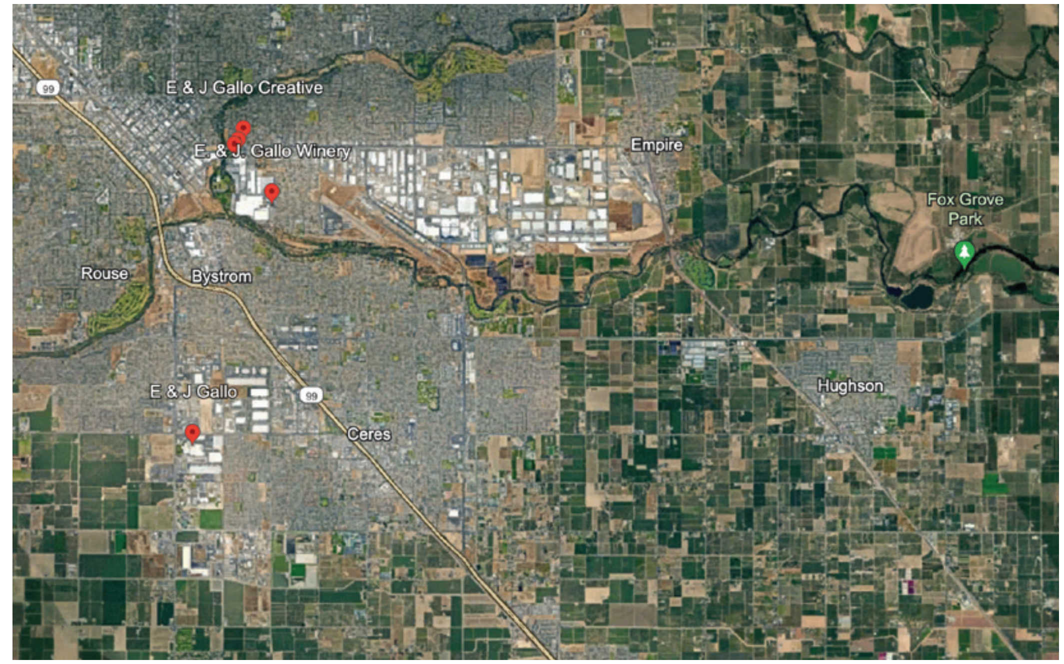
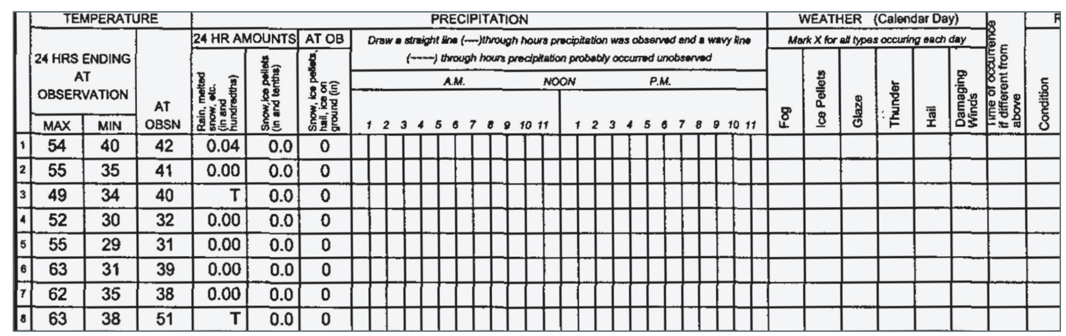
August 26, 2024

# Microscopes, Telescopes, and Macroscopes

Macroscopes are software tools that help people explore patterns in data that are too large, too small, or too complex to see with the naked eye. Interactive by nature, they can be used to ask and answer questions of data.

Imagine a view of Earth from a space station, then that of a hawk riding the wind over seaside cliffs, and finally zoom in to observe one particular flower near the cliff's edge from the perspective of a butterfly. A similar approach can be applied to complex systems like the interconnected factors that impact public health, global weather patterns, or the international movement of refugees. Macroscopes pair the ability to view large-scale systems with the ability to zoom in to local patterns and trends in order to access massive stores of detailed data. As digital data and computational power grow, macroscopes are needed to make sense of multifactor, multimodal datasets.

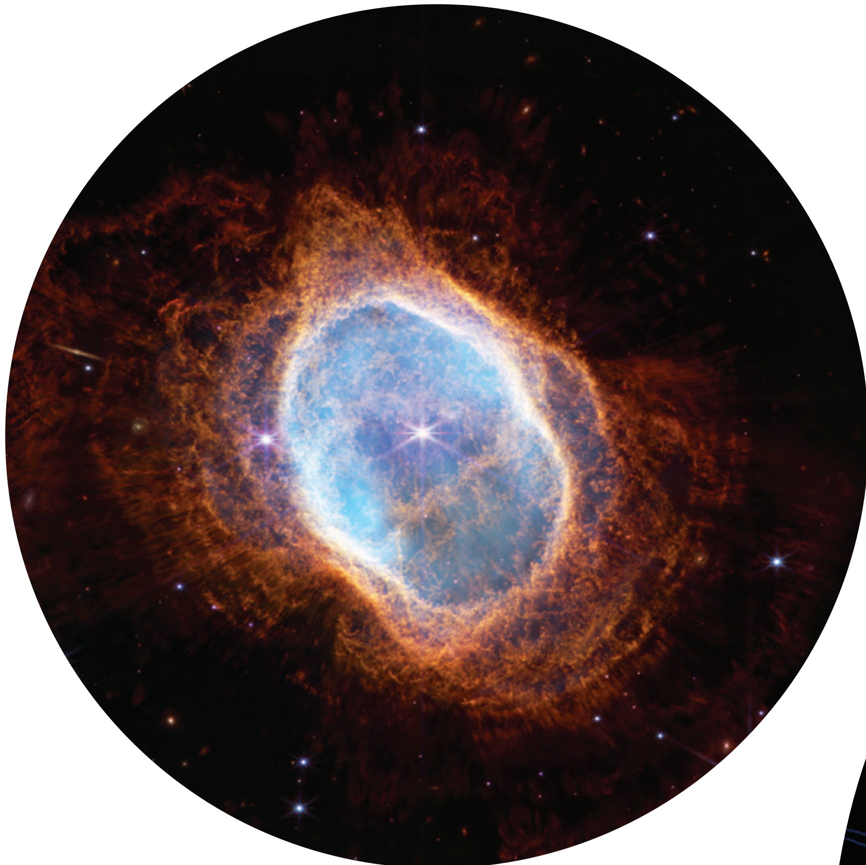


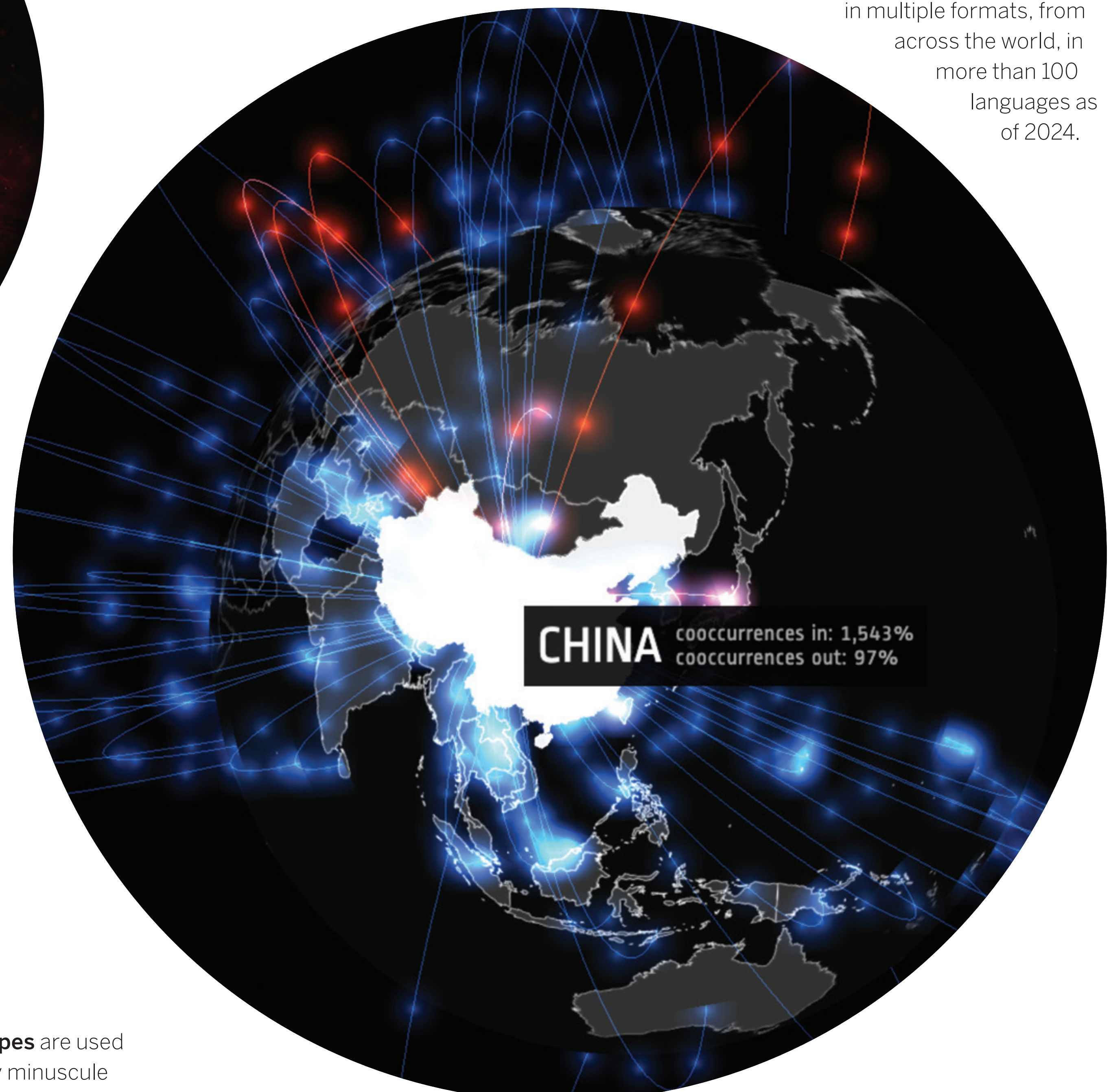
| | TEMPERATURE | | | PRECIPITATION | | | | WEATHER (Calendar Day) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 24 HRS ENDING AT OBSERVATION | | | 24 HR AMOUNTS | | AT OB | Draw a straight line (----)through hours precipitation was observed and a wavy line (~~~~) through hours precipitation probably occurred unobserved (A.M. 1 2 3 4 5 6 7 8 9 10 11 NOON P.M. 1 2 3 4 5 6 7 8 9 10 11) | Mark X for all types occuring each day | | | | | | | |
| | MAX | MIN | AT OBSN | Rain, melted snow, etc. (in and hundredths) | Snow, ice pellets (in and tenths) | Snow, ice pellets, hail, ice on ground (in) | | Fog | Ice Pellets | Glaze | Thunder | Hail | Damaging Winds | Time of occurrence if different from above | Condition |
| 1 | 54 | 40 | 42 | 0.04 | 0.0 | 0 | | | | | | | | | |
| 2 | 55 | 35 | 41 | 0.00 | 0.0 | 0 | | | | | | | | | |
| 3 | 49 | 34 | 40 | T | 0.0 | 0 | | | | | | | | | |
| 4 | 52 | 30 | 32 | 0.00 | 0.0 | 0 | | | | | | | | | |
| 5 | 55 | 29 | 31 | 0.00 | 0.0 | 0 | | | | | | | | | |
| 6 | 63 | 31 | 39 | 0.00 | 0.0 | 0 | | | | | | | | | |
| 7 | 62 | 35 | 38 | 0.00 | 0.0 | 0 | | | | | | | | | |
| 8 | 63 | 38 | 51 | T | 0.0 | 0 | | | | | | | | | |

**A macroscope in action**

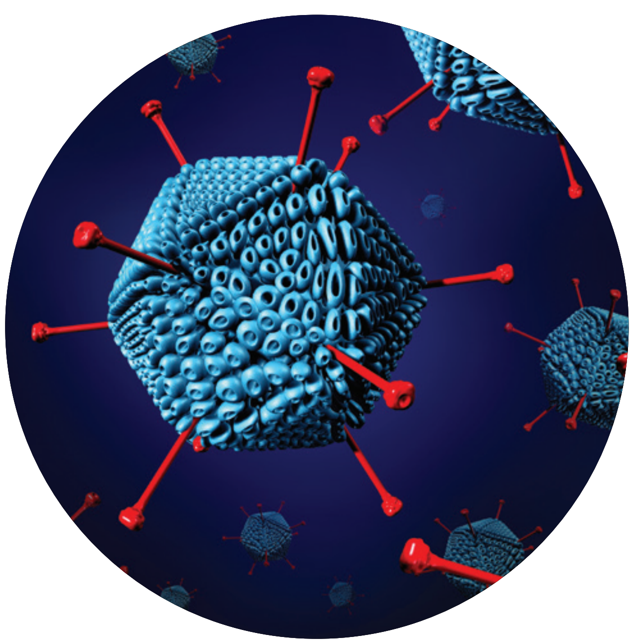
IBM developed a precision agriculture macroscope that allowed E. & J. Gallo Winery to monitor and adjust irrigation across 12,000 acres of grapes, based on the analysis of satellite imagery (see top right), historical weather records (middle right), and real-time soil sensor readings (bottom right). Irrigation was controlled in 30 x 30-meter blocks, providing the precise amount of water needed for optimum growth. Blocks irrigated using this system saw a 26% increase in grape yield, coupled with a 15% increase in water efficiency, compared with blocks not using the macroscope.



**Telescopes** make it possible to observe faraway objects. This image of the Southern Ring Nebula was captured using the James Webb Space Telescope.




**Macroscopes** heighten our ability to explore complexity. This image is from *Mapping Global News* (page 28), based on the GDELT Project, a macroscope that continually monitors news in multiple formats, from across the world, in more than 100 languages as of 2024.



**Microscopes** are used to magnify minuscule objects. This image shows an adenovirus.

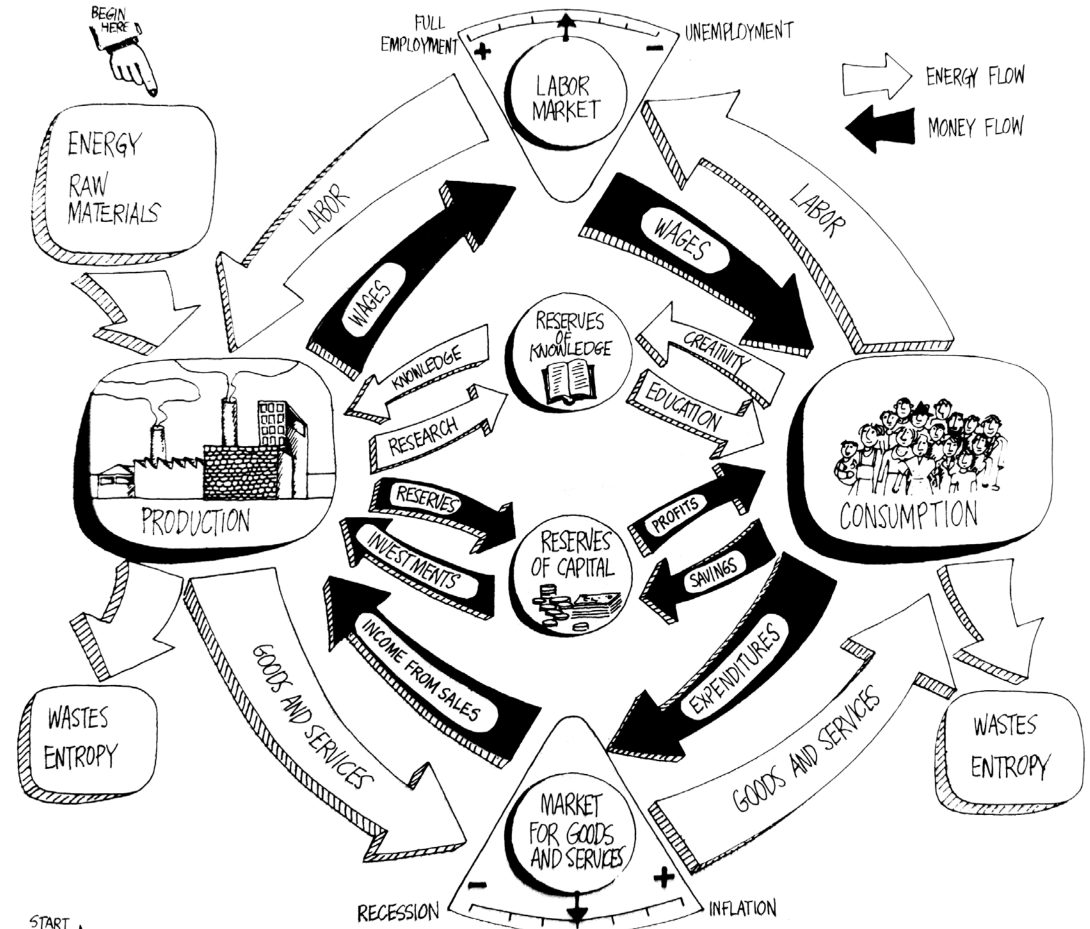
# Impactful and Memorable

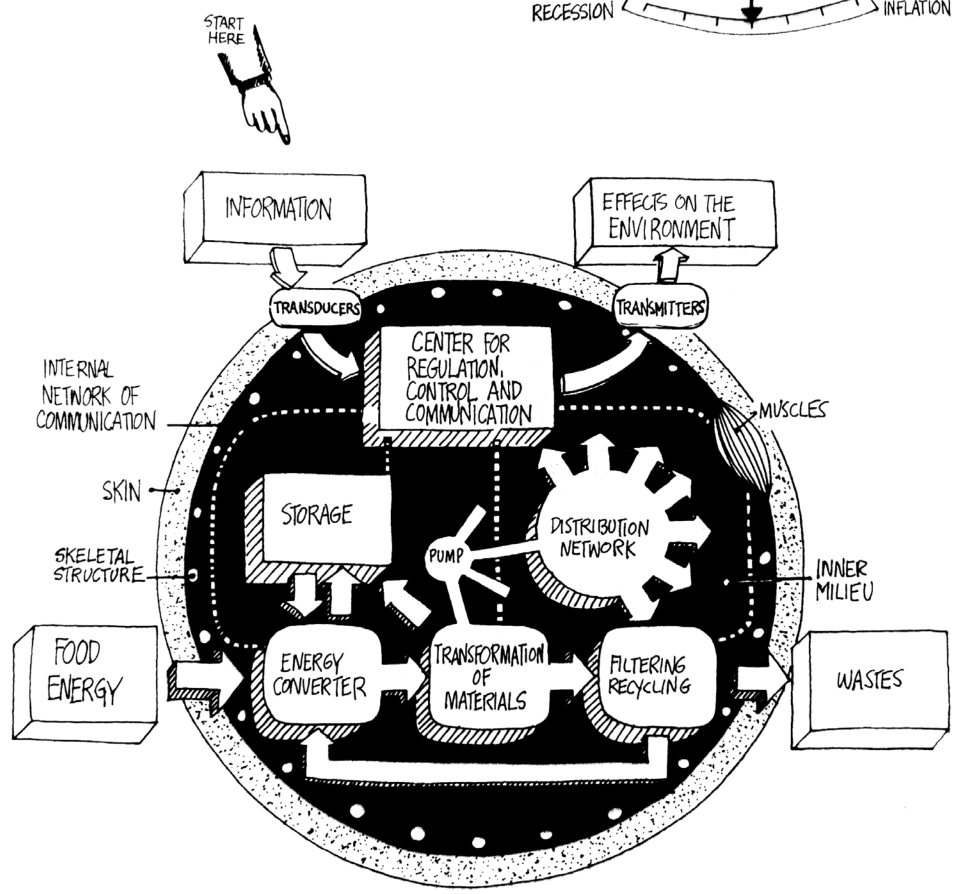
Macroscopes are remarkable tools with an interdisciplinary history. They encourage users to see the world through a systemic lens, providing new insights and allowing for deeply memorable experiences. Because they are interactive, they can support multiple viewpoints and different communication channels (such as visual, audio, and haptic). They invite their users to go on data adventures, discover new facts, and discern how the various elements of a system are interconnected.

## Origins

The term "macroscope" has appeared in many fields of study. During the 1950s, the term was used in forestry by Perry H. Merrill, in geography by Lawrence M. Sommers and Clarence L. Vinge, and in history by Philip Bagby. Over the next two decades, authors William A. Hargreaves and Kay H. Blacker used the term in psychiatry, Piers Anthony in science fiction, and Howard T. Odum in ecology. In these early appearances, the macroscope is described as a tool providing a holistic view of a topic.

In *The Macroscope: A New World Scientific System*, published in 1979, Joël de Rosnay expands the concept of a macroscope as a tool for observing and managing systems—see two examples on right. For de Rosnay, a French biologist and computer scientist with a strong focus on the future of research technology, the macroscope would be the "symbol of a new way of seeing and understanding." It was to be a tool "not used to make things larger or smaller but to observe what is at once too great, too slow, and too complex for our eyes."

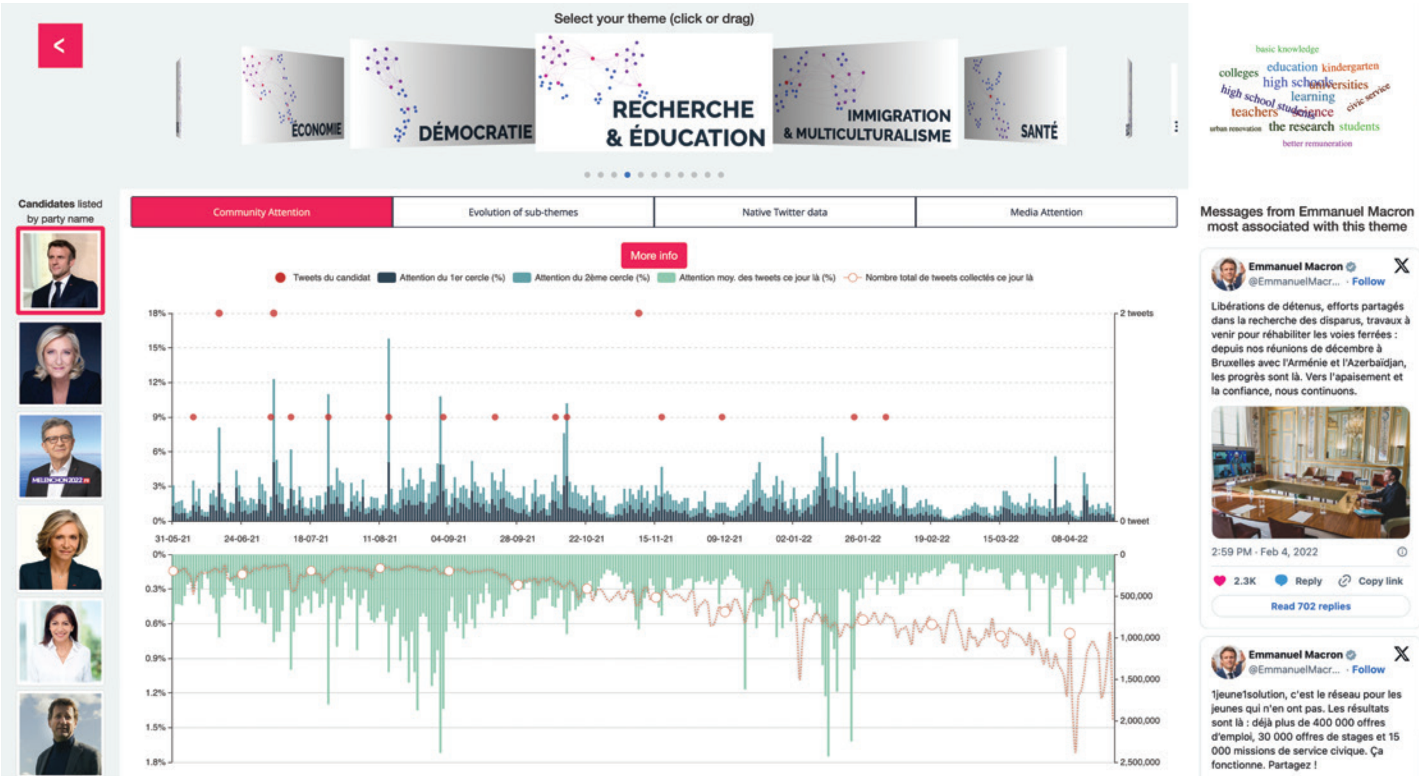


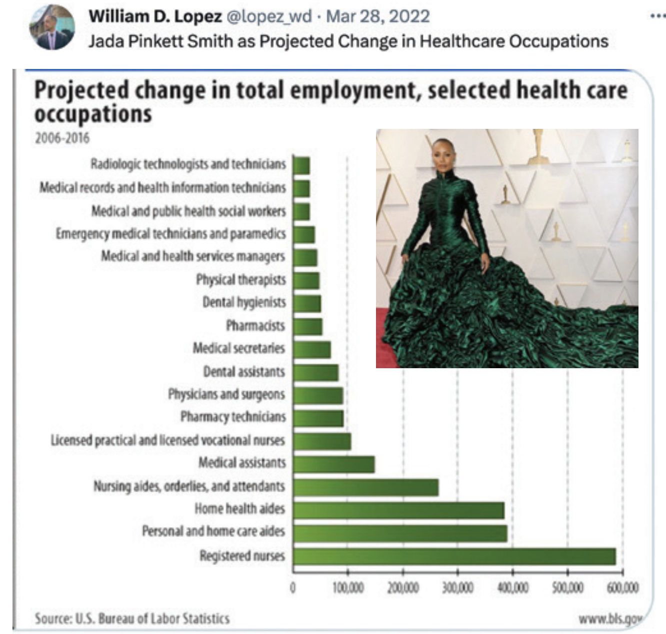




**Macroscopic views**
Illustrations from *The Macroscope* by Joël de Rosnay show models of complex systems that can be used to manage real-world systems.

Above left, we see the "functioning of the economic machine" when viewed as an open ecosystem, with the main flows of energy and money balancing each other.

Below left is a macroscopic view of the human body as a system of energy and information transformation, where the patterns and relationships evident in a living organization are repeated at multiple levels.




**Themes that resonate**

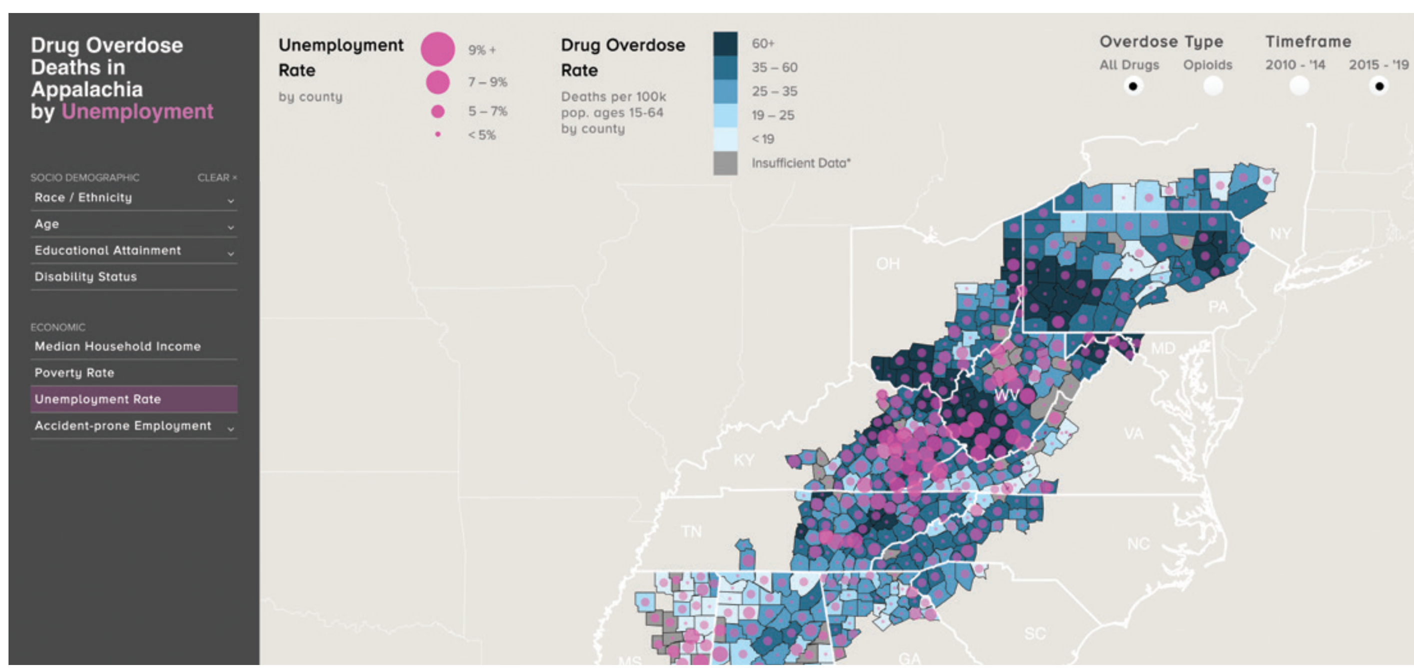
The macroscope *Politoscope* (page 72) is designed for citizens to analyze social media discourse by and about candidates in French elections. The dashboard overview allows citizens to view posts related to particular themes such as research and education (as shown above), immigration and multiculturalism, the economy, and the environment. Filtering the information so that it can be viewed through the lens of themes that are of particular interest to the user means the information is timely, relatable, and memorable.

# Memorable

Unexpected or distinctive events that cause an emotional response are memorable. William D. Lopez's series of tweets pairing Oscars outfits with public health graphs surprises us with its juxtaposition of disparate topics. Each data visualization is mirrored by a celebrity photograph from the red carpet—such as that of Jada Pinkett Smith (above), whose emerald-green gown echoes the projected change in healthcare occupations.

# Impactful

Macroscopes can be especially powerful when they help policymakers, frontline workers, and other experts solve complex social, technical, or environmental problems. Developed at the height of the opioid epidemic in 2019, the *Appalachian Overdose Mapping Tool* (on right and on page 64) was designed to help the Appalachian Regional Commission, a federal economic development agency, determine which factors correlate with increased rates of opioid overdose at the county level. Drug prevention or increased policing is often the first solution proposed by policymakers to combat overdose cases. Using this macroscope, community members could use data and research studies to demonstrate how factors like broadband access, proximity to highways, and the availability of mental health services may have a much larger and longer-lasting impact.

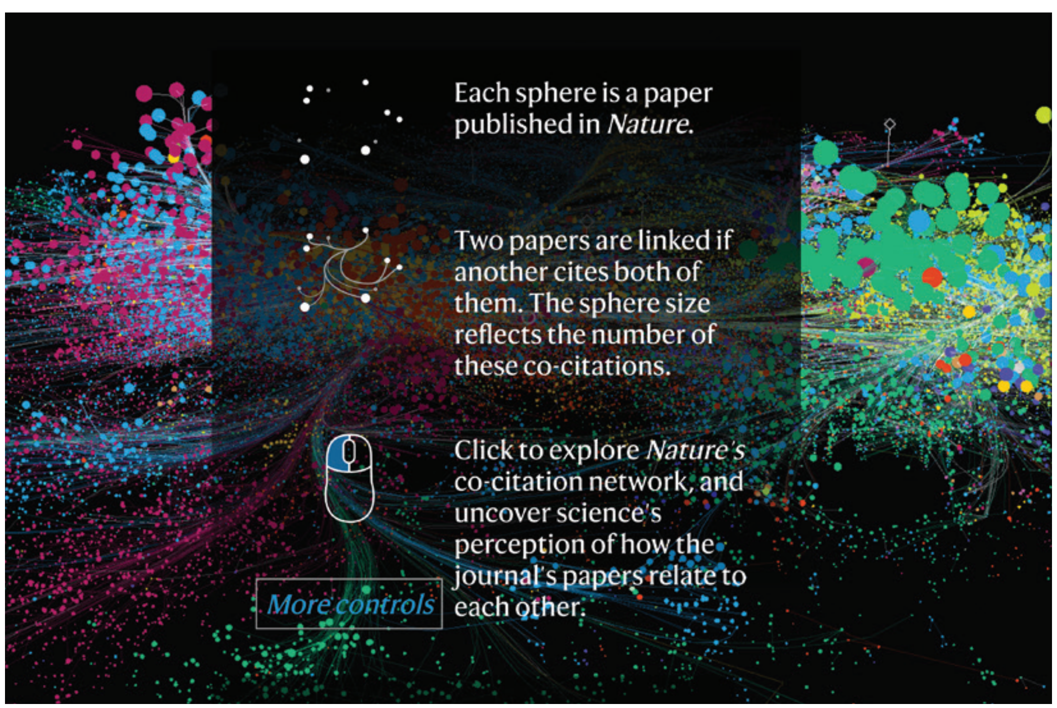


# Interactive and Tangible

Interactive visualizations are powerful tools for data analysis and exploration, with far-reaching possibilities. You can examine 150 years of publications in *Nature 150* (page 88), travel the world with *River Runner* (page 126), or study the stars using *Star Mapper* (page 102).

## Interactive

Two-dimensional data visualizations, when printed and exhibited, are already rich in detail, inviting you to lean in, get lost in the imagery, and learn from the content. Macroscopes go further by enabling you to zoom, filter, and access seemingly endless layers of detail. As well, macroscopes that provide robust filters and combine multiple complex datasets are invaluable for generating hypotheses and communicating insights. Interaction supports the customization of data explorations, making data adventures more engaging and memorable. Frequently, tutorials or other forms of guidance are employed to introduce users to the range of possible actions—such as the animated introduction used for *Nature 150* (page 88, see detail below) and the "example tour" given in *The Whole Picture* (page 128).



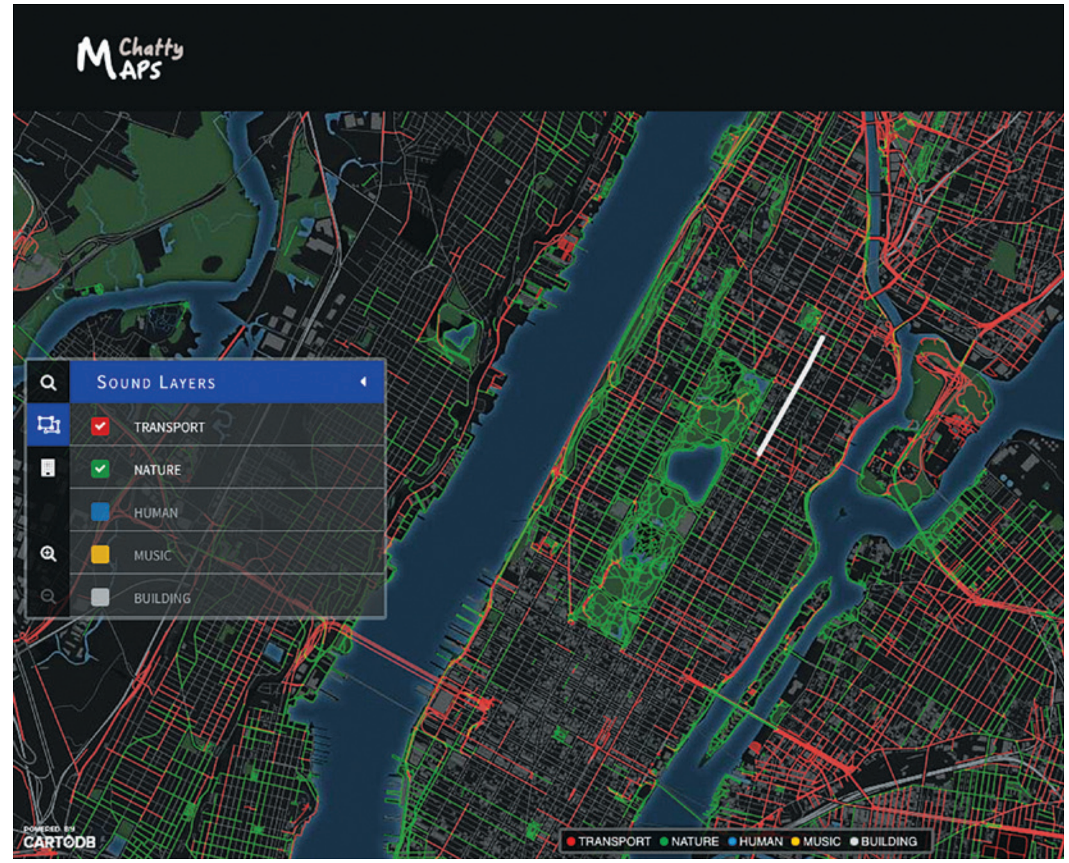

**Individualized adventures**
Guided interactions shape users' data explorations.


**Experiential data encounters**
Here, a child wanders through a 3D map showing the geographical locations of 8 billion humans on Earth.

# Tangible

Online technology can be alienating. Since we absorb so much information through our senses, tangible data visualizations can help us anchor data in a given place or time, so that the physical setting and our own body movements work to ground that data in physical reality. Thus, literally touching the embodied data allows us to feel touched by it—informed, inspired, or otherwise moved by that data.


**Relatable comparisons**
Hans Rosling used everyday objects in his talks to make data tangible. In his TED Talk on income inequality and population, colored boxes are used to signify 1 billion people in either the industrialized (blue) or developing (green) worlds.




**Sensory experiences**
Good City Life, the team behind *Smelly Maps* (page 36), has taken on the challenge of mapping different sensory experiences in urban landscapes. In the *Chatty Map* of New York City above, they convert Central Park's nature sounds into visual green space, surrounded by the red traffic noises that dominate most cityscapes.

***Shape of Science*** is a three-foot-tall clay sculpture that makes the history of science tangible by giving it a physical, three-dimensional form that invites playful interaction. The sculpture embodies the idea that science, like mushrooms, can grow in many directions. Mushroom-shaped shelves represent different areas of science—from philosophy and astronomy at the base, to neuroscience, nanoscience, and other areas on top. There are five main branches of science, and many shelves span multiple branches, symbolizing interdisciplinary connections. As time progresses upwards, science grows in scope and activity. There is growth toward the future and erosion in the past. Ideas serve as nutrients, spawning new outgrowths. Shelves differ in size, indicating the volume of scientific research in each area. Pathways tunnel through the sculpture so that visitors can trace the evolution of scientific ideas back to their origins, using marbles; they simply place a marble at the top, contemporary level and observe the areas of science it travels through before it reaches the bottom. Since many sciences draw on more than one area of research, different runs will result in alternative marble trajectories. Some intellectual journeys are gentle, steady paths, while others make for a wild ride.

# Systematic and Iterative Design

Data visualization design is a systematic, iterative process that addresses specific user needs and questions. It can be taught, learned, and effectively practiced.

**Using data visualizations to answer questions**
Macroscopes render complex data into actionable knowledge. They help people answer the fundamental questions of *when*, *where*, *what*, and *with whom* (see examples at right). Some macroscopes even employ predictive computational models to help users understand *why* we see certain trends, patterns, and outliers in the given data.

**Data Visualization Literacy Framework**
The *Atlas of Forecasts* introduced a modeling framework for transforming high-quality data into easy-to-understand data visualizations to guide data-driven decision-making. A typology of key terms, major process steps, and widely used graphic symbols and variables are given on the opposite page.

## Questions

**When?**
Graphs that depict temporal data to show trends and/or seasonality are commonly used to answer questions about timing, trends, or rhythms.

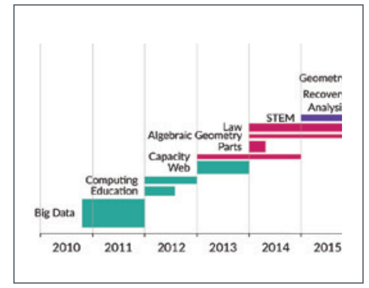
**Where?**
Geospatial data and maps are widely used to understand the impact of space, to navigate to new places, or to map future geospatial events.

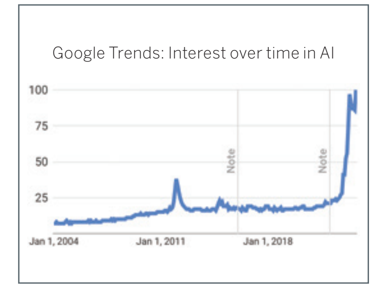
**What?**
Linguistic, text-based analysis is widely applied to analyze written, spoken, or generated text to identify frequently used words, evolving topics, or interdependent lines of thought.

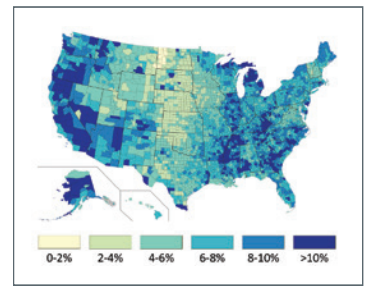
**With whom?**
Network data, analyses, and visualizations prove valuable for understanding the types of interactions (namely social, professional, or topical) between groups of individuals.

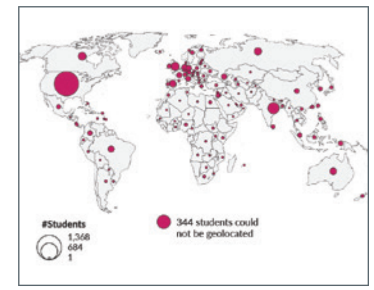
**Why?**
Data models that aim to predict the patterns we see in real-world data can help us understand why certain structures and functions emerge, thrive, or die, and how they might evolve in the future.

## Exemplary Visualizations

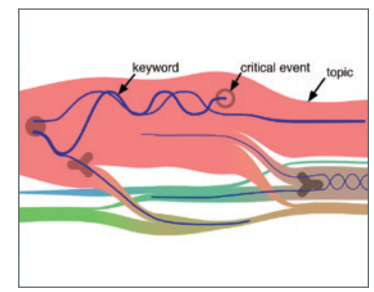


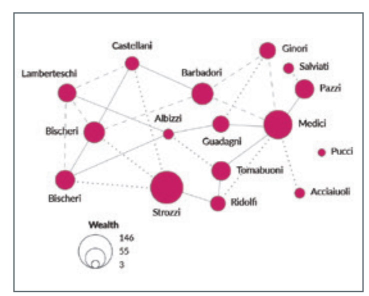



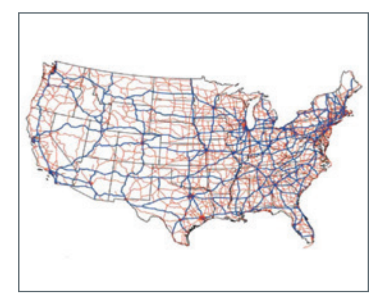



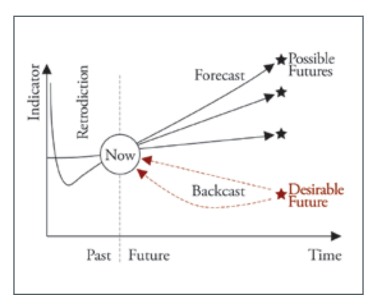



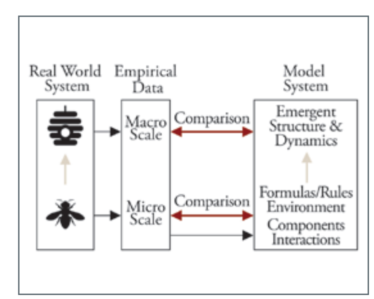






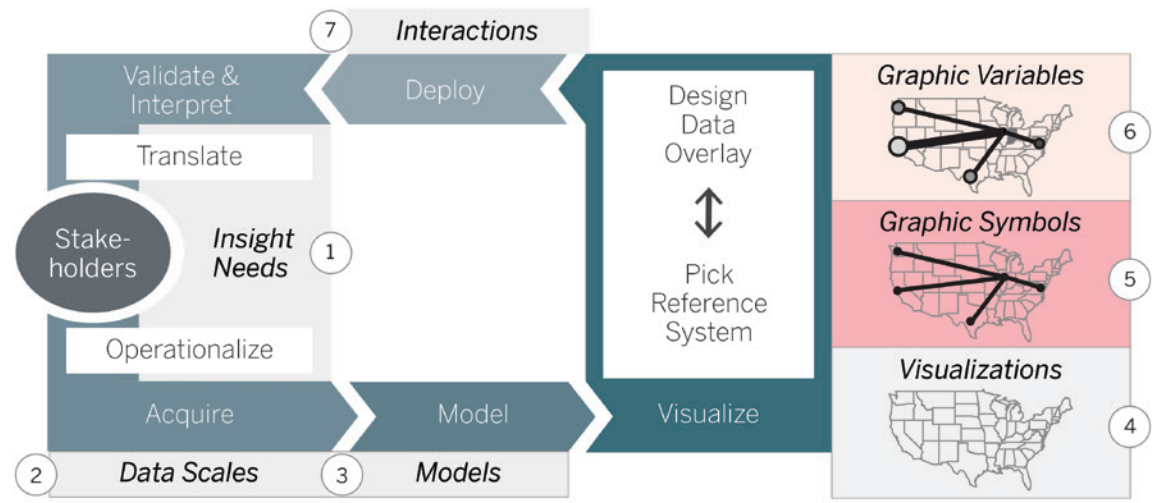
# Typology

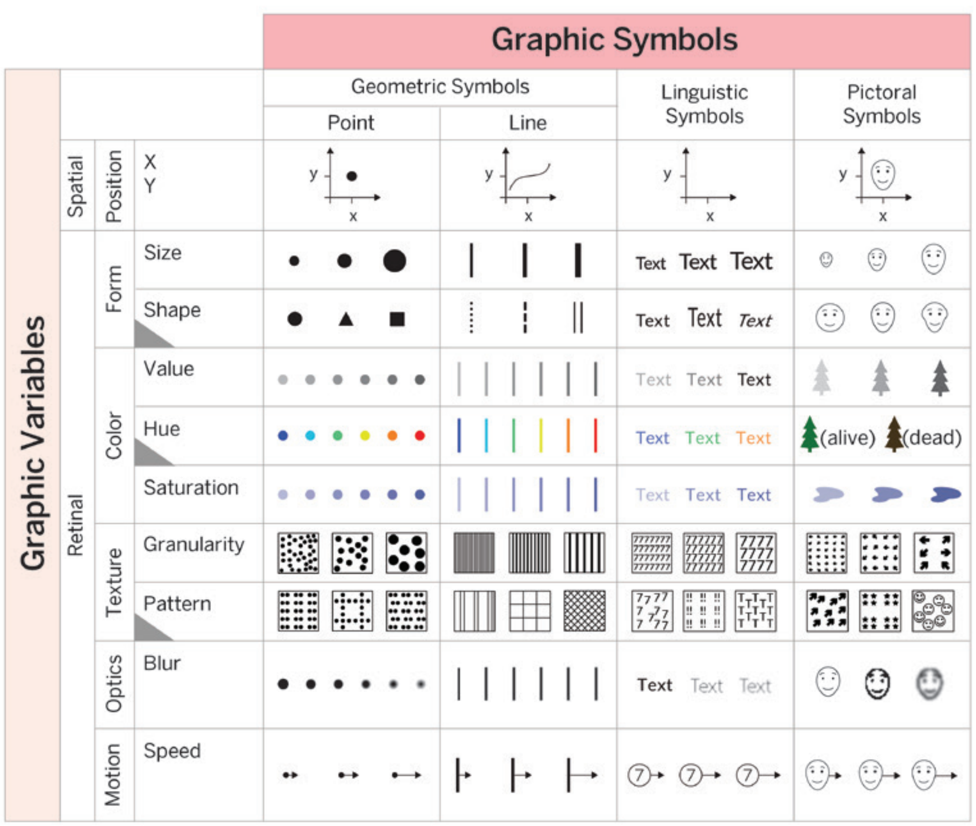
The Data Visualization Literacy Framework (DVL) defines a typology of core concepts. Insight need types provide guidance on what a user wants to understand—from basic insight needs (categorization, sorting, temporal, or network questions) to dynamic phenomena (modeling goals such as synchronization, phase transition, adaptation, and learning). Data scales cover nominal, ordinal, interval, and ratio data based on the types of logical mathematical operations that are permissible. Models might be descriptive (such as statistical temporal or topical analyses) or predictive. Visualization types include tables, charts (like pie charts), graphs (like scatterplots), maps, trees, and networks. Graphic symbols and variables are detailed below. Interactions include such functionalities as zoom, search and locate, filter, details on demand, history, extract, link and brush, projection, and distortion.

| 1 Insight Needs | 2 Data Scales | 3 Models | 4 Visualizations | 5 Graphic Symbols | 6 Graphic Variables | 7 Interactions |
|---|---|---|---|---|---|---|
| *Basic*<br>• categorize/cluster<br>• order/rank/sort<br>• ...<br>*Phenomena*<br>• oscillation<br>• synchronization<br>• ... | • nominal<br>• ordinal<br>• interval<br>• ratio | • descriptive<br>• predictive | • table<br>• chart<br>• graph<br>• map<br>• tree<br>• network | • geometric symbols<br>• linguistic symbols<br>• pictorial symbols | • spatial position<br>• retinal<br>form<br>color<br>optics<br>motion | • zoom<br>• search and locate<br>• filter<br>• details-on-demand<br>• history<br>• extract<br>• link and brush<br>• projection<br>• distortion |

# Process

There are six major steps in developing a visualization: identify stakeholders and their insight needs, acquire data, model data, visualize data, deploy the visualization, and validate and interpret the visualization with stakeholders. The seven typology terms serve to guide process design, implementation, and documentation.




# Graphic symbols and variables

Graphic symbols can be geometric (point, line, area, surface, volume), linguistic (text, numerals, and punctuation marks), or pictorial (images, icons, and statistical glyphs).

Graphic variables are grouped into spatial variables (describing spatial position) and retinal variables; the latter are further divided into form (size, shape, rotation, curvature, angle, closure), color (value, hue, saturation), texture (spacing, granularity, pattern, orientation, gradient), optics (blur, transparency, shading, stereoscopic depth), and motion (speed, velocity, and rhythm). Qualitative nominal variables (shape, hue, and pattern) each have a gray triangular mark.

Different graphic symbols and variable types can be combined. For example, a geometric symbol can be both color- and size-coded and might also have an associated linguistic symbol label.

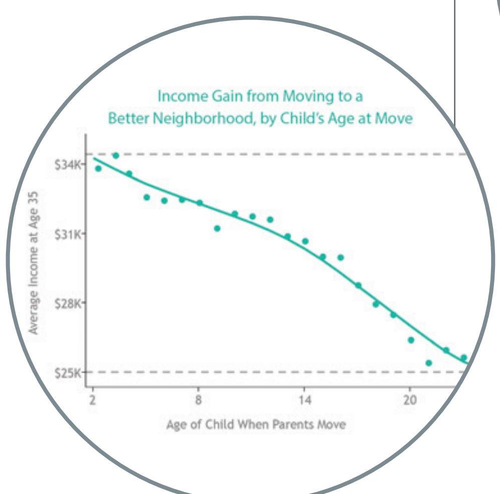
# Design Examples

## Opportunity Atlas

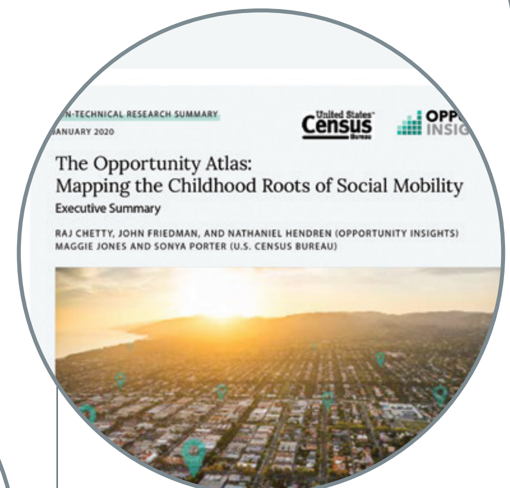
The *Opportunity Atlas* (page 92) makes searchable a vast collection of demographic and economic data that allows U.S. city councils, mayors' offices, and community organizers to better understand and address economic inequality in their own locales.

**Acquire data**
The original research, conducted by Opportunity Insights, used the anonymized data of 20 million Americans from three sources housed at the U.S. Census Bureau: (1) the Census 2000 and 2010 short forms; (2) federal income tax returns from 1989, 1994–1995, and 1998–2015; and (3) the Census 2000 long form and the 2005–2015 American Community Survey (ACS) forms.

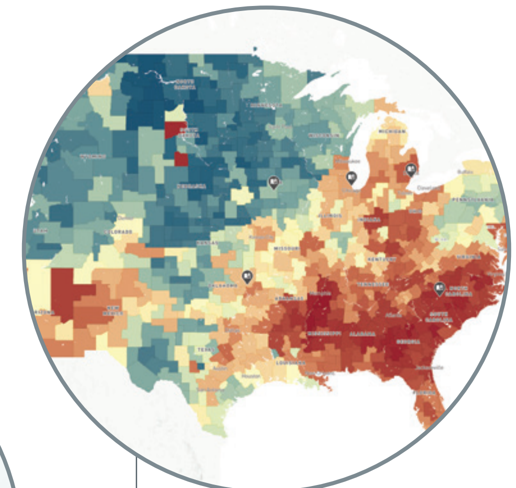

**Analyze and visualize data**
The researchers then generated tract-level estimates through nonlinear and exposure-weighted regression, which led to key findings such as that shown below: moving to a better neighborhood earlier in childhood can improve economic mobility in adulthood, with an increase in income by several thousand dollars.




**Deploy and interpret data**
The results were then published in October 2018 as a National Bureau of Economic Research working paper. News of the *Opportunity Atlas* reaches several popular publications, newspapers, and television news segments.




**Iterate to improve visualization**
Produced collaboratively by the paper's authors and the design team at Darkhorse Analytics, the *Opportunity Atlas* is an interactive visualization that allows users to explore and engage with the report's data. The study continues to be a topic of conversation in economics journals, academic blogs, and university postings.

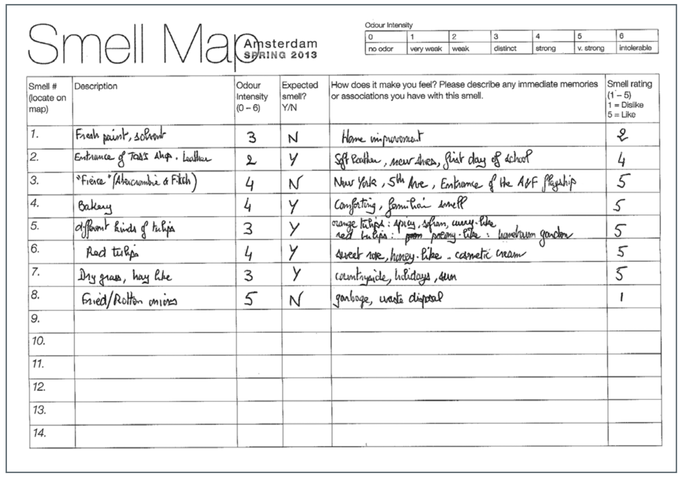


# Smelly Maps

*Smelly Maps* (page 36) makes it possible to visually explore and compare the smells of different cities.

**Take a smell walk**

Macroscope makers recruited locals to take “smell walks” around their city and record distinct odors in terms of location, intensity, personal associations, and other information (see form at right). Below is an Amsterdam city map overlaid with the notes of participants via color-coded, geobased loops.

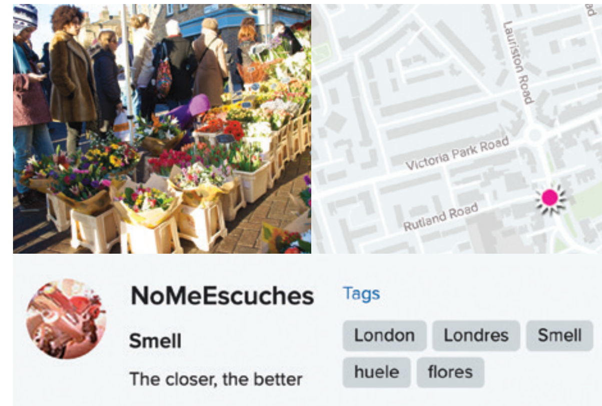


Smell Map Amsterdam SPRING 2013

Odour Intensity

| 0 | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| no odor | very weak | weak | distinct | strong | v. strong | intolerable |

| Smell # (locate on map) | Description | Odour Intensity (0 – 6) | Expected smell? Y/N | How does it make you feel? Please describe any immediate memories or associations you have with this smell. | Smell rating (1 – 5) 1 = Dislike 5 = Like |
|---|---|---|---|---|---|
| 1. | Fresh paint, solvent | 3 | N | Home improvement | 2 |
| 2. | Entrance of Tod's shop. Leather | 2 | Y | Soft leather, new shoes, first day of school | 4 |
| 3. | "Fierce" (Abercrombie & Fitch) | 4 | N | New York, 5th Ave, Entrance of the A&F flagship | 5 |
| 4. | Bakery | 4 | Y | Comforting, familiar smell | 5 |
| 5. | different kinds of tulips | 3 | Y | orange tulips: spicy, saffron, curry-like<br>red tulips: ~~pom~~ peony-like: hawthorn garden | 5 |
| 6. | Red tulips | 4 | Y | sweet rose, honey-like . cosmetic cream | 5 |
| 7. | Dry grass, hay like | 3 | Y | countryside, holidays, sun | 5 |
| 8. | Fried/Rotten onions | 5 | N | garbage, waste disposal | 1 |
| 9. | | | | | |
| 10. | | | | | |
| 11. | | | | | |
| 12. | | | | | |
| 13. | | | | | |
| 14. | | | | | |

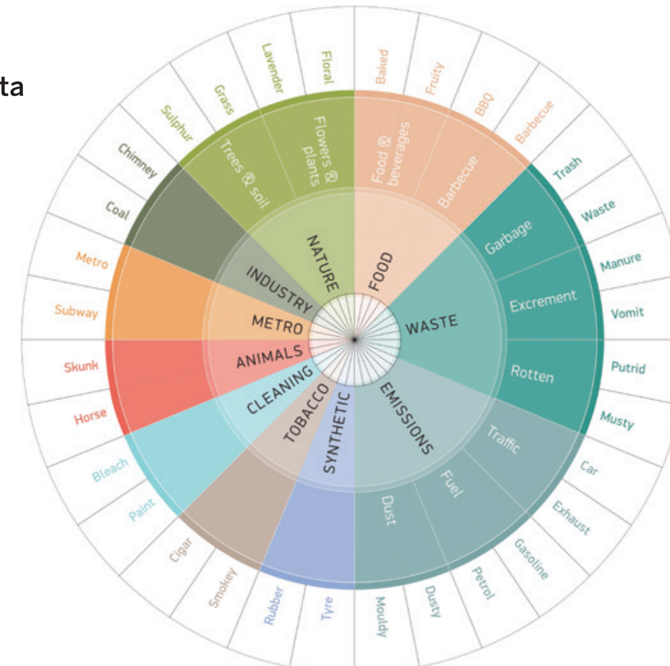




**Acquire data**

Researchers used descriptions from the smell walks to search social media for geotagged smell posts, like this flower-related one from Flickr user NoMeEscuches.

**Analyze data**

The Smellscape Aroma Wheel shows the co-occurrence of descriptive terms, grouped by categorial clusters for semantically similar words. Here, the 10 main cluster terms appear in black type near the center, while examples of constituent words reside in the outer ring.




**Visualize data**

Street segments (the sections of a street between two intersections) were identified using OpenStreetMap, a collection of crowdsourced online maps. Data from smell walks and social media were mapped onto those segments. The inset at left, atop a London road map, shows a *Smelly Map* indicating where London’s nature smells are concentrated.

# Explainable and Accessible

Over the last decade, interactive data visualizations have evolved in response to technological advances, societal needs, and cultural trends. Two key changes are the efficient usage of data storytelling and design for broad accessibility.

## Storytelling

Macroscopes that create stories using data as evidence can be powerful tools for explanation and inspiration. Stories bring context to data insights and inspire actions. Often, people need to be touched emotionally in order to change their behavior for the better. Data stories have the power to elicit emotions, show how given elements are interconnected, and ultimately cause positive changes in personal, institutional, and global narratives, by answering the implicit yet universal question of "Why should I care?"

Data storytelling can take many formats, some more interactive than others. Written narratives, videos, and scrollytelling all lend themselves to shaping a storyline that fleshes out the data and makes it more memorable.

**Our bodies are wired for stories**

When we are drawn into a story, our bodies produce and release various hormones. With cortisol, our palms may get sweaty and our hearts race as the protagonist faces challenges and the story builds to a climax. Oxytocin keeps us connected to the characters and makes us care. As the plot resolves, the satisfaction of a good ending triggers the release of dopamine, the "feel good" neurotransmitter.

**The shapes of stories**

Author Kurt Vonnegut described how typical story plots can be visualized as graphs, where the x-axis represents good fortune/bad fortune and the y-axis represents time—from the beginning of a story to the conclusion. The graphs below visually represent the increasing tension as a story builds to a climax, the fortunes of the protagonists change, and plot twists emerge.

### Man in Hole

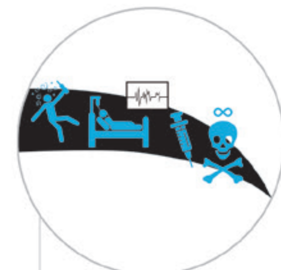
The main character gets into trouble then gets out of it again and ends up better off for the experience.

Arsenic and Old Lace
Harold & Kumar Go To White Castle

### Boy Meets Girl

The main character comes across something wonderful, gets it, loses it, then gets it back forever.

Jane Eyre
Eternal Sunshine of the Spotless Mind



### From Bad to Worse

The main character starts off poorly then gets continually worse with no hope for improvement.

The Metamorphosis
The Twilight Zone

### Which Way Is Up?

The story has a lifelike ambiguity that keeps us from knowing if new developments are good or bad.

Hamlet
The Sopranos

### Creation Story

In many cultures' creation stories, humankind receives incremental gifts from a deity. First major staples like the earth and sky, then smaller things like sparrows and cell phones. Not a common shape for Western stories, however.

### Old Testament

Humankind receives incremental gifts from a deity, but is suddenly ousted from good standing in a fall of enormous proportions.

Great Expectations

### New Testament

Humankind receives incremental gifts from a deity, is suddenly ousted from good standing, but then receives off-the-charts bliss.

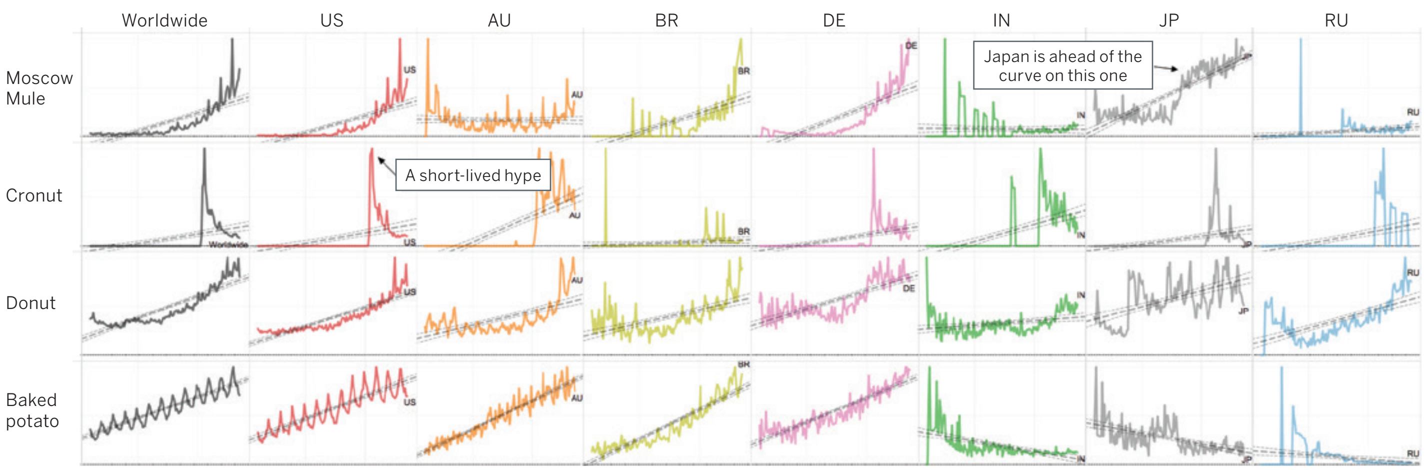
Great Expectations
*w/ Dickens Alternate Ending*

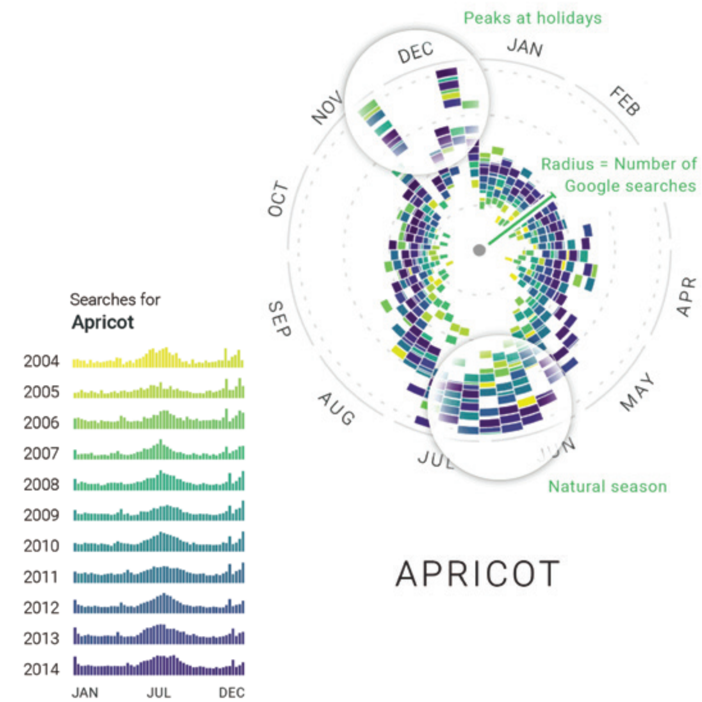
### Cinderella

It was the similarity between the shapes of Cinderella and the New Testament that thrilled Vonnegut for the first time in 1947 and then over the course of his life as he continued to write essays and give lectures on the shapes of stories.

# Rhythm of Food

The *Rhythm of Food* (page 62) mines Google search terms and uses an innovative visualization type, called "year clocks," to highlight seasonal trends related to food. This design decision drastically improves the ability of the interactive visualization to convey information.




### Seasonality of food

The *Rhythm of Food* macroscope began as a tool to measure regional, year-by-year fluctuations in culinary interest. However, as creator Moritz Stefaner looked at the data visualizations that emerged, he became interested in food's seasonality and how the design could highlight those patterns. In the graph above, the linear nature of the timelines highlights long-term trends. One major pattern is the long-term rise and fall in popularity of certain foods in certain regions: for example, the popularity of the baked potato steadily rises in most countries, but not in India, Japan, and Russia. Another clear pattern can be seen when a food becomes trendy and Google searches soar as people rush online to learn more; for instance, U.S. interest in the Cronut peaked intensely yet briefly in 2013.

### Showing seasonality

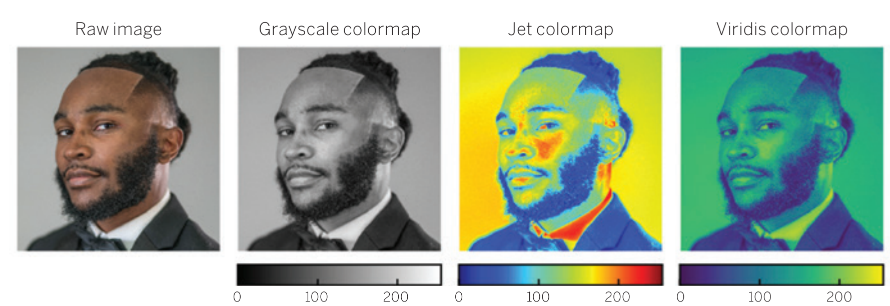
The illustration above shows linear, year-by-year timelines changing into year clocks, a custom radial chart that Stefaner designed specifically for this project. All the information displayed in the linear timelines also appears on the year clocks. The layout of the latter, however, accentuates annual seasonality while preserving long-term fluctuations of interest.

## Accessibility

The W3C Accessibility Initiative provides international accessibility standards and resources for developing materials that can be used as broadly as possible. Color choices, font choices, use of screen readers, and data provided in alternate formats can all affect ease of use and access to content.

*Rhythm of Food* was designed using the Viridis color scale (above), created by Stéfan van der Walt and Nathaniel Smith as an alternative to the widely used Jet color palette (below).

The intent was to create a color scale that would be perceptually uniform so as to better depict fine gradations in the data, render intelligibly in grayscale, and be more pleasing to the eyes (see comparison at right).




Viridis is also historically important as its choice of colors represents the growing sensitivity to color-blindness—the inability to distinguish between certain colors, particularly red and green.

# *Places & Spaces* Through the Years

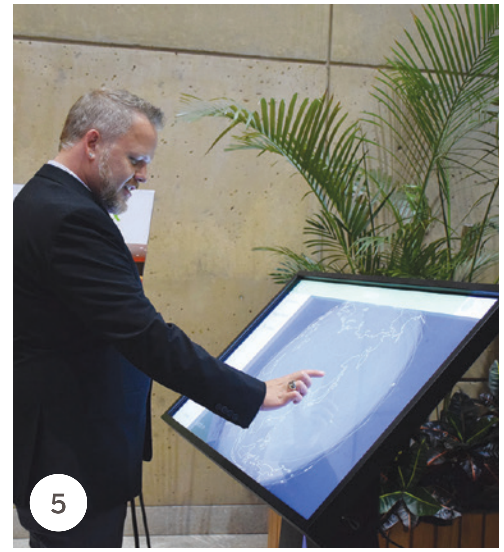
From 2005 to 2014, the *Places & Spaces: Mapping Science* exhibit brought 10 new maps of science to the general public annually. By the end of that first decade, the exhibit had grown to encompass not only 100 science maps, but also an interactive display of worldwide scientific endeavors, hands-on activities for kids, illuminated globes, an award-winning animated film, and an informative and dynamic website.

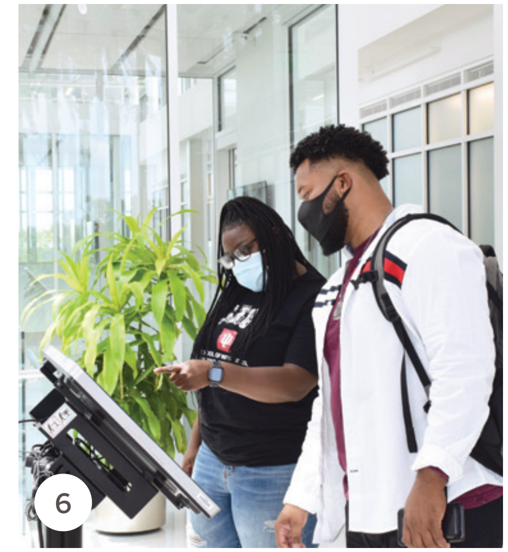
In its second decade, from 2015 to 2024, *Places & Spaces: Mapping Science* presented the perfect opportunity for the exhibit to explore new territory. We moved beyond the frames of the static maps of science and into the world of macroscope tools for interacting with science.

To accomplish this, we needed a new "frame" to display interactive visualizations developed by experts around the globe. We decided to use a large touchscreen kiosk as hardware. Our team implemented software to run macroscopes developed using different programming languages in a unifying technical setup. The Macroscope Kiosk user interface supports browsing and interacting with the 40 macroscopes in a communal setting in museums, libraries, and other public places.

① Visitors enjoying science maps from the exhibit's first decade at the 2015 International Science Festival in Gothenburg, Sweden; ② The 2017 Gordon Research Conference in Lewiston, Maine; ③ Todd N. and Andrew Theriault selecting publications of interest on the *AcademyScope* visualization, 2015.

Today, 40 macroscopes can be explored via a touchscreen kiosk that provides visual and technical coherence—serving as an exciting entry point for exploring the world of science interactively.



④ The debut of the *Places & Spaces* 18th iteration, "Macroscopes for a New Perspective," at the University of Michigan's Clark Library, 2022; ⑤ Exploring the *Earth* macroscope at the IU Art Museum, 2016; ⑥ Students enjoying the macroscopes in Luddy Hall, Indiana University, 2020; ⑦ The exhibit team viewing André Skupin's *Coronavirus SoS*, 2023; ⑧ Science Fest 2019, Indiana University; ⑨ First Thursdays at Indiana University, 2019.


Over the last 20 years, the exhibit has traveled to 466 venues in 167 cities in 30 countries on six continents. Some venues are shown here and many more are captured at **scimaps.org** and in the exhibit's annual reports on our Zenodo community page (**zenodo.org/communities/macroscopes**). There are 8 million website visits, 215 press releases, and the exhibit team co-organized 41 workshops on data visualization and science mapping.





① Using Science On a Sphere (SOS) to display maps of science at the 2015 SC (formerly Supercomputing) Conference in Austin, Texas; ② Scott Weingart and Todd N. Theriault prepare for the 17th iteration debut at the University of Notre Dame, 2021; ③ Katy Börner bringing maps of science to Morgenstern Books in Bloomington, Indiana, 2021; ④ Elizabeth G. Record introducing Science Fest visitors to the *Virus Explorer*, 2021.


⑤ Macroscope Kiosk, 2019; ⑥ Science Centre World Summit in Tokyo, Japan, 2017; ⑦ Indiana Governor Eric Holcomb meets *Amatria*, 2019; ⑧ Exhibit assistant Ezra Engels demonstrating macroscopes at Indiana University's annual Science Fest, 2022; ⑨ CNS research scientist Andreas Bueckle showcases the latest gear in VR data visualization, 2022; ⑩ Todd N. Theriault's avatar leads a virtual exhibit tour, 2022; ⑪ Rita Colwell, Ben Shneiderman, James Hendler, Katy Börner, and Peter Arzberger at the AAAS Annual Meeting, 2016; ⑫ Panel discussion at the IEEE CIS 2017 conference.

# 40 Macroscopes in 10 Years

The 40 macroscopes can be grouped topically into eight themed categories (listed below left). Each map in the visual timeline (below right) is coded with the icon of the most appropriate category.

### Communication and Culture

Exploring how the social fabric is woven through art, music, literature, digital content, and other channels through which we communicate the human condition.

### Economy

Understanding the flow of financial resources and how their distribution affects how people experience the world.

### Global Relations

Tracing how interactions among sovereign states impact international trade, economy, migration, and the state of peace.

### Health and Well-Being

Visualizing how social and economic standing impacts health, education, and human flourishing.

### Knowledge and Scientific Research

Reflecting on the nature of knowledge creation and acquisition, of scientific inquiry and progress.

### Natural World

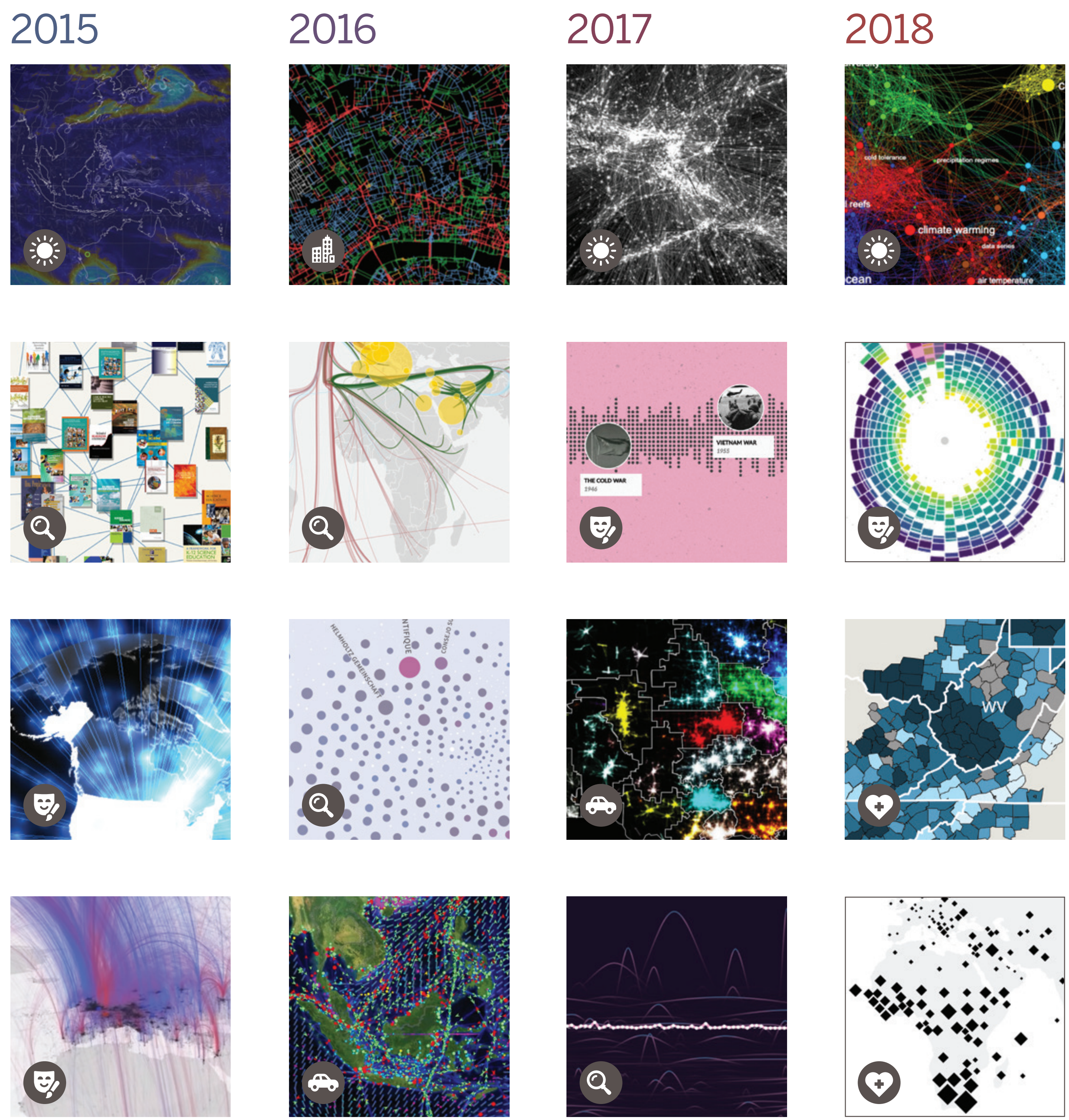
Understanding our planetary home and how we manage its resources, to the world beyond our solar system.

### Transportation

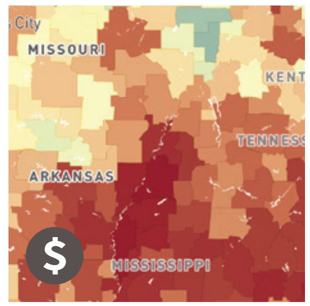
Tracing the patterns of movement that impact the flow of traffic and products and that otherwise shape our lives.

### Urban Landscapes

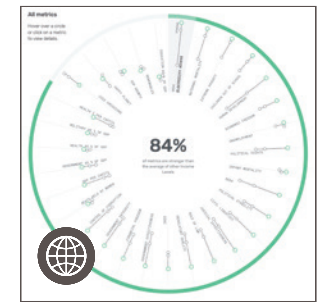
Mapping, understanding, and optimizing the urban environment that is home to more than half of the world's population.

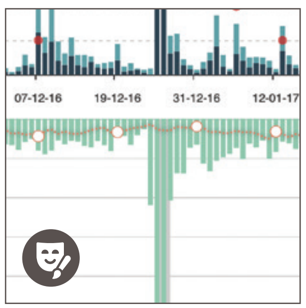


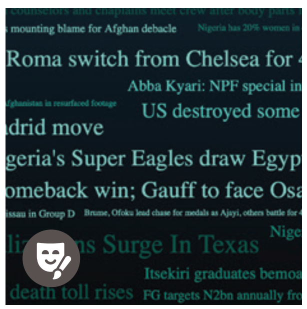
2019 2020 2021 2022 2023 2024

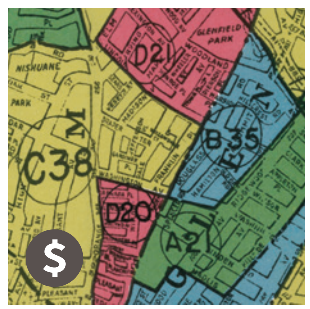





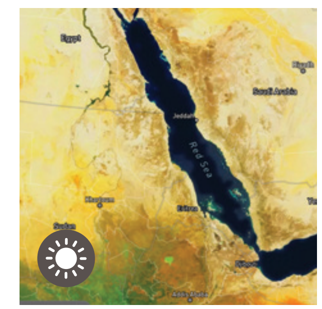


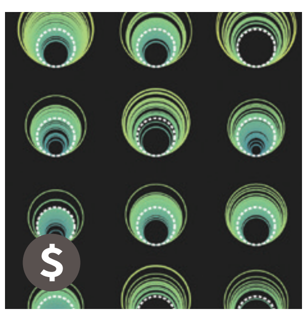



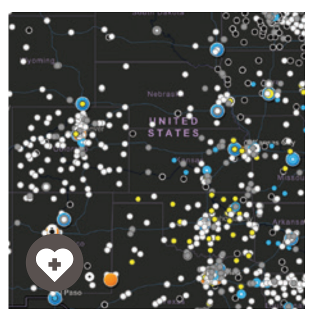



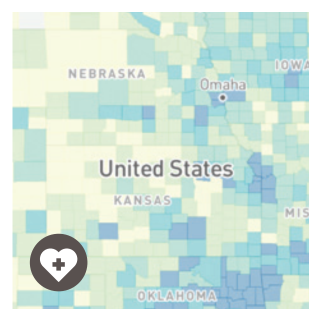





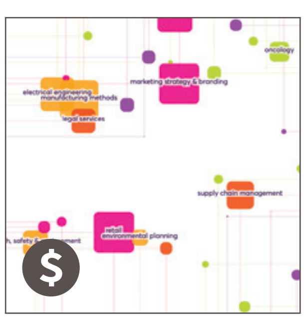


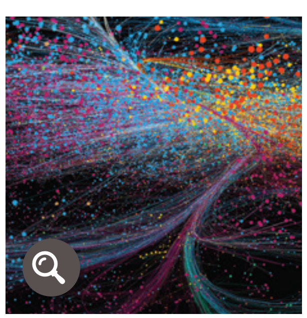


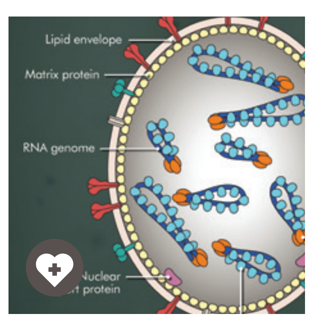



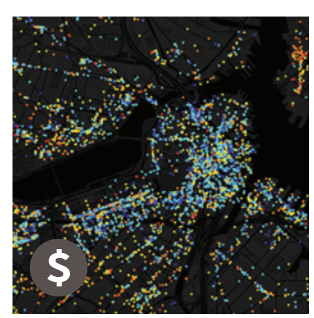


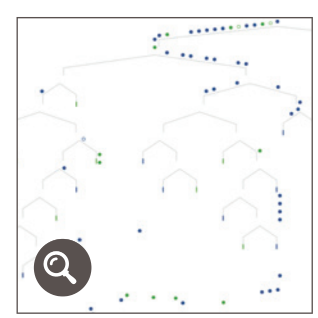


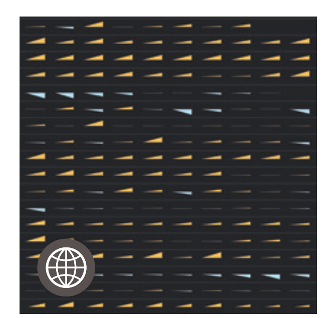


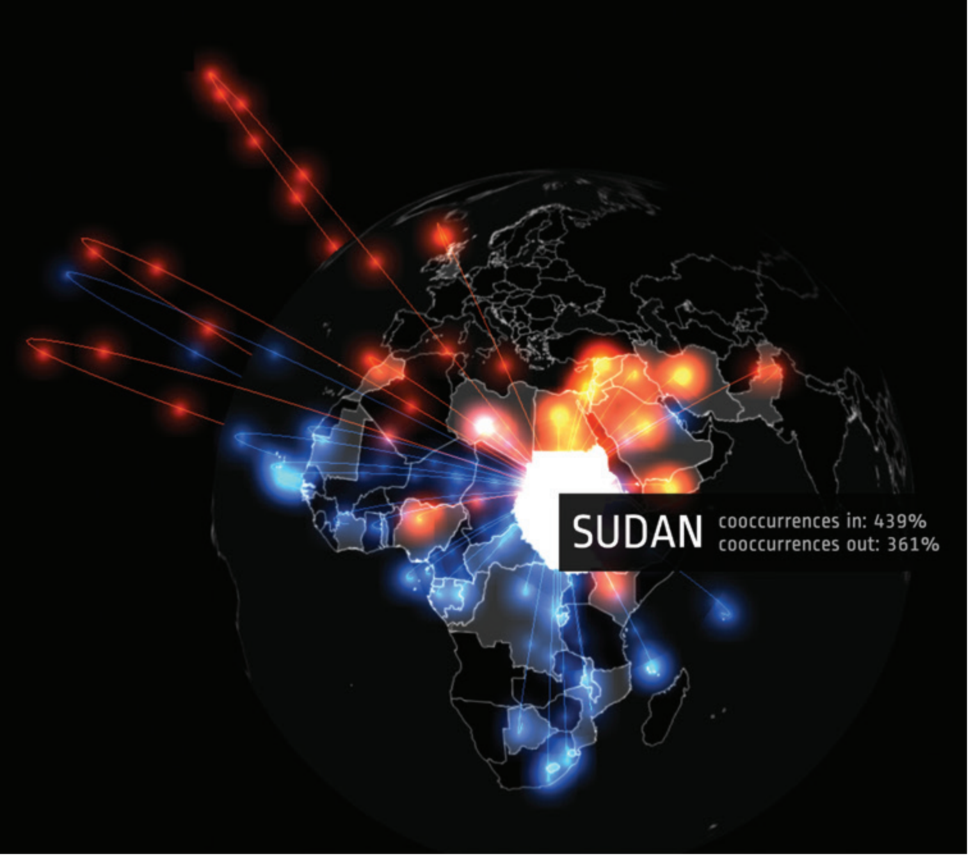










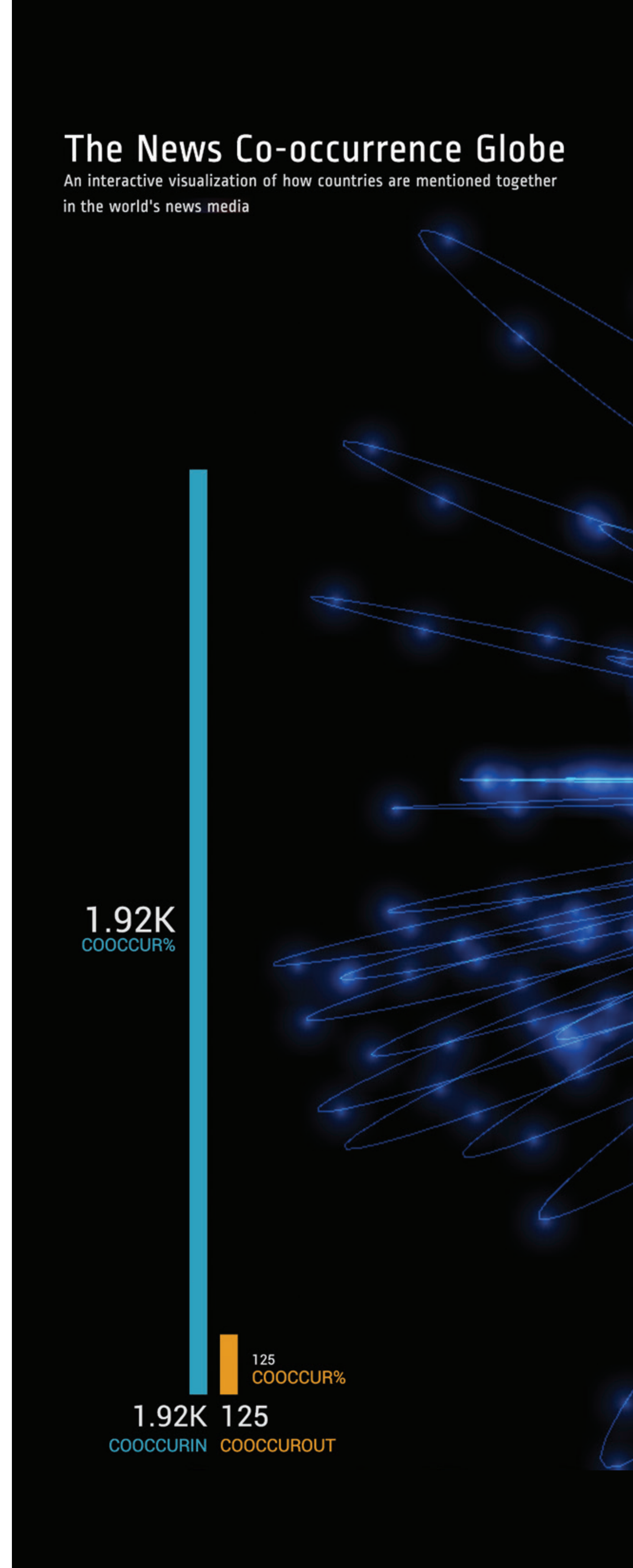

**The pulse of connectivity**
In this example of Sudan from the week of April 5–11, 2015, the red outgoing lines mean that 10% or more of the news stories mentioning Sudan also mentioned destination countries such as Saudi Arabia, Pakistan, the United Kingdom, and Israel, among others. Blue incoming lines mean that 10% or more of any news stories mentioning source countries such as Lesotho and Botswana, among others, also mention Sudan. The size and frequency of energy pulses along connecting lines indicate the strength of those connections based on the number of times two countries are co-mentioned in news stories.

# Mapping Global News

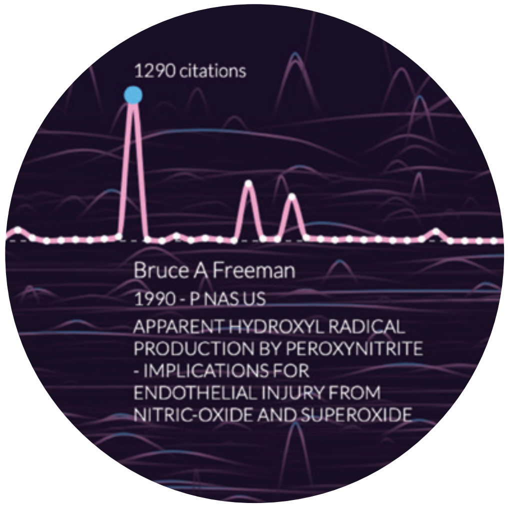
**MAKER**
Kalev Leetaru

**YEAR**
2015

Most often, the news we consume reflects our own local or national perspective. But what if we could see what "local" news looks like around the world? Would this global view change how we assign importance to our own issues and priorities? Drawing on data from news stories published in 65 languages, *Mapping Global News* gives us a broader perspective on the concerns and connections of the international community. The visualization is based on the GDELT Project, an open-data, real-time index of worldwide media that can identify the many social, political, and geographical factors driving global society. It reveals the "geographic communities" created by the world media; countries are connected if they are mentioned together in news stories. By highlighting the various and often unexpected geographic interdependencies created by the local media, this macroscope makes the interconnectedness of our world tangible.



+
–
CHINA
SEARCH
ABOUT
Visit our Zenodo community (zenodo.org/communities/macroscopes) to watch a demo of this macroscope by creator Kalev Leetaru.
CHINA
cooccurrences in: 1,920%
cooccurrences out: 125%
Feb 22
Mar 1
Mar 8
Mar 15
Mar 22
Mar 29
Apr 5
Apr 12
Apr 19
Apr 26
May 3
May 10
May 17
May 24
COOCCURR
IN%
OUT%




**Science career paths**
Each line represents the publication record of a single scientist, and the dots along that line denote their published papers. The height of each bump along the line is determined by the number of citations that paper received in the ten years following its publication. The blue dot represents the publication with the largest number of citations.

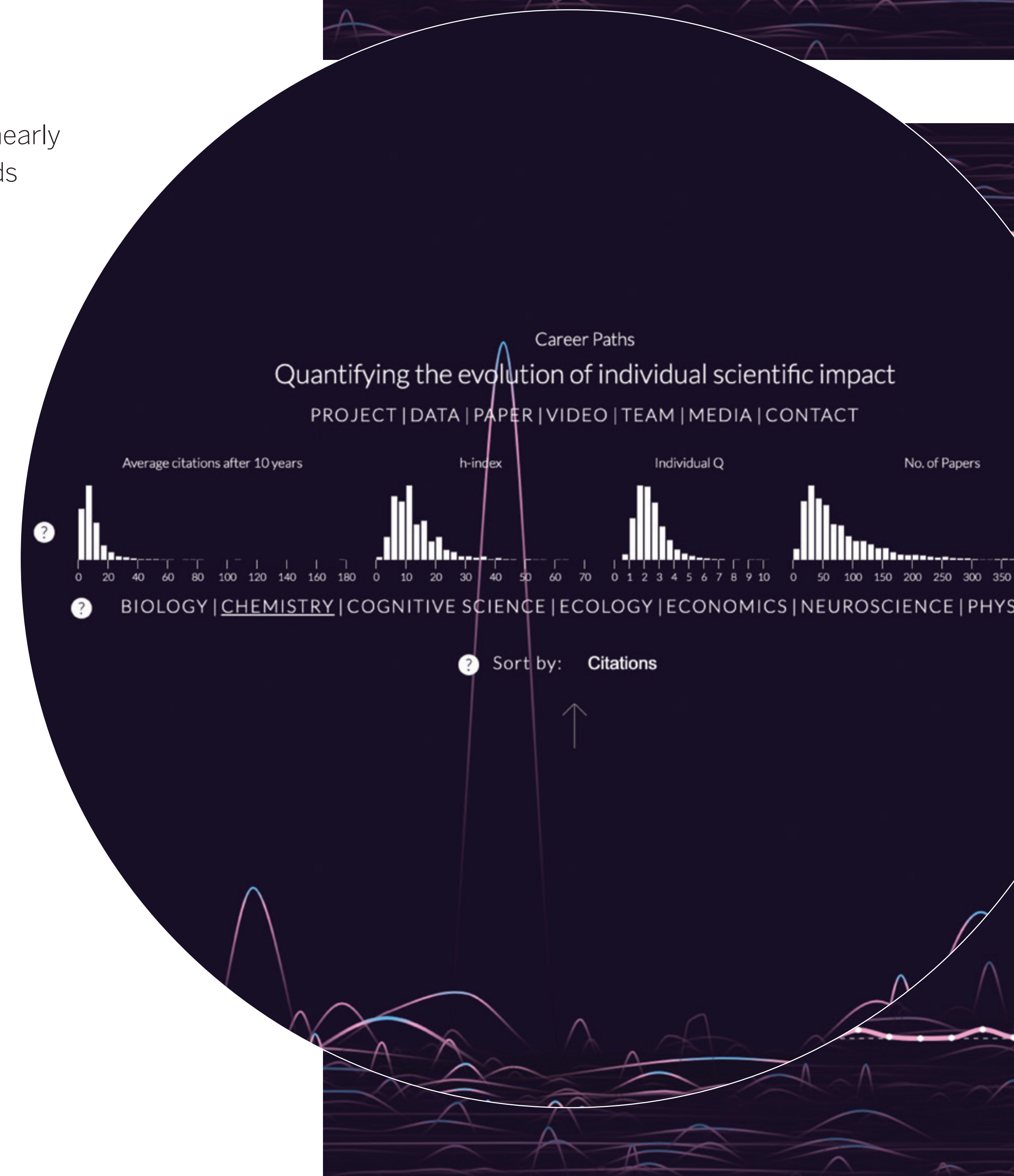
# Science Paths

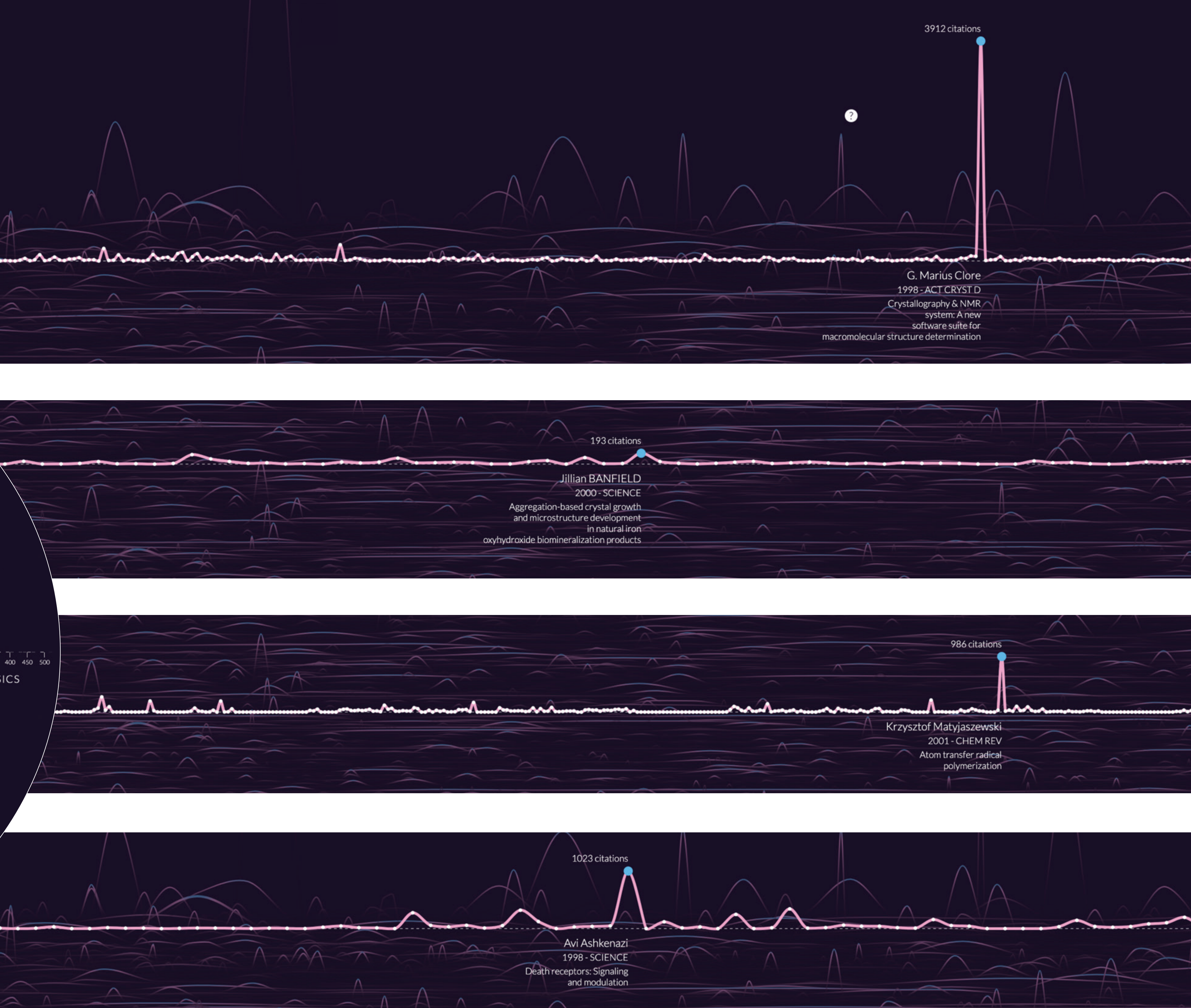
**MAKERS**
Kim Albrecht
Albert-László Barabási
Roberta Sinatra

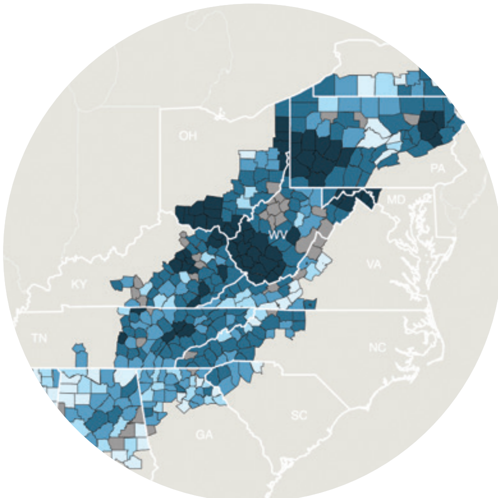
**YEAR**
2017

*Science Paths* analyzes the publication histories of nearly 10,000 scientists working in seven disciplines. It finds that the most influential work of a scientist's career is randomly distributed within their body of work. That is, the highest-impact work has the same probability of falling anywhere in the sequence of papers published by that scientist. It could be the very first or last publication, or it might appear midcareer. The team coined this phenomenon the "random impact rule."

This visualization shows the random impact rule in all its power. Users can explore careers in different disciplines and rank scientists according to different career parameters, such as the total number of papers in each scientist's career—across which impact peaks may occur at any point, from the beginning of a career (at left) to the end of a career (at right).




3912 citations
G. Marius Clore
1998 - ACT CRYST D
Crystallography & NMR system: A new software suite for macromolecular structure determination
193 citations
Jillian BANFIELD
2000 - SCIENCE
Aggregation-based crystal growth and microstructure development in natural iron oxyhydroxide biomineralization products
400 450 500
986 citations
Krzysztof Matyjaszewski
2001 - CHEM REV
Atom transfer radical polymerization
1023 citations
Avi Ashkenazi
1998 - SCIENCE
Death receptors: Signaling and modulation



**The opioid toll**
While the opioid epidemic has ravaged communities across the United States, the Appalachian region in the eastern part of the country has witnessed particular devastation. In 2019, Appalachian residents were 41% more likely to die from a drug overdose than Americans in any other region.

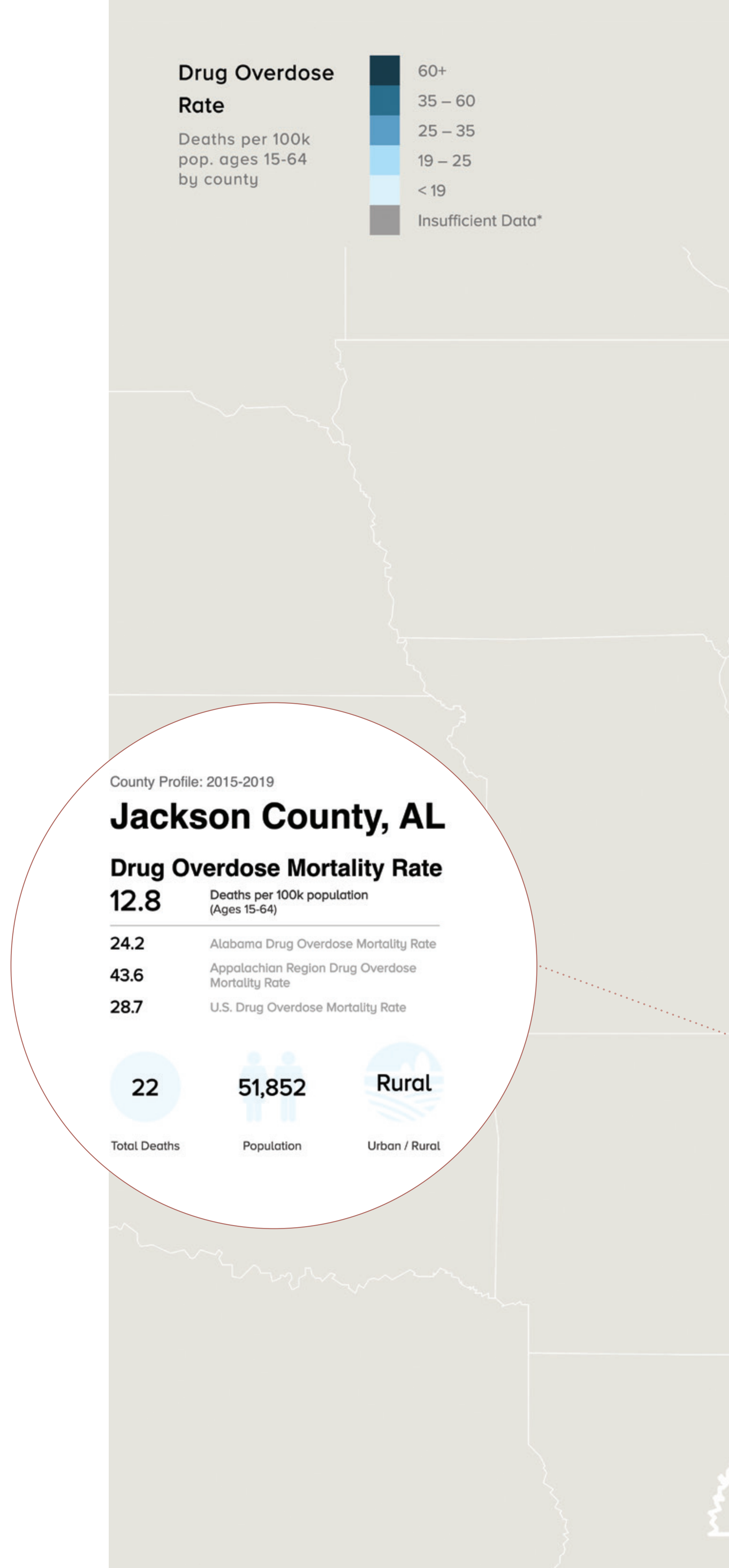
# Appalachian Overdose Mapping Tool

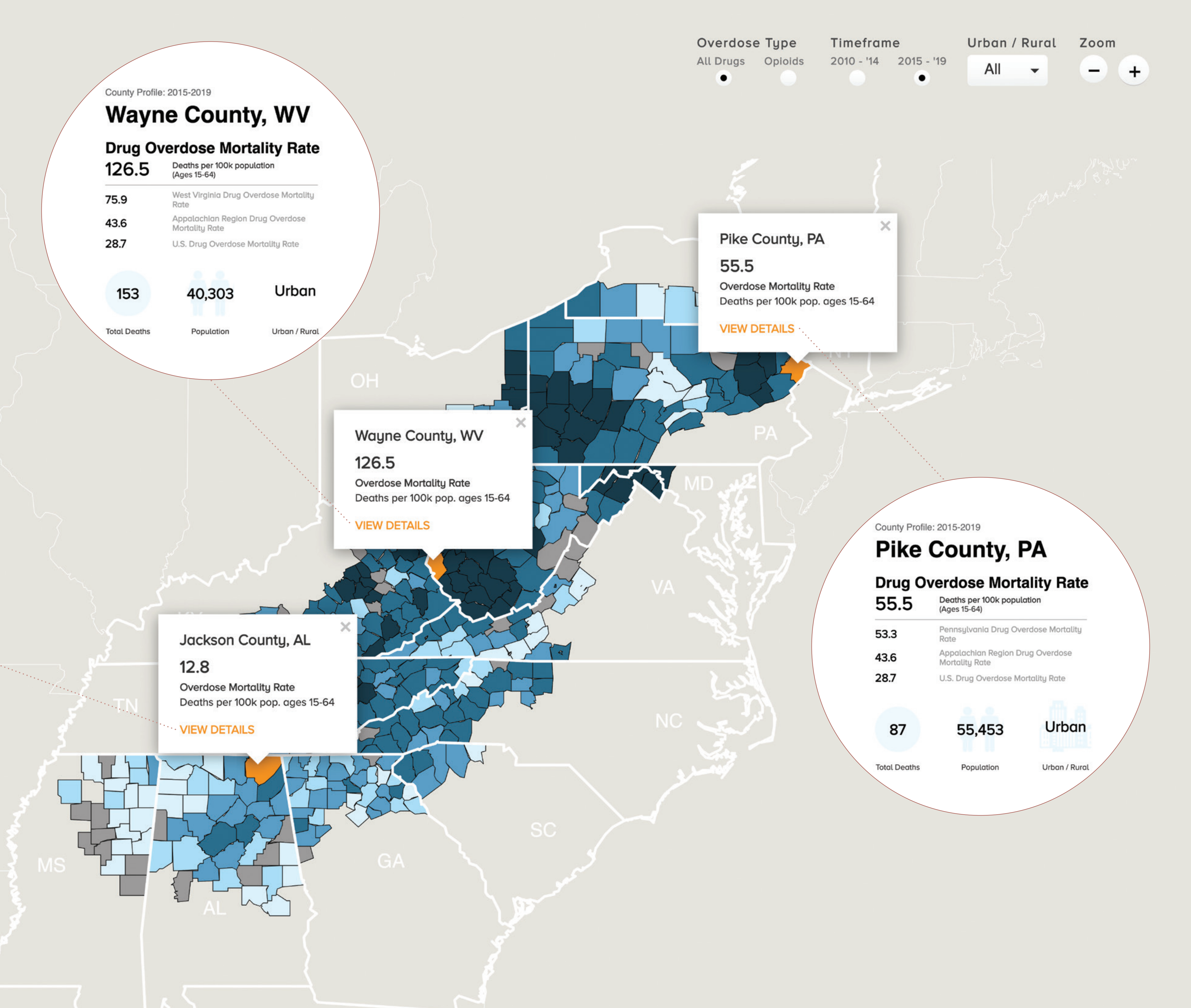
**MAKERS**
Ned English
Megan Heffernan
Peter Herman
Michael Meit

**YEAR**
2018

The *Appalachian Overdose Mapping Tool* shows county-level overdose mortality data. You can select overlays of socioeconomic factors (such as poverty, unemployment, educational attainment, and disability) to look for patterns and trends throughout Appalachia; zoom in to display data for each of the 420 Appalachian counties; or compare rural and urban counties within Appalachia. See how quickly the opioid epidemic grew by comparing data from two time periods: 2010–2014 and 2015–2019.

The *Appalachian Overdose Mapping Tool* supports community planning and response, particularly in terms of strategies to address the opioid crisis. The tool uses data from the CDC's National Vital Statistics System, the U.S. Census Bureau's American Community Survey, and the U.S. Bureau of Labor Statistics' Quarterly Census of Employment and Wages. It was developed by members of the nonpartisan research organization NORC at the University of Chicago. The macroscope proved so useful that the U.S. Department of Agriculture funded a national version in 2020. See page 5 to learn more about the real-world impact of this powerful macroscope.





Overdose Type
All Drugs
Opioids
Timeframe
2010 - '14
2015 - '19
Urban / Rural
All
Zoom
County Profile: 2015-2019
Wayne County, WV
Drug Overdose Mortality Rate
126.5
Deaths per 100k population (Ages 15-64)
75.9
West Virginia Drug Overdose Mortality Rate
43.6
Appalachian Region Drug Overdose Mortality Rate
28.7
U.S. Drug Overdose Mortality Rate
153
Total Deaths
40,303
Population
Urban
Urban / Rural
Pike County, PA
55.5
Overdose Mortality Rate
Deaths per 100k pop. ages 15-64
VIEW DETAILS
Wayne County, WV
126.5
Overdose Mortality Rate
Deaths per 100k pop. ages 15-64
VIEW DETAILS
Jackson County, AL
12.8
Overdose Mortality Rate
Deaths per 100k pop. ages 15-64
VIEW DETAILS
County Profile: 2015-2019
Pike County, PA
Drug Overdose Mortality Rate
55.5
Deaths per 100k population (Ages 15-64)
53.3
Pennsylvania Drug Overdose Mortality Rate
43.6
Appalachian Region Drug Overdose Mortality Rate
28.7
U.S. Drug Overdose Mortality Rate
87
Total Deaths
55,453
Population
Urban
Urban / Rural
OH
PA
MD
VA
TN
NC
SC
GA
AL
MS


NATURE
A WEEKLY ILLUSTRATED JOURNAL OF SCIENCE
THURSDAY, NOVEMBER 4, 1869


**Cover to cover**
On left, the first issue of *Nature* from November 4, 1869, with its understated-yet-stylish front page. On right, *Nature*'s November 2019 issue, featuring a colorful visualization of more than 88,000 scientific articles published in the intervening 150 years.

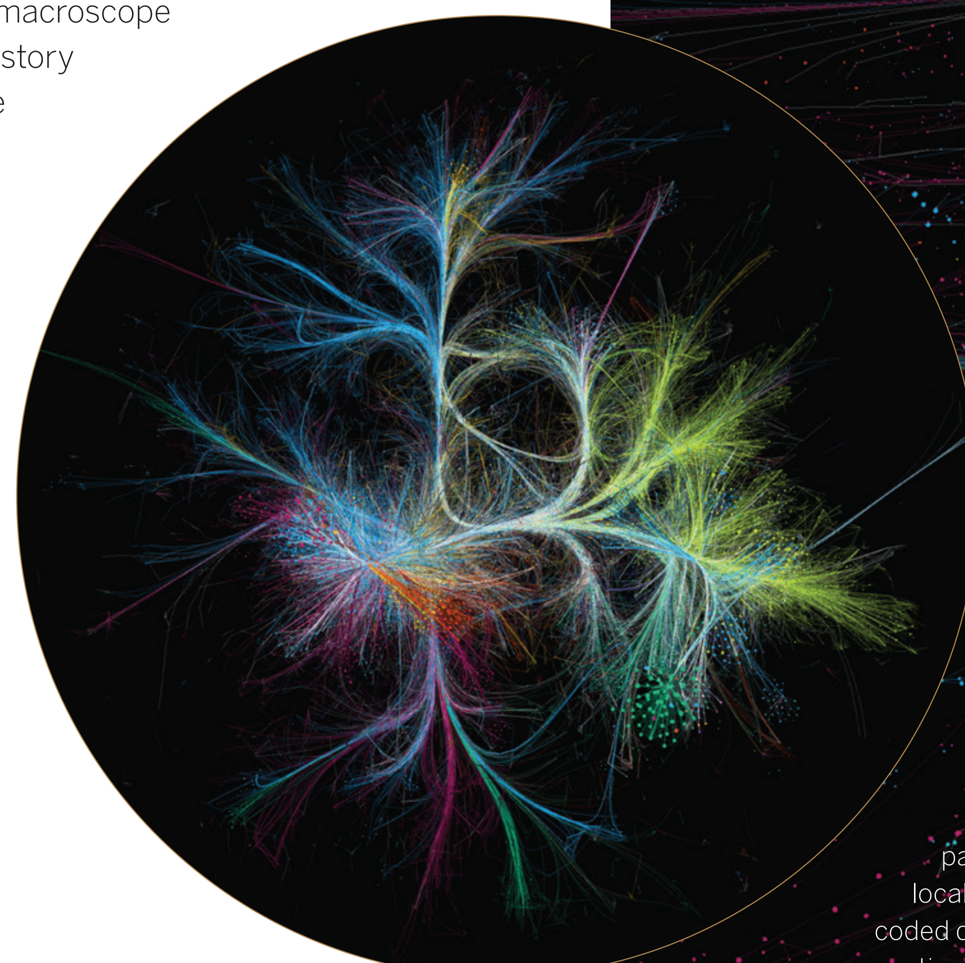
# *Nature* 150

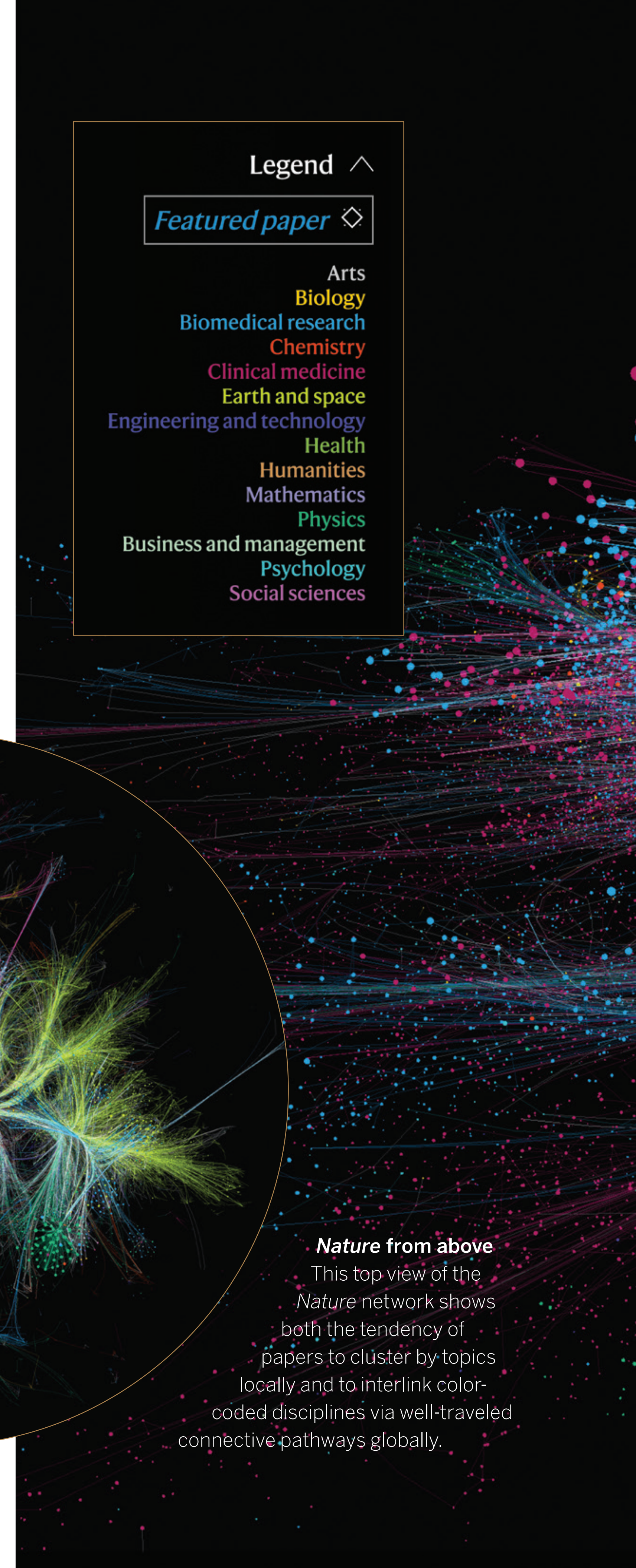
**MAKERS**
Alice Grishchenko
Alexander Gates
Qing Ke
Onur Varol
Mauro Martino
Albert-László Barabási

**YEAR**
2020

*Nature 150* is an interactive map of more than 88,000 papers published in the journal *Nature* since its founding in 1869. Created by current and former members of the Barabási Lab at Northeastern University, the macroscope visualizes the journal's publication history as a network of influence. Each node represents a published paper, and two paper nodes are connected if a third paper cites them both. Nodes are color-coded by scientific discipline, showing how scientific and artistic works spread influence both within and beyond their disciplines.

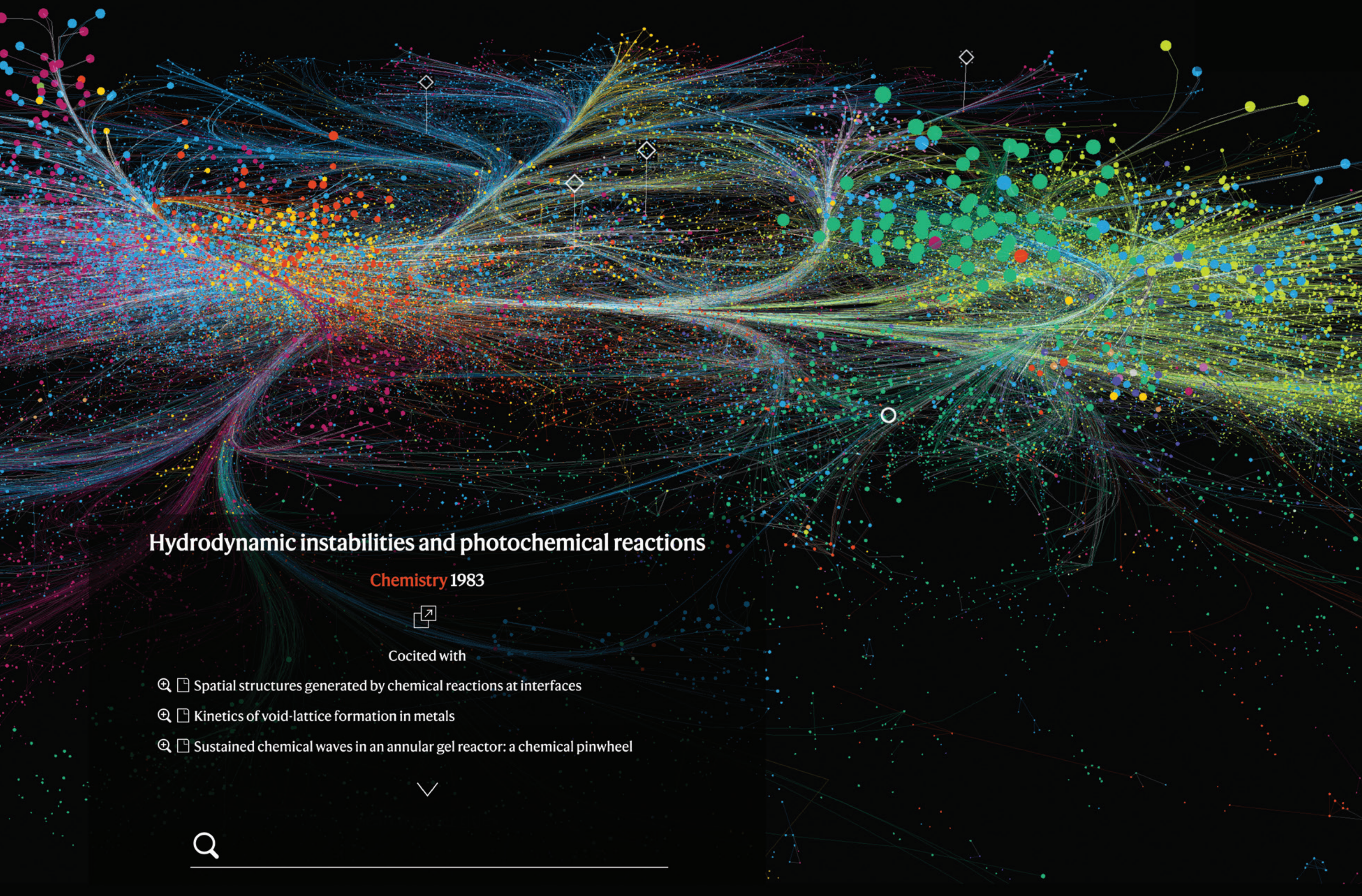
This network analysis shows that today's scientific work is highly interdisciplinary—a fact that should come as very good news. After all, it is becoming quite clear that solving global challenges like pandemics and climate change will require close collaboration by experts from many disciplines.

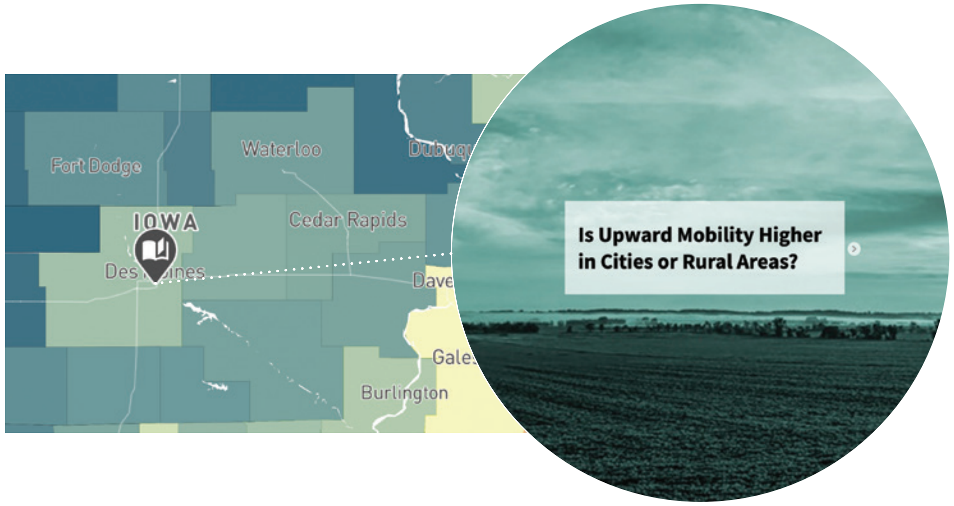




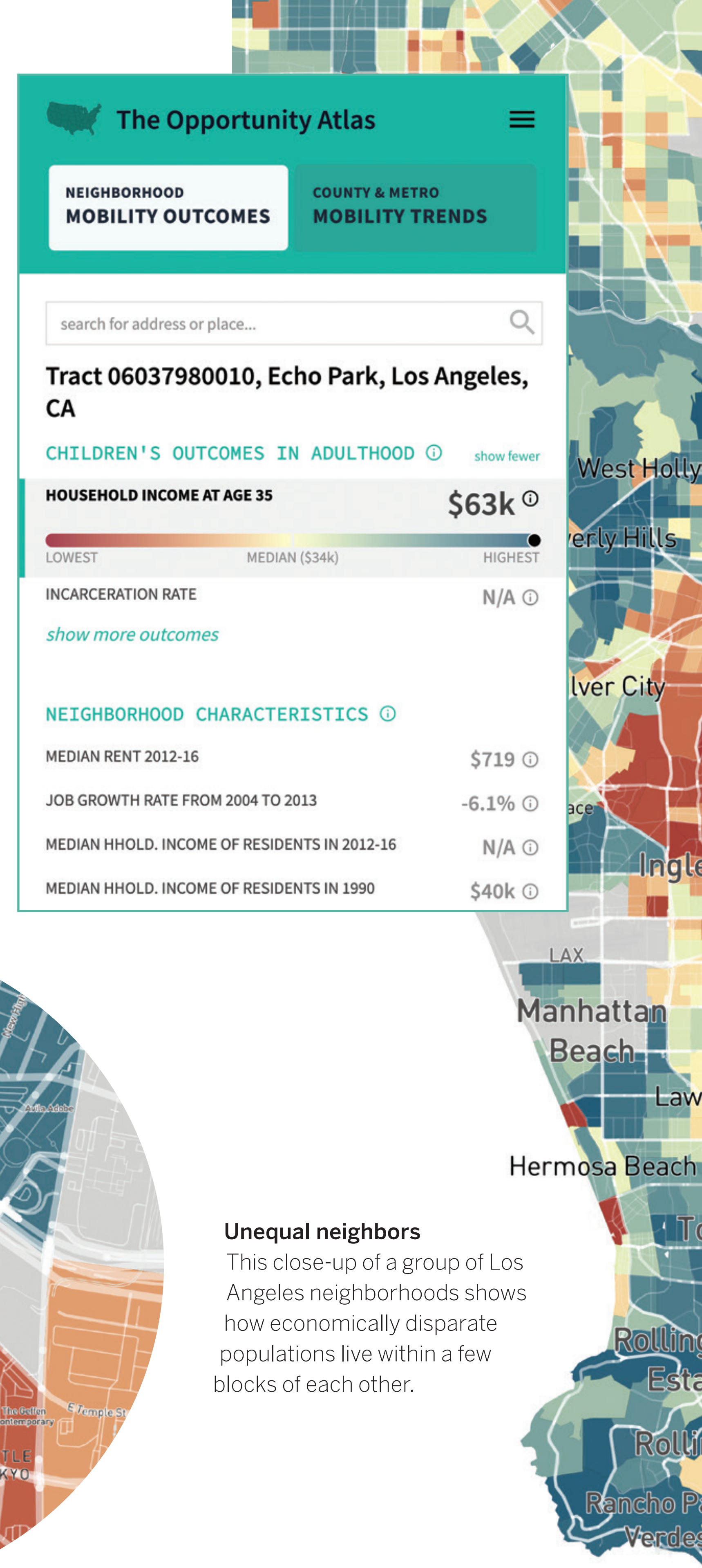

***Nature* from above**
This top view of the *Nature* network shows both the tendency of papers to cluster by topics locally and to interlink color-coded disciplines via well-traveled connective pathways globally.

Visit our Zenodo community (**zenodo.org/communities/macroscopes**) to learn more about the making of *Nature 150*.






**Did you know?**
Clicking on the map's book icon leads to in-depth stories that bring greater context to *Opportunity Atlas* data.

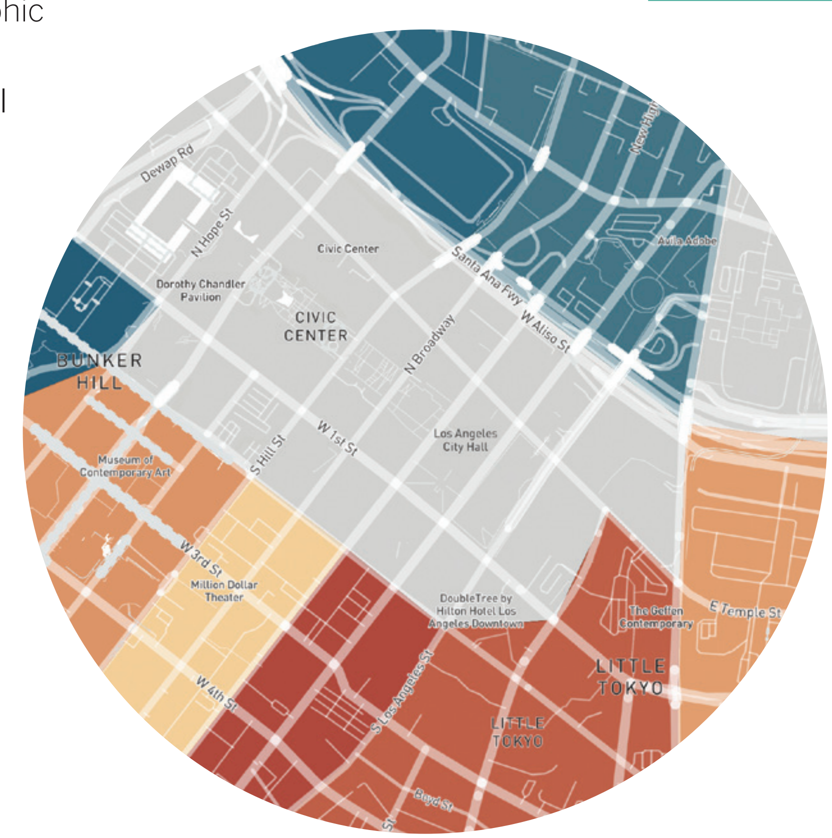



# Opportunity Atlas

**MAKERS**
Raj Chetty
John N. Friedman
Nathaniel Hendren
Joey Cherdarchuk
Eugene Chen
Daniel Haight

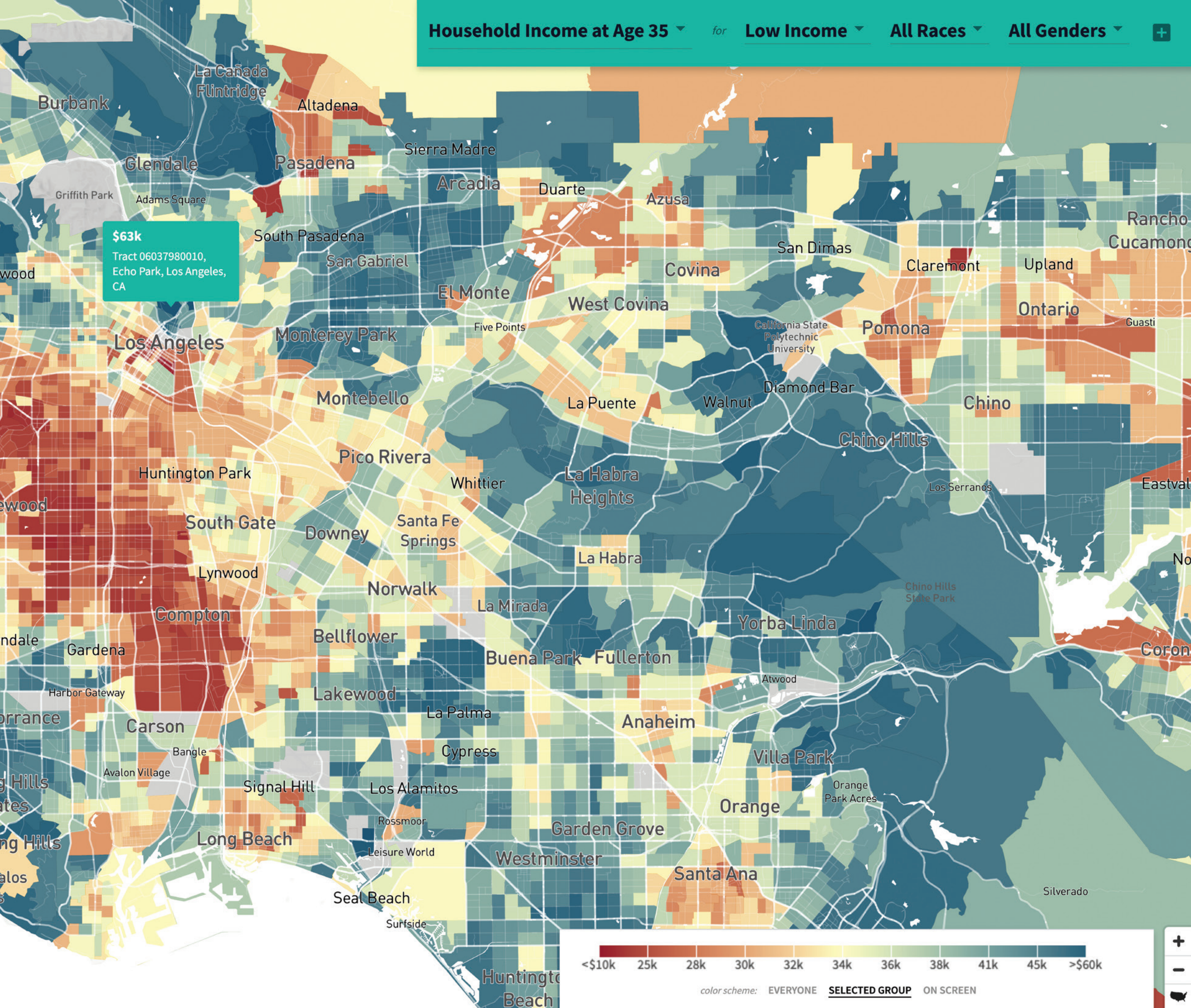
**YEAR**
2018

As this macroscope demonstrates, the neighborhood in which a child grows up plays a substantial role in determining their future economic mobility. The *Opportunity Atlas* is a collaboration between the research group Opportunity Insights and the consulting and design firm Darkhorse Analytics. It measures the average economic mobility of children from every neighborhood in the United States by demographic subgroups like race, gender, and parental income. An essential tool for policymakers, community organizers, and advocacy groups, the *Opportunity Atlas* enables targeted, data-driven solutions that proactively address income inequality. See page 135 to learn the steps taken by the creators of *Opportunity Atlas* to ensure the ethical use of sensitive data.




**Unequal neighbors**
This close-up of a group of Los Angeles neighborhoods shows how economically disparate populations live within a few blocks of each other.

Check out our Zenodo community (**zenodo.org/communities/macroscopes**) for interviews with John N. Friedman and Eugene Chen about the making of this macroscope.


Household Income at Age 35
for
Low Income
All Races
All Genders
$63k
Tract 06037980010, Echo Park, Los Angeles, CA
La Cañada Flintridge
Burbank
Altadena
Sierra Madre
Glendale
Pasadena
Griffith Park
Adams Square
Arcadia
Duarte
Azusa
Rancho Cucamong
South Pasadena
San Gabriel
San Dimas
Covina
Claremont
Upland
El Monte
West Covina
Ontario
Guasti
Five Points
California State Polytechnic University
Pomona
Los Angeles
Monterey Park
Diamond Bar
Montebello
La Puente
Walnut
Chino
Chino Hills
Pico Rivera
Huntington Park
Whittier
La Habra Heights
Los Serranos
Eastval
South Gate
Downey
Santa Fe Springs
La Habra
Lynwood
Norwalk
La Mirada
Chino Hills State Park
Compton
Yorba Linda
Bellflower
Gardena
Buena Park
Fullerton
Coron
Atwood
Harbor Gateway
Lakewood
La Palma
Anaheim
Carson
Bangle
Cypress
Villa Park
Avalon Village
Signal Hill
Los Alamitos
Orange
Orange Park Acres
Rossmoor
Garden Grove
Long Beach
Leisure World
Westminster
Santa Ana
Seal Beach
Silverado
Surfside
<$10k
25k
28k
30k
32k
34k
36k
38k
41k
45k
>$60k
color scheme:
EVERYONE
SELECTED GROUP
ON SCREEN

**Crowdsourced data collection**

By design, information on police surveillance is not easy to come by. It takes initiative, time, and quite a bit of (online) detective work to track down data on the nearly 18,000 law enforcement agencies currently active in the United States. Toward that end, the Electronic Frontier Foundation (EFF) mobilized an army of journalism students at the University of Nevada to perform some open-source intelligence gathering. First, the online repository GovSpend was used to identify areas of the country where equipment had been purchased. Then, students were tasked to find evidence for employed surveillance technologies in news reports and government documents. The EFF also developed the Report Back system, which assigns short research tasks to student volunteers. In addition, members of the public can submit information about surveillance practices in their own areas.

# Atlas of Surveillance

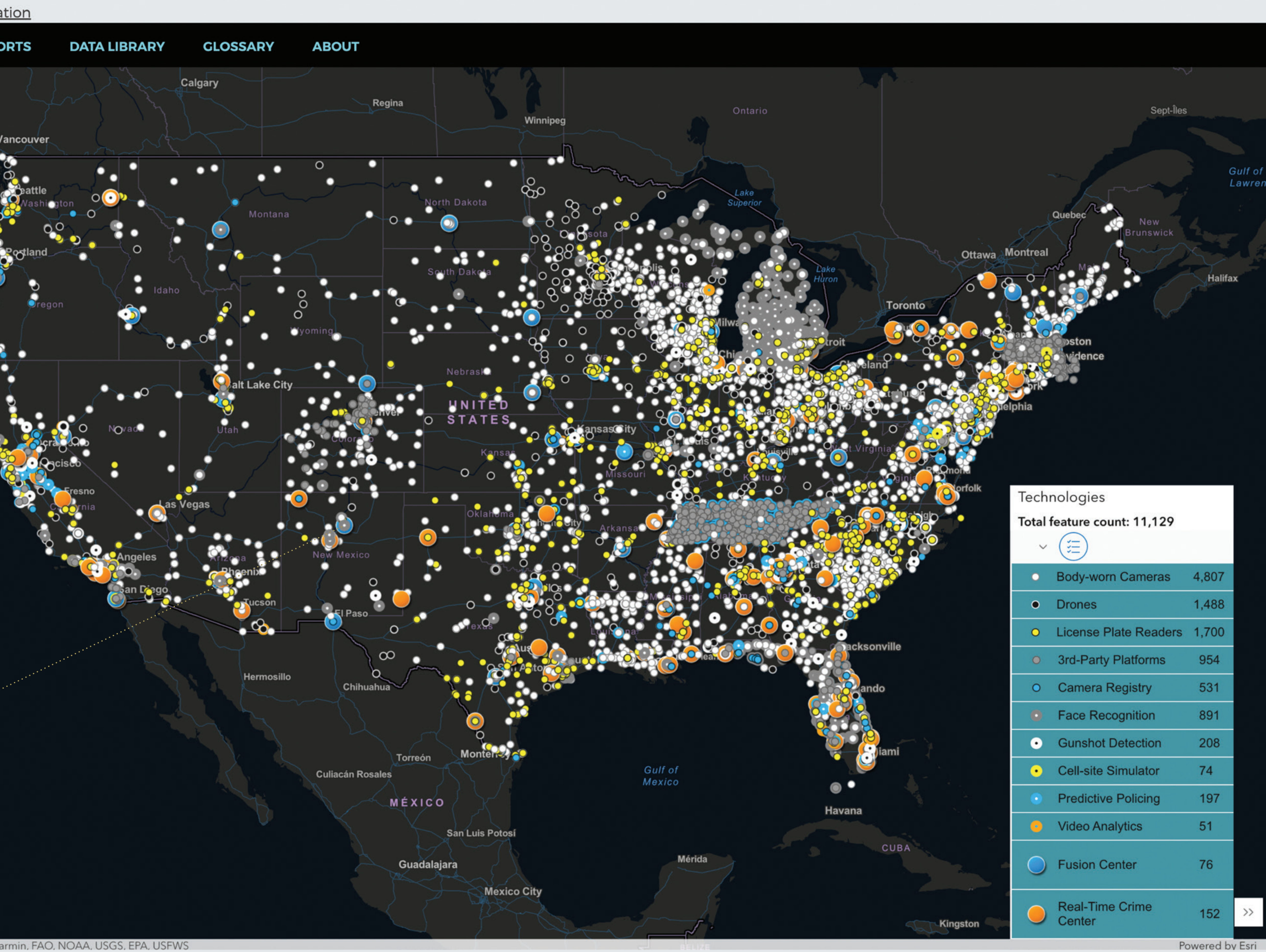
**MAKER**
Electronic Frontier Foundation

**YEAR**
2021

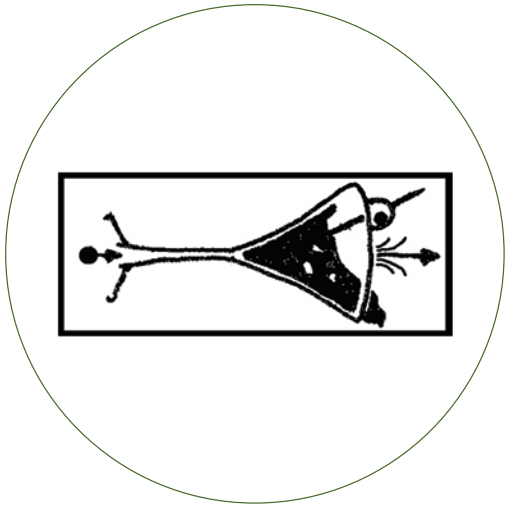
The *Atlas of Surveillance* is a collaborative effort between the Electronic Frontier Foundation (EFF) and the Reynolds School of Journalism at the University of Nevada. Through a combination of crowdsourcing and data journalism, they are creating the largest-ever repository of data that specifies which surveillance technologies are being used by which law enforcement agencies. The *Atlas of Surveillance* focuses on the most pervasive technologies, including drones, body-worn cameras, face recognition, cell-site simulators, automated license plate readers, predictive policing, camera registries, and gunshot detection. The aim of the *Atlas of Surveillance* is to serve as a resource for journalists, academics, and concerned members of the public to check what technologies are used locally and how different technologies are deployed across the country.


**Who is watching you?**

The importance of the *Atlas of Surveillance* is twofold: it collects information that is normally scattered throughout government documents, local news reports, watchdog databases, and other locations; then it makes it all easily accessible in one place. Clicking one of the map's color-coded nodes brings up a listing of surveillance tactics used in that area, as well as links to documentary evidence. In Santa Fe, for instance, authorities utilize facial recognition technologies, body cameras, and video analytics. The city is also home to one of 76 of the nation's so-called "fusion centers"—controversial sites established in the wake of the September 11 attacks—which collect surveillance data and share it between local and federal agencies. The *Atlas of Surveillance* provides descriptions of all the surveillance tactics that it tracks.



ation
ORTS
DATA LIBRARY
GLOSSARY
ABOUT
Technologies
Total feature count: 11,129
Body-worn Cameras 4,807
Drones 1,488
License Plate Readers 1,700
3rd-Party Platforms 954
Camera Registry 531
Face Recognition 891
Gunshot Detection 208
Cell-site Simulator 74
Predictive Policing 197
Video Analytics 51
Fusion Center 76
Real-Time Crime Center 152
UNITED STATES
MÉXICO
CUBA
Gulf of Mexico
Calgary
Regina
Winnipeg
Ontario
Sept-Îles
Quebec
Ottawa
Montreal
Toronto
Halifax
New Brunswick
Lake Superior
Lake Huron
Montana
North Dakota
South Dakota
Idaho
Wyoming
Nebraska
Utah
Kansas
Oklahoma
Arkansas
Missouri
New Mexico
Kansas City
Las Vegas
Fresno
Tucson
El Paso
Jacksonville
Havana
Hermosillo
Chihuahua
Torreón
Culiacán Rosales
San Luis Potosí
Guadalajara
Mexico City
Mérida
Kingston
armin, FAO, NOAA, USGS, EPA, USFWS
Powered by Esri



**Preparing for launch**

*Star Mapper* presents its material in what is known as a "martini glass structure." Here, each of the tabs along the bottom leads to a new view of the same subject matter. And each new view involves learning a feature of the tool's functionality. This linear, step-by-step instruction forms the stem of the glass, and it is where the designer exerts more control over the experience. When the glass widens out—in this case, for the "Explore" feature—that's when users are ready to take control.

# Star Mapper

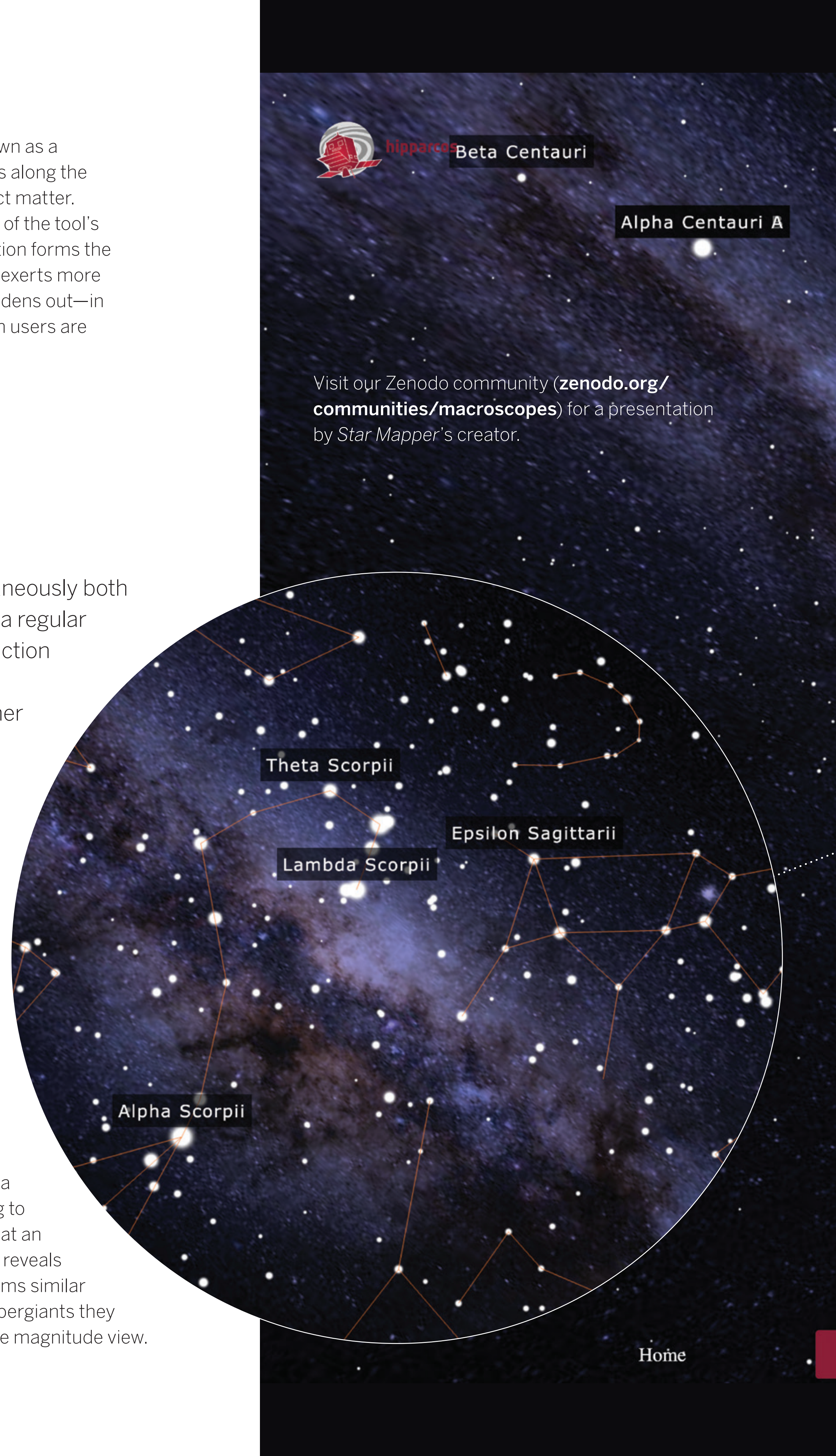
**MAKER**
Jan Willem Tulp

**YEAR**
2016

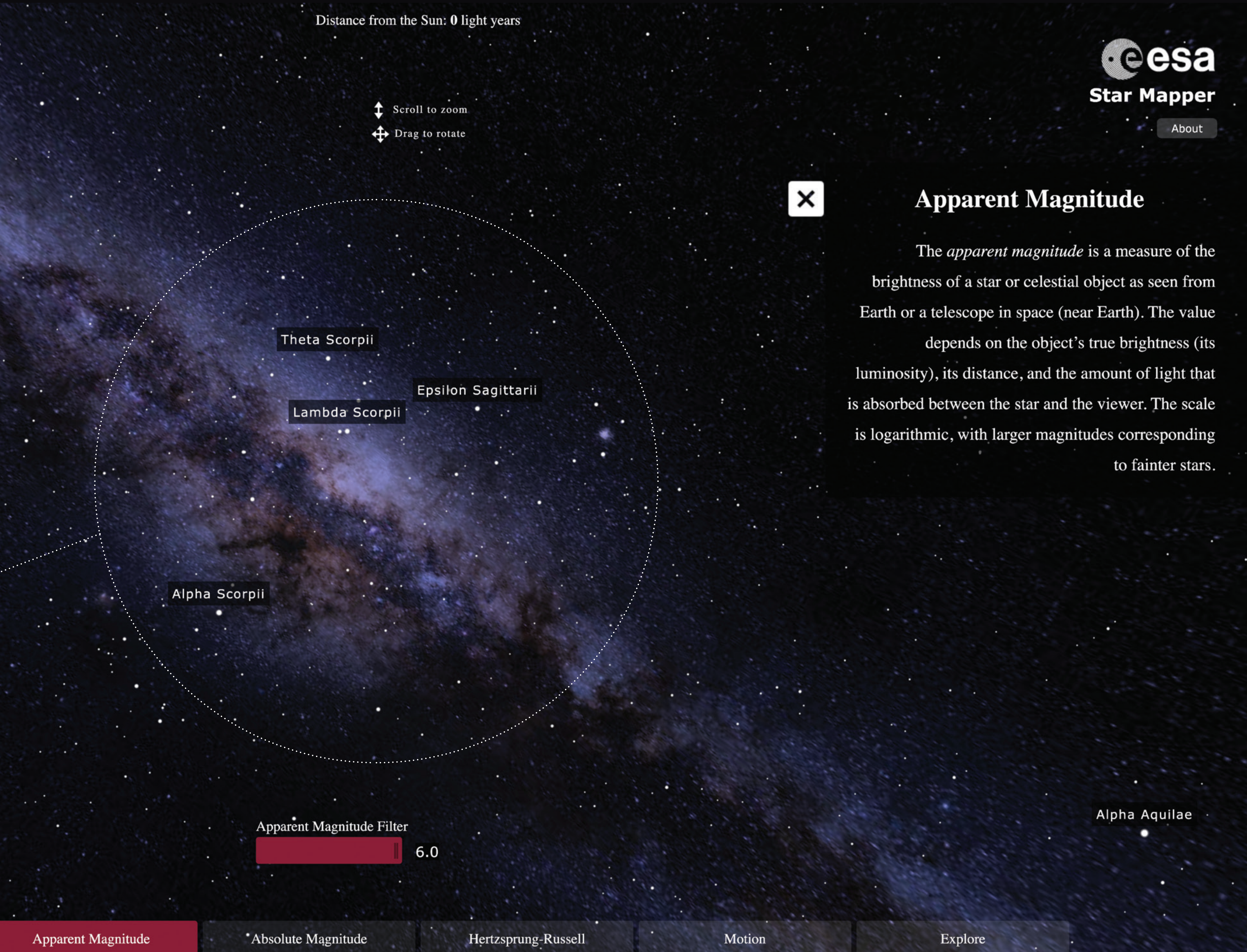
Celestial objects have the distinction of being simultaneously both mundane and mysterious. Although we see them on a regular basis, we realize that such sightings convey only a fraction of what there is to know about them. And that's what makes this macroscope from data experience designer Jan Willem Tulp such a valuable tool for stargazers of all stripes. Using data from the European Space Agency's *Hipparcos* mission, Tulp's *Star Mapper* enables the interactive exploration of nearly 60,000 stars. Different filters allow different features of the stars to come to the forefront: you can toggle between apparent and absolute magnitude views, study how stars evolve with the Hertzsprung-Russell diagram, and track the movement of stars through space.

**A choice of some magnitude**

Two of the views offered here relate to stellar magnitude, the measure used to indicate a star's brightness. While the main image at right shows apparent magnitude, how bright stars might appear to a viewer on Earth, the inset shows some of those same stars according to their absolute magnitude, or how bright they would look if all placed at an equal distance from the observer (in this case, 10 parsecs). The inset reveals how some stars—like Alpha Scorpii, whose apparent magnitude seems similar to many of its neighbors in the main image—appear more like the supergiants they actually are when seen from the absolute magnitude view.



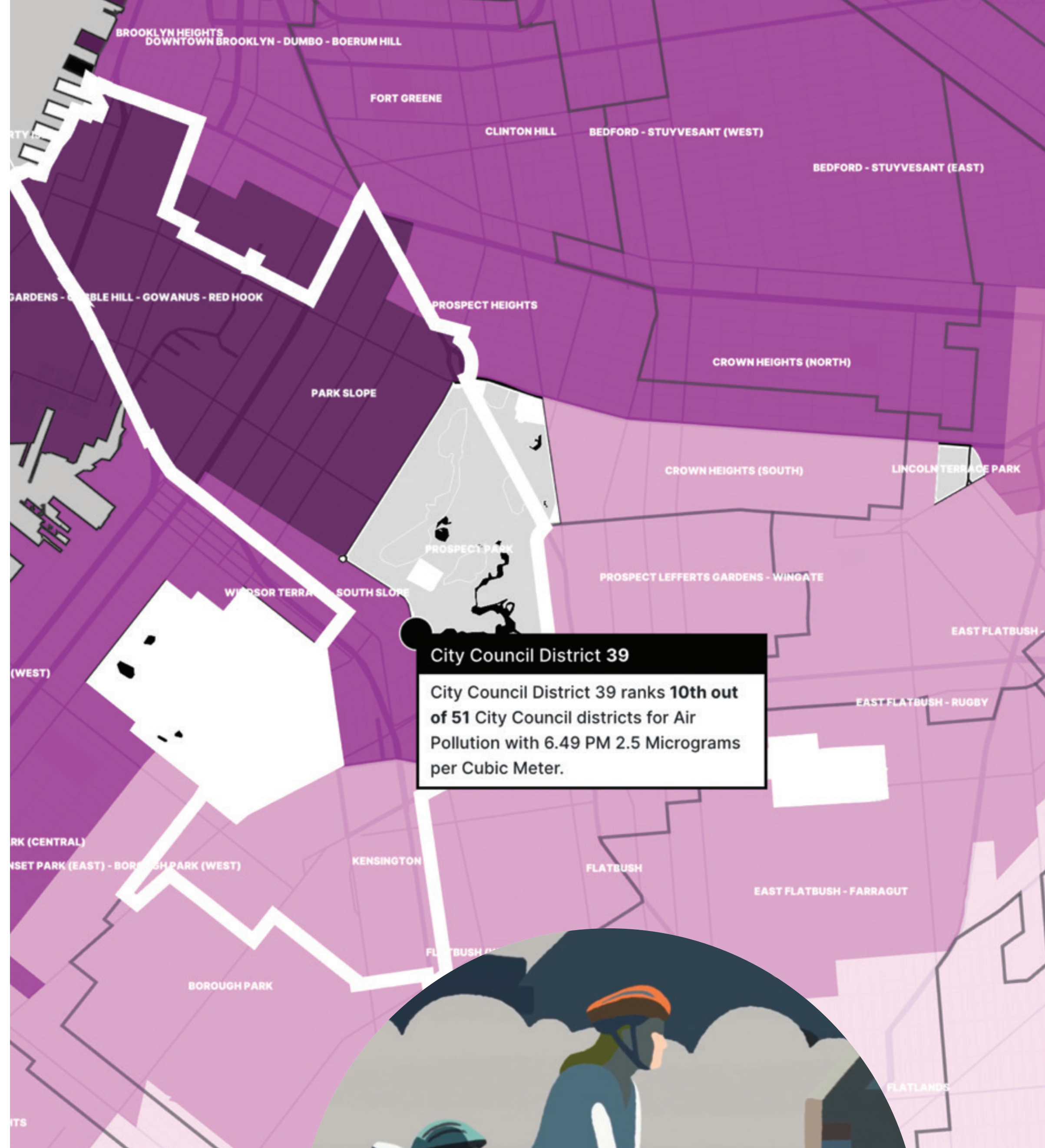

Visit our Zenodo community (**zenodo.org/communities/macroscopes**) for a presentation by *Star Mapper*'s creator.


Distance from the Sun: **0** light years
Scroll to zoom
Drag to rotate
esa
Star Mapper
About
Apparent Magnitude
The *apparent magnitude* is a measure of the brightness of a star or celestial object as seen from Earth or a telescope in space (near Earth). The value depends on the object's true brightness (its luminosity), its distance, and the amount of light that is absorbed between the star and the viewer. The scale is logarithmic, with larger magnitudes corresponding to fainter stars.
Theta Scorpii
Epsilon Sagittarii
Lambda Scorpii
Alpha Scorpii
Alpha Aquilae
Apparent Magnitude Filter
6.0
Apparent Magnitude
Absolute Magnitude
Hertzsprung-Russell
Motion
Explore

Spatial Equity NYC

# Open Data as a Tool for Social Change

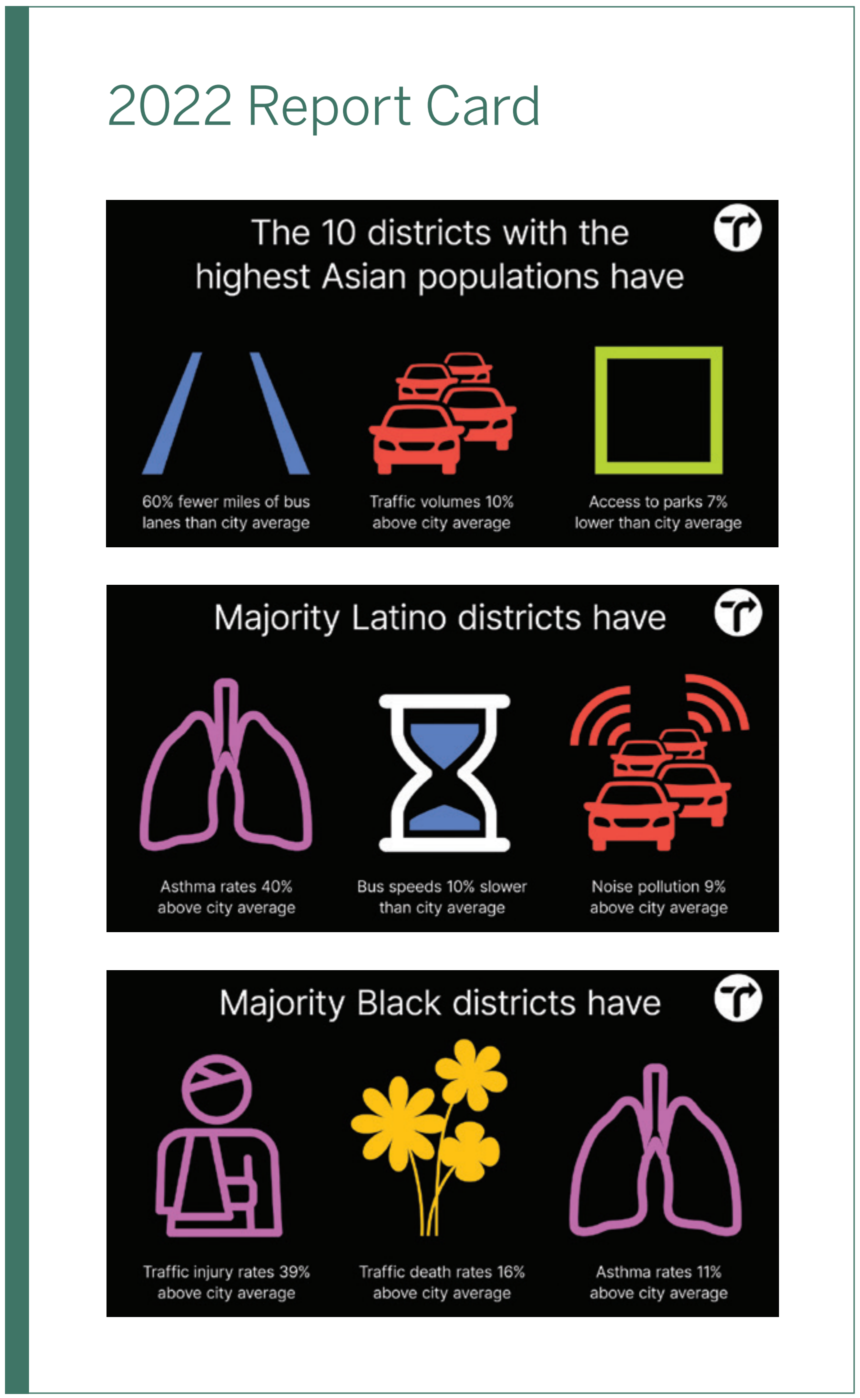
Transportation Alternatives, a nonprofit organization interested in reducing the number of personal cars in New York City, knew from the beginning that its goal was to use existing open data for the purpose of political advocacy. The project team, through various public forums, identified two major roadblocks that often get in the way. Datasets are collected in different measurement units—for example, by zip code or census tract. For this project, it was important to aggregate the data by political subdivision as this makes it easy for advocates to share citable data that is aggregated by the districts they represent. A second issue is that many city officials find it challenging to bring together both the time and the skills to run analyses of open datasets. Transportation Alternatives solved this problem by providing a report card that succinctly presents an analysis of various metrics of social inequity, along with potential solutions.

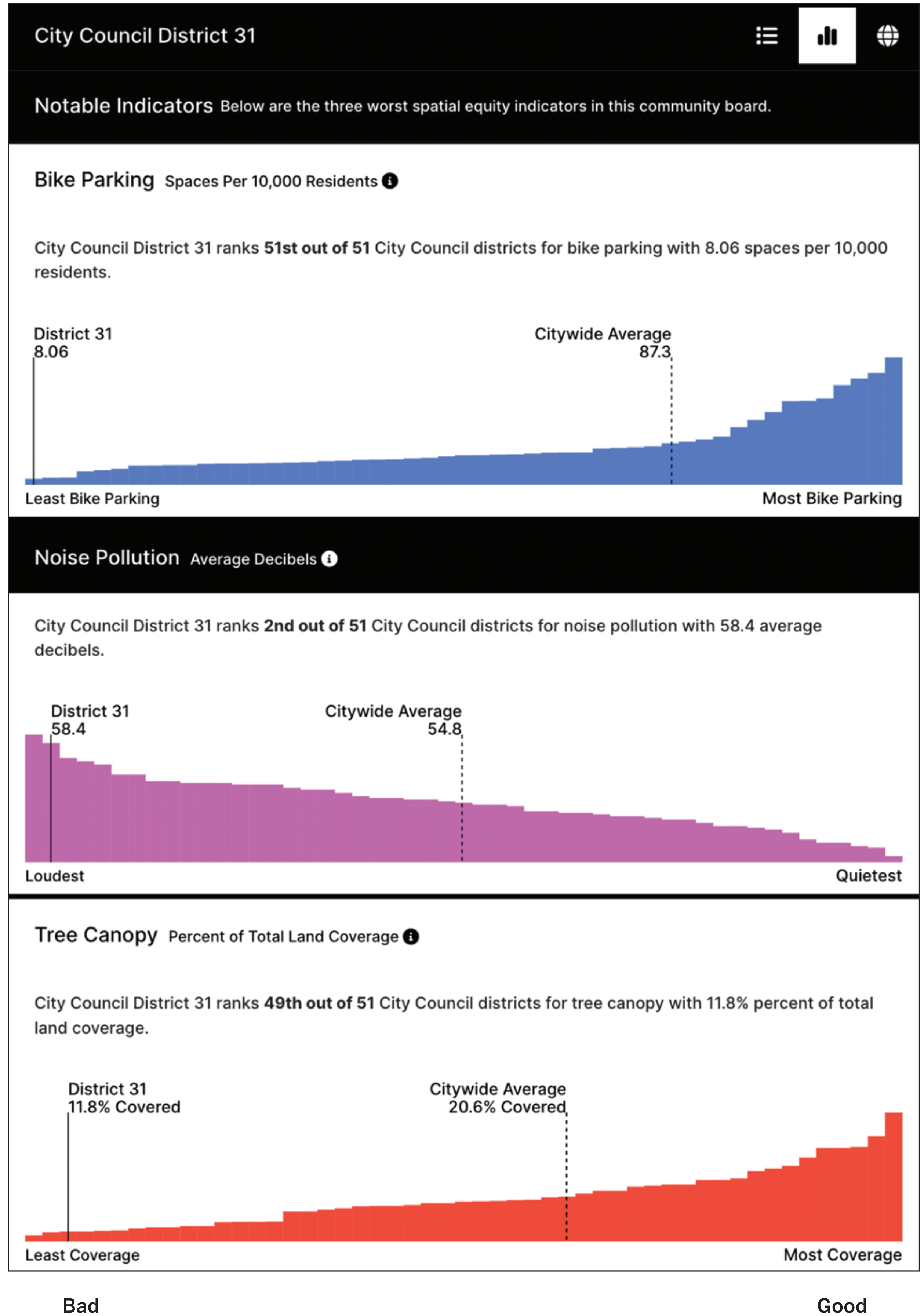



*"Open data ... represents information that allows people to take action on their own behalf. Digital technology shifts government transparency from the optical metaphor of looking through a window to the navigational metaphor of entering through a portal."*

**—Craig Campbell, Research Fellow, New York City Mayor's Office of Data Analytics**

**New York City's commitment to open data**
One of the greatest challenges of this project was the amount of data: not too little, but too much. This embarrassment of riches is a result of New York City's long-standing commitment to open data, prompted by the corruption reform of the early 1900s. The city has maintained a data dictionary since 1993, and the municipal government enacted a 2012 open-data law that went beyond agreeing to provide data when requested, by requiring data to be provided on a regular basis and in an accessible format.



# Insight Needs and Working with Data

The challenges and opportunities encountered when building the data visualizations featured in Part 2 may be hidden from view in the final product. Yet detailed information on why certain data filters or thresholds were applied or why a specific visualization metaphor was used can help viewers better interpret the presented data and act on insights gained.

The Data Visualization Literacy Framework introduced on pages 8–9 and exemplified on pages 10–13 provides the terminology and a process model to systematically capture and communicate why and how a data visualization came into existence. The framework is used here to discuss the key challenges and opportunities that both the makers and users of data visualizations might encounter.

## Insight Needs

Identifying and articulating user needs is not easy. While users generally want faster, better, trendier, and ever-cheaper products, they typically cannot envision qualitatively new solutions to existing problems.

A close collaboration among users, designers, scientists, engineers, and subject-matter experts is required to identify the sweet spots that users desire and which are also technically feasible and economically viable. Here, viability covers the short term (such as the initial launch) and the long term (including continuous data and software updates, plus 24/7 service). Each sweet spot is then converted into a user story—detailing who needs what and why—that serves to guide technical development, deployment, and training.

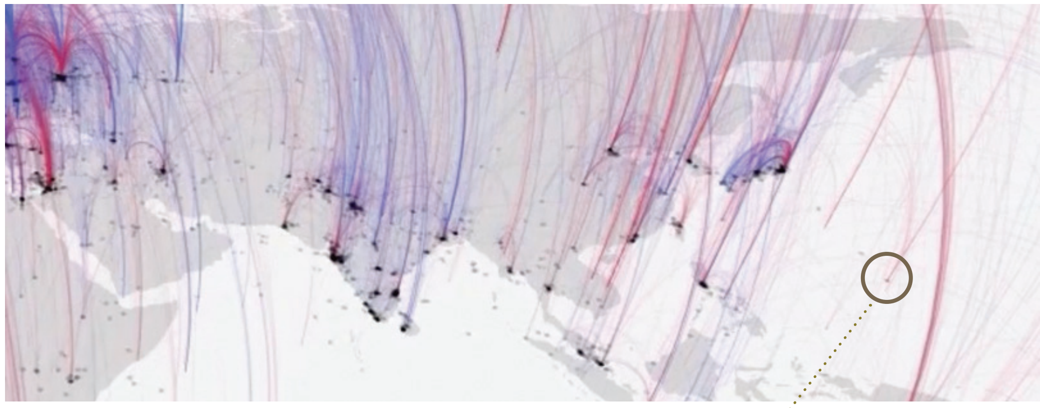
## Acquiring Data

One limiter in the development of macroscopes is the availability of usable data that can be meaningfully combined. Frequently, existing data does not have the quality or coverage needed to render the most actionable visualizations. However, collecting new data is expensive and time-consuming. An iterative data curation and visualization development process can lead to ever-better data and visualizations while providing the opportunity to incorporate stakeholder feedback.

Typically, the very first visualization of data reveals data errors, missing and incomplete data, and misconceptions about how data was collected. The initial visualization is then used to arrive at stakeholder consensus on how to improve data collection, linkage, access, and usage, as well as to adjust the visualization to meet insight needs. Often, it takes multiple iterations to improve data, analyses, and visualizations.

Full data lineage and provenance—of all data sources, algorithms, and parameter values used, as well as visualization libraries employed—make it possible to rerun analyses and re-render visualizations. Reproducibility is a core value in scientific research, and rerunning analyses with alternative datasets can lead to new insights through comparison.


**Data acquisition and re-representation**
In order to tell the journalistic story of why Spain's built environment is more vertical than that of most countries, the project team for *Spain Lives in Flats* (page 116) collected and combined datasets that include building footprints, building heights, and construction dates for 12 million buildings. This involved developing an R script to download cadastral data from 7,610 municipalities and then combining that information into a single 200-gigabyte file. For Edificio España (top left), Madrid's eighth-tallest skyscraper, one can see the building footprint superimposed on the satellite image (middle left), and then the same image with an additional data layer showing the roof details (bottom left).



## Missing and Incomplete Data

Since missing or incomplete data is common, it is important to communicate to users how such data challenges are addressed. For example, *Charting Culture* (page 32)—which visualizes the birth and death locations of 120,000 individuals over 2,600 years—uses data that includes shipboard deaths and births without precise geographic locations. The designers have visualized the missing locations of all deaths as one aggregate: a single point in the middle of the Atlantic Ocean.

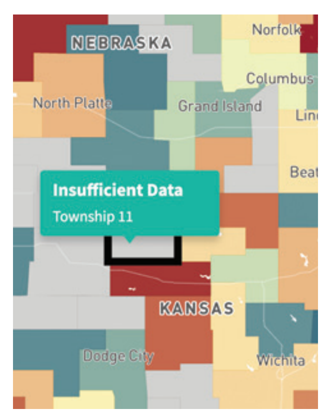

## Analyzing Data

There are thousands of algorithms that can be used to clean, filter, sort, analyze, or model data. Identifying which algorithm to use for a particular purpose is challenging. Conducting formal algorithm comparisons requires expertise, time, and computational resources. Algorithm competitions like those run on such platforms as CodaLab, Tianchi, or Kaggle can help identify the best algorithm. They welcome developers from around the globe to compare and evaluate different approaches using high-quality data and well-defined success criteria.

**Data ethics and privacy**

Data ethics—the moral principles that guide how organizations gather, protect, and use data—continues to evolve as the data economy expands. It has become feasible to collect immense volumes of data unobtrusively, continuously, and automatically and it is nearly impossible to predict how a particular dataset might be used in the future and what techniques might be developed that would allow people and the data generated about them to be linked. Various groups have articulated principles for approaching the ethics of data management and use. In 2016, for example, the General Data Protection Regulation (GDPR) codified into law the concept that Europeans own their own data and have the power to control its use anywhere in the world. Notice the message below from the *Opportunity Atlas* (page 92), which includes U.S. Census Data on income and other sensitive topics, assuring users that the Census Bureau is acting as a responsible data steward and monitoring the use of census data for unethical disclosure. Data privacy, including people's right to maintain control over their own data, is likely to remain a legal battlefield for the foreseeable future.


The Census Bureau has ensured appropriate access and use of confidential data and has reviewed these results for disclosure avoidance protection (Project 7519874: CBDRB-FY18-319, CBDRB-FY23-0375, CBDRB-FY24-0143).

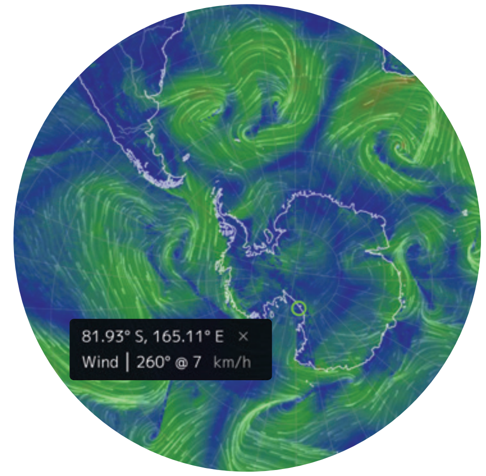



**Anonymizing data**

The *Opportunity Atlas* aggregates data at the census tract level, each of which contains an average of 4,000 people.

If data is shown for a specific gender, age, or race, there might be less than 20 people in a demographic group; in such cases, the map shows "Insufficient Data" to protect privacy and comply with federal data disclosure standards.

# Visualization, Adoption, and Preservation

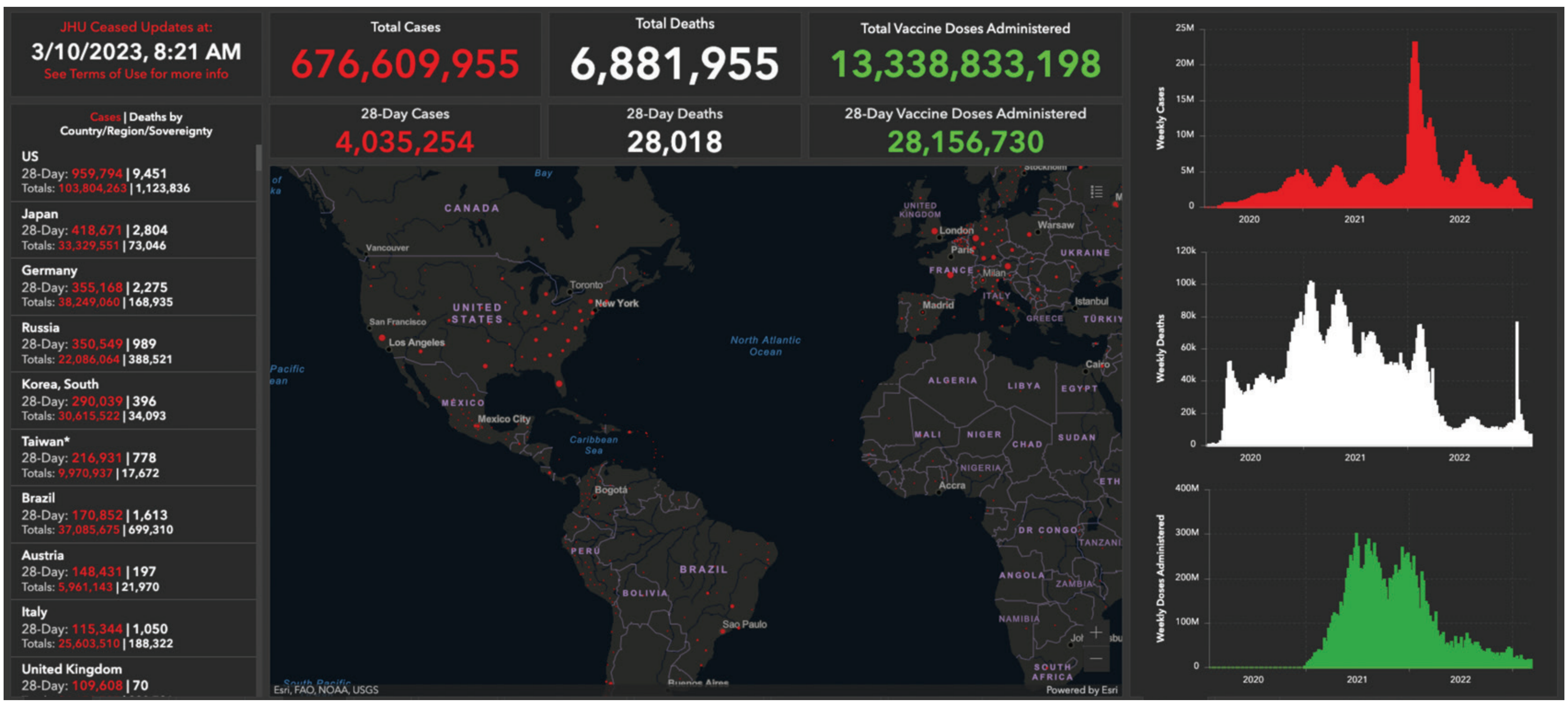


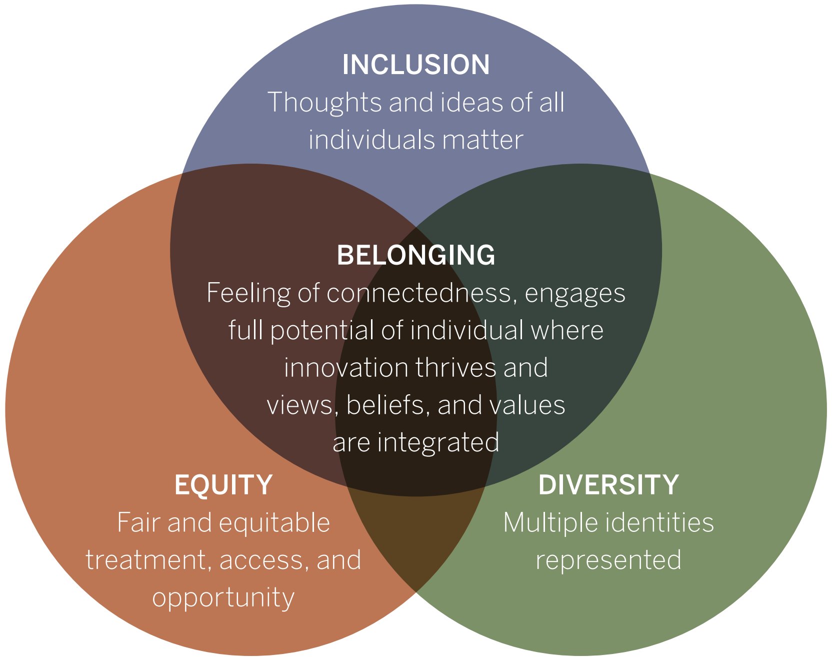

To create a visualization, one needs to pick a reference system and decide how to design data overlays. The number of possible combinations of graphic symbols and variable types is vast (page 9) and selection criteria are complex. However, many theoretical and practical guidelines exist that take human perception and cognition into account and are based on formal user studies. Here, we introduce several challenges of particular relevance for interactive visualizations.

## Visualization

When moving from static visualizations to interactive ones, it becomes possible to visualize data that may be continually updating, providing an ever-current view of the world at large. For example, the datasets represented in *Earth* (left and on page 24) refresh at various intervals, from once daily to every three hours. However, the computational resources required to support dynamic data updates, analyses, and visualizations can be considerable.

With regard to visualizing data about people, sensitivity as to how people are represented has drawn significant attention, and best practices continue to evolve. Ideally, macroscopes should be designed inclusively, incorporating data that reflects and serves a diverse range of users representing different age groups, genders, ethnicities, institutional affiliations, languages, and cultures.






## Adoption

The principles of diversity, equity, and inclusion illustrated on the left are essential for developing visualizations that foster a sense of belonging. This inclusive approach can lead to widespread acceptance and transformative changes in existing practices. Just as Henry Ford's automobiles necessitated new financing options to make them accessible to those who could not otherwise afford them, effective visualizations must be designed with inclusivity in mind to ensure they resonate with diverse users and are broadly adopted.

However, users who contribute to creating innovative solutions do not always benefit from the outcomes. For example, pathologists label magnetic resonance tomography (MRT) or computed tomography (CT) images to improve the accuracy of machine learning algorithms; while these tools enhance early disease detection, they may also render certain aspects of a pathologist's work obsolete. Similarly, employees who develop data visualizations to improve corporate efficiency might later face changes to their roles as work processes are optimized.

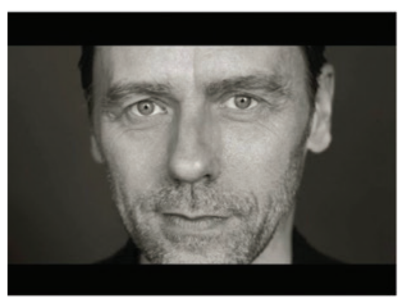
**COVID-19 dashboard**
The COVID-19 pandemic introduced global citizens to data visualizations as tools for interpreting rapidly changing public health situations. The Johns Hopkins Coronavirus Resource Center tracked and broadcast data from around the globe nonstop from January 22, 2020, to March 10, 2023. The *COVID-19 Dashboard* (at left) served as a trusted information resource for individuals, news organizations, and governments. Over the period tracked, 677 million people contracted COVID, 6.9 million died, and 13 trillion vaccinations were administered.

Plus, global data visualization literacy increased considerably as millions learned to read graphs with logarithmic axes and what it means to "flatten the curve."


Andrew Levinson on the *United States Water Crisis* macroscope

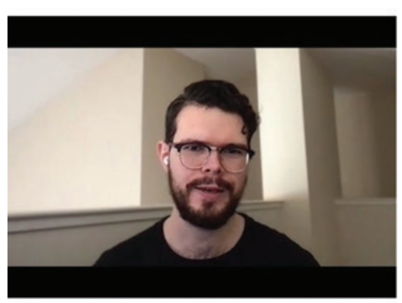

Andrew Levinson on the virtues of working ahead

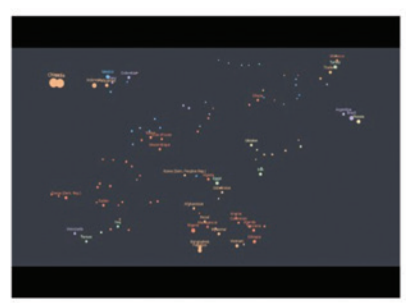

Carrie Longley on communicating science through sculpture


Ingo Günther: Artist of spherical information


Kalev Leetaru on how news stories create unlikely communities


Marc Smith: Taking snapshots of virtual communities


Nikita Rokotyan on creating *An Alternative Data-Driven Country Map*


Nikita Rokotyan on the power of dimensionality reduction


Steven Ross on the origins of the *Watson News Explorer*

## Preservation

When stored in dark, dry, temperature-controlled environments, books and maps can be preserved for hundreds of years. Macroscopes, on the other hand, are an ephemeral resource, as they might rely on real-time data streams that run dry. Interactive behavior is also difficult to preserve—as new web browser generations are deployed, some data visualizations will stop working properly. Indeed, several of the macroscopes discussed in Part 2 now work only partially and have been replaced by videos and interviews showcasing their past functionality. In that way, demonstrations of their unique interactive nature are available to future audiences at **scimaps.org** and the *Places & Spaces* Zenodo community at **zenodo.org/communities/macroscopes**.

# Human–Machine Symbiosis

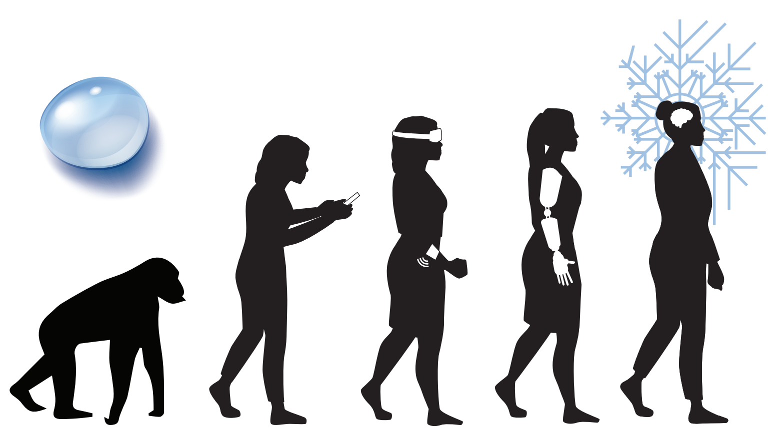
The most urgent questions we face today are those that have preoccupied human thought for centuries: What makes us human? How can we ensure that all humans flourish? What does the future of being human entail? Macroscopes can help us answer these questions by providing easy access to complex data—with a low floor for novices (to quickly grasp the given content) and a high ceiling for experts (to achieve expansive, high-level results). They can help us explore different interventions and agree on desirable futures that can be implemented locally and globally.

## Machine learning

The recent deployment of large language models (LLMs) and other deep learning models makes it possible to use massive datasets to generate answers, code, poems, and visuals at a quality and quantity never seen before. Soon, LLMs will have absorbed much of human culture—including many of our human biases and weaknesses. How can we ensure that these models do not simply reproduce or exploit the worst of human nature? How can we know what an artificial intelligence system has learned? How can we predict what it is capable of doing or how it might react in a new situation? In other words, how can we engage in human–machine symbioses that will ideally protect and heal, not harm, all of us and our planet?

Macroscopes such as *A Visual Introduction to Machine Learning* (page 120) help communicate visually how AI learns. Other macroscopes help us explore what is happening globally as well as long-term trends. This might save lives in medical practice, increase security and efficiency in transportation, improve food safety and sustainable farming, and help reduce or reverse climate change.

**Sentient architecture**
*Amatria* is a sentient architecture installation in Luddy Hall, Indiana University Bloomington. Foreshadowing a future where interlinked sensors, actuators, and artificial intelligence are omnipresent, this responsive sculpture was created to demonstrate how embedded technologies affect humans who live and work in spaces that combine human and machine intelligence, and how this symbiosis impacts what humans create next. *Amatria* has inspired poems and musical compositions, served as an interdisciplinary community gathering place, and is frequently used as a background in graduation, wedding, or other photos.



**From water drop metaphor ...**
For many millennia, humans have inhabited or built homes that use the least amount of surface area to enclose the most volume—keeping heat inside while allowing for safe shelter.

**... To snowflake metaphor**
Today, our lives are filled with electronic devices, and the effects of global warming are noticed around the world. We see the increased need to cool rather than heat the spaces we inhabit and to embrace local and global connections.

# Humanexus

*Humanexus* is a semidocumentary animation that visualizes human communication from ① prehistoric times to ③ today and ⑤ beyond. It aims to make tangible the enormous changes in the quantity and quality of our collective knowledge and the impact of different media and communication systems on knowledge exchange. Over time, knowledge exchange has become more global, effective, and rapid.

② With the advent of computers in the 1940s and the popularization of the internet in the 1990s, information exchange between computers and humans became possible.

③ Today, we are expanding and interlinking our social and technological networks on a global scale, we have moved much of our activities online, and most of our digital footprints are stored and can be traced and mined by others.

④ The intensity and immediacy of information flow effectively creates a global brain, or a humanexus of billions of biological brains and many more technological artifacts that are continuously searching, sensing, reasoning, and acting. In the process, our lifestyles, knowledge, and communication are shifting continuously and drastically.

⑤ If we have not yet destroyed elements critical to our survival on Earth, various uncanny futures potentially await: We might drown in the great flood of (un)confirmed facts, wash out our identity in massive information waves, or become disembodied and detached from the real world. Many people may decide to discard their mortal body and to upload their intellect to the internet, yet their individual identity in cyberspace might get quickly diluted and soon erased. Alternatively, we can combine human and machine intelligence to invent sustainable futures, use technology without abusing it, and master technology to ensure that we remain in control of our collective destiny. In addition, we might aim to answer questions about the meaning of life, how to reduce suffering on Earth, and what futures are most desirable for all of us.


Watch the Humanexus animated semidocumentary film at our Zenodo community (**zenodo.org/communities/macroscopes**).

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We are grateful to work with a phenomenal team of colleagues, friends, and experts around the globe on the exhibit and the macroscopes featured in it. The works of 112 macroscope makers are presented in this *Atlas* and we cherish the close collaboration and fruitful interactions with these world-leading experts (see Macroscope Maker Biographies, page 140).

There are significant technical and logistic challenges involved in bringing interactive visualizations to venues around the globe while accommodating continuously evolving web browsers and operating systems. To address these, the CNS programmer team—including Bruce W. Herr II, Leonard Cross, Daniel Bolin, Gurjaspal Singh Bedi, and Bhushan Khope—worked closely with Michael Boyles, David Reagan, and Patrick Beard from Indiana University's Advanced Visualization Laboratory to create and maintain a touchscreen kiosk for displaying the macroscopes. We thank Esmé Middaugh, Linnea Holt, and Ezra Engels who served as exhibit assistants helping with the exhibit submission, review, and implementation process and the considerable logistic challenges in bringing maps and macroscopes to many venues around the globe.

The current and past exhibit advisory board members listed below brought their considerable expertise to bear on the project by providing guidance and gathering to deliberate the selection of pieces each year. The exhibit ambassadors listed below served as local hosts and contacts for exhibit and data visualization events and efforts across all continents except Antarctica.

Together, over the last 10 years, we had the pleasure of introducing our collection of visualizations to nearly 475 venues, welcomed tirelessly by kind hosts at the David J. Sencer Museum at the U.S. Centers for Disease Control and Prevention, the Davos Economic Forum, the International School and Conference on Network Science, Vanderbilt University, and many other venues. In addition, we co-organized a number of related events, including a 2021 Dagstuhl Seminar in Germany on *Multi-Level Graph Representation for Big Data Arising in Science Mapping*, a Data Visualization Bazaar in 2022 that included AI-generated textile designs and social robotics, a 2019 Association of Science Technology Centers (ASCT) workshop introducing the Make-A-Vis technology platform for data visualization literacy in science museums, the 2023 International Conference on Scientometrics & Informetrics (ISSI), and a 24-hour online event in 2023 titled *Macroscopes: Interactive Data Visualizations* that brought together more than 600 experts from many scientific disciplines to communicate the power of data visualizations to experts and general audiences.

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① Exhibit curators Todd N. Theriault, Katy Börner, and Elizabeth G. Record with exhibit assistant Ezra Engels in front of *Spain Lives in Flats*, from the exhibit's 19th iteration, 2023; ② Exhibit advisor Francis Harvey transporting exhibit posters to display in Leipzig, Germany, 2018; ③ Curator Elizabeth G. Record and exhibit assistant Linnea Holt unpack maps in the IU warehouse for the 16th Iteration debut event, 2020; ④ 2023 in-person retreat attendees from left, Stephen M. Uzzo, Todd N. Theriault, Tim Utter, Gary Berg-Cross, Elizabeth G. Record, Katy Börner, and Ezra Engels.


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