Atlas of Forecasts

Modeling and Mapping Desirable Futures

Katy Börner

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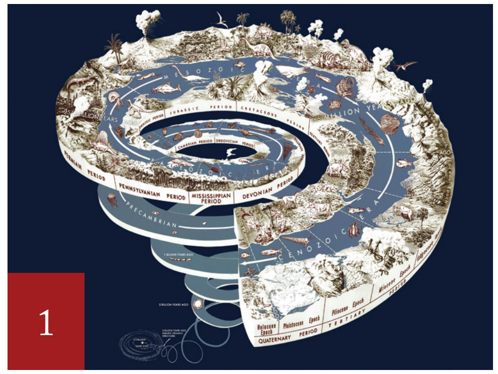

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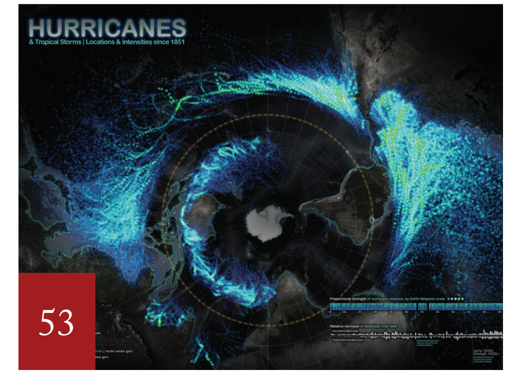

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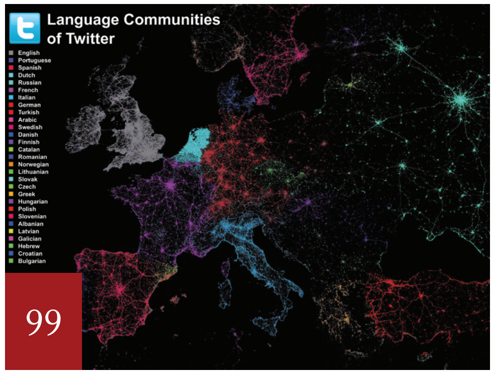
Language Communities of Twitter

Foreword

This is a wonderfully instructive guide on using models to forecast the future—serving not only as a compendium of model forecasts, but as a veritable atlas of what is otherwise a difficult and precipitous terrain to navigate. It catalogs the way scientists attempt to forecast the future using computer models; and in parallel with the two previous *Atlases* in this series, it shows how experts and nonexperts alike might exploit the power of data visualization to make sense of a world where predictions are an essential means of designing a better future.

We build models primarily to understand the world through abstraction and simplification. As part of that understanding, we expect our models to have some predictive power, or at least to inform us about possible futures, if not to enable us to produce good designs for such futures. In this sense, models allow us to sharpen key questions and engage in considered speculation, while at the same time offering us ways to explore what is likely to happen in the near future and engage in long-term speculation. In all these contexts, models help us conduct a dialogue about our objects and systems of interest, as well as the stakeholders who empower them, so that we might improve our understanding in order to generate insights into the unknowable future.

In the middle of the last century, use of the term "model"—to represent the translation of a theory into a visual form for experimentation in making predictions—was still very new. The term took hold as it became increasingly evident that digital computation provided the right kind of environment for exploring models of systems on which we could not experiment directly. As these ideas matured, traditional scientific laboratories also began to develop computational models alongside physical experimentation, with the term "model" in widespread use by the millennium. All these perspectives are embraced by Katy Börner in *Atlas of Forecasts*. Each *Atlas* she has produced, and particularly this one, is underpinned by models—they were used extensively in her *Atlas of Science: Visualizing What We Know* (2010), which illustrates the power of maps in science, and in her *Atlas of Knowledge: Anyone Can Map* (2015), which focuses on the power of visualization. In this third *Atlas*, the power of models that enable us to develop theory and predict alternative futures forms the backdrop on which the role of models in forecasting is explored.

Furthermore, during this period when models, and especially computer models, have come to the fore, we have learned much more about the context in which we might use such models for forecasting. We are now far more skeptical of our ability to forecast than we were in the middle of the last century, as our love affair with positivism—the search for "truth"—has weakened. This is due as much to the emergence of a pluralistic world, wherein many different theories compete for our attention, as it is to the existence of many different models reflecting manifold perspectives on the increasing complexity of our technologies and politics. In short, we now know that the future is unknowable and that only in principle are we able to design and invent it, and we certainly cannot predict what we might invent. In developing models in science and policy, we therefore face a set of tangled dilemmas on how our models can best be used. The recent emergence of the COVID-19 virus shows how we always need to be aware of the limits to our models and how those models need to be adapted to events that we might never be able to forecast. The intricacy of this argument is reflected in many discussions about both the past and the future; as the great mathematician Pierre-Simon Laplace said in 1814, "We may regard the present state of the universe as the effect of its past and the cause of its future."

In this *Atlas*, Katy Börner first provides us with a bird's-eye view of the long history of developments in the generic field of modeling, introducing a wide range of models that define the scope of our forecasting abilities. Models can be classified in countless ways, from descriptive to predictive to prescriptive. They can be organized by scale; by the way their components are represented, from aggregates to agents; by the different methods used for simulating the dynamics that describe the system in question; and by the way their components are integrated using networks and similar logics. In the Preface, Börner outlines the structure of the *Atlas*, showing how such ideas about models form an essential prelude to applications in the areas of population, transportation, digital communications, and urbanization. The maps of science that emerge from those ideas then take us forward to using models to map and forecast various futures that embrace arguments pertaining to risk, bias, uncertainty, and sustainability.

The development of models across the many domains presented in the *Atlas* will continue to advance. Future developments in integrating models of different sectors at different scales will make it possible to build models that are ever closer to the physical and social systems being simulated. The focus is currently moving to generating various kinds of digital twins which are digital replica of systems of interest—also called counter-modeling. Plus, there are novel models that show how description, prediction, and prescription can be integrated to inform our understanding of the future. While many of the models that Katy Börner includes are quantitative, important qualitative representations are also illustrated, particularly with respect to the way models are used to inform a broader dialogue about how we can best understand a system of interest and optimally explore, manage, and design it for a better future. The three *Atlases* together produce a living portrayal of the dynamism of modeling, simulation, and visualization, and together tempt us to speculate on what terrain the next *Atlas* might map.

Michael Batty
Center for Advanced Spatial Analysis
University College London

Preface

Many personal and professional decisions can be difficult to navigate, especially when it comes to making the most well-informed choices. Examples include how to find or maintain trusted friendships, what and where to study, what job to take, whom to marry, or where to live and work. Decisions like these tend to become easier when you use the power of big data and predictive models to understand the importance of time and space, the power of social or professional networks, and how what has worked before is likely also to be successful in the future.

People regularly benefit from computational predictive models when following recommendations for books by Amazon, movies on Netflix, or partners suggested by online dating sites. Similarly, models in the sciences aid in the synthesis of information, enabling appropriate plans and actions toward achieving optimal results.

In particular, models that track and predict climate change or the spread of disease can help us identify and agree upon long-term, global solutions. Models of science and technology (S&T) development help us invest our resources—not only time, expertise, and funding, but also focus and compassion—in a way that maximizes return on investment; the impact of workforce education on progress in S&T development; predict information diffusion and product adoption; and understand the likely consequences of different policies on people's future behavior.

Validated models tell us the probability of a particular outcome—given a set of parameters and based on current knowledge and data. They help provide credible scientific evidence in a complex, ever-changing world. Visualizations of model results help communicate the likely consequences of today's decisions on tomorrow's state of the world.

This *Atlas of Forecasts* introduces major model classes and applications to a general audience, using real-world examples and advanced data visualizations. It demonstrates the power of models to understand and predict the structure and dynamics of diverse sociotechnological systems, from micro to macro levels. It also serves as a visual index to more than 1,300 books, papers, and case studies written by international experts, all cited in the *References & Credits* section.

As the third book in this trilogy, it builds on work presented in the *Atlas of Science: Visualizing What We Know* (2010), which introduced the power of science maps to guide our search for knowledge, helping us navigate and communicate the changing structure of science and technology, while making sense of the avalanche of data generated by new science and technologies. It also expands on the *Atlas of Knowledge: Anyone Can Map* (2015), which introduced a theoretical 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 which tools and workflows are best for answering a specific question.

The *Atlas of Forecasts* is organized as follows:

Part 1 introduces the utility and power of models; discusses which models might be used when; reviews the long history of humanity's efforts to forecast the future; and provides examples of models that truly make a difference.

Part 2 explains the general modeling process and details model design, visualization, and validation; then introduces and presents widely used expert-based descriptive and predictive model classes.

Part 3 starts with a discussion of model substrates—such as population, transportation, digitization, or urbanization—that provide important context for real-world modeling efforts; and then showcases specific models that have been successfully used to understand and/or support decision-making in education, science, technology, and policymaking at the micro, meso, and macro levels.

Part 4 features 30 large-format maps that aim to foretell and positively impact developments by inviting users to explore maps, trends, and likely futures of S&T mapmaking.

Part 5 envisions desirable futures by discussing modeling opportunities, the influence of human biases, managing modeling risks, building model-thinking capacity; and broadcasting actionable S&T forecasts.

The website at **http://scimaps.org/atlas3** features high-resolution images, references, and press coverage.

Work on this *Atlas* started more than 10 years ago. At that time, many of our colleagues and clients had adopted science maps for understanding and communicating past and current S&T developments. They were proud to be part of larger, interdisciplinary, and dynamically evolving teams in fields of science that saw rapid progress; they had metrics beyond single numbers—including citation counts or *h*-index—to evaluate the structure and dynamics of progress; and they were making informed decisions based on insights gained from S&T maps. However, they wanted to understand the likely impact of strategic and resource allocation decisions on future developments. Thanks to many significant factors—namely the increasing availability of scholarly and other relevant data; computational models developed in physics, economics, informatics, social science, and other fields; and available computational resources to run these models—it became possible to develop, run, compare, and validate S&T models. Key models and visualizations; their use in education, science, technology, and policymaking; and the likely futures of S&T models are featured in this book. It is our hope that this third *Atlas* will empower many to embrace not only the power of maps but also the power of computational modeling for personal and professional decision-making—so we can collectively identify pathways toward desirable futures.

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August 26, 2020

Acknowledgments

It has been an honor and absolute pleasure to discuss the development, application, and communication of models with scholars around the globe and to collaborate on models that make a difference in the real world.

Interestingly, many if not all existing modeling approaches—independent of their origin in physics, economics, epidemiology, social or other sciences—have also been used to understand the structure and/or dynamics of science and technology. Models originally developed to predict the spreading of disease or cascading power failures were almost immediately repurposed to predict such phenomena as the spreading of ideas or information cascades.

Over the last 10-plus years, our team has co-organized a number of events that brought together experts from many different scholarly domains to discuss and advance the modeling and visualization of developments in education, science, technology, or policy. The premiere workshop—co-organized with colleagues from the Royal Netherlands Academy of Arts and Sciences, in Amsterdam, the Netherlands—brought together experts to inventory and describe different types of models. That led to the next workshop on "Modeling the Structure and Evolution of Science," supported by the James S. McDonnell Foundation and held at Indiana University in Bloomington, Indiana. Relevant scholarly work was published in special journal issues—"Science of Science: Conceptualizations and Models of Science" in *Journal of Informetrics* (2009); "Modeling Science: Studying the Structure and Dynamics of Science" in *Scientometrics* (2011); and "Simulating the Processes of Science, Technology, and Innovation" in *Scientometrics* (2016)—showcasing research results and editorials that aimed to compare different model classes and create synergies across disciplinary boundaries. The Springer book *Models of Science Dynamics* (2012) provides a general introduction and diverse model examples.

Growing interest in explanatory and predictive models resulted in a burgeoning of the scope of events and the number and diversity of invited experts. Three events in particular—Forecasting Science: Models of Science and Technology Dynamics for Innovation Policy (2015) at the 15th International Conference on Scientometrics & Informetrics in Istanbul, Turkey (organizers are shown in the middle image); the Modeling Science, Technology & Innovation Conference (2016) at the National Academies in Washington, D.C., sponsored by the U.S. National Science Foundation (NSF) (see group photo below); and Modeling and Visualizing Science and Technology Developments (2017), an Arthur M. Sackler Colloquium at the Beckman Center in Irvine, California (see group photo on the far right)—brought together more than 400 experts from 40-plus disciplines, as well as various industries and government agencies, to discuss different model classes and applications, share data and code, and start novel collaborations. Extended versions of the best presentations from the Sackler Colloquium were published in a special issue on "Modeling and Visualizing Science and Technology Developments" in the *Proceedings of the National Academies of Science* (2018), available at **https://www.pnas.org/modeling**.

This *Atlas* aims to communicate the results from the many scholarly events and publications to a much larger community of decision-makers, so more of them can benefit from the explanatory and predictive power of models. Many models use advanced mathematics to cover complex dynamics, yet most decision-makers need immediate access to validated models and actionable insights. This

Modeling Science, Technology & Innovation Conference, National Academies, Washington, D.C.

Atlas features visualizations of model designs and results together with examples drawn from different domains (education, science, technology, and policymaking) and across different scales (micro, meso, macro) to support model implementation by many.

David Chavalarias, Richard Conroy, Susan M. Fitzpatrick, Fernando Galindo-Rueda, Iulia Georgescu, Wayt Gibbs, Eleanor B. Goldstone, Volker Grimm, Francis Harvey, Brian Hitson, Juan Mateos-Garcia, Michael A. McRobbie, Staša Milojević, William B. Rouse, Hiroki Sayama, Walter T. Schaffer, Andrea Scharnhorst, André Skupin, Robin Wagner, Morgan Wells, Mary Beth West, Uri Wilensky, and Larry Zhang kindly provided substantive expert comments on an earlier version of this *Atlas*.

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The work presented here was also supported and informed by extended stays and intensive collaborations with colleagues at the National Institutes of Health in (2010) and the Eidgenössische Technische Hochschule Zürich (ETH) in Switzerland (2011); sabbaticals at the Royal Netherlands Academy of Arts and Sciences (KNAW) in Amsterdam, The Netherlands (2012) and Organisation for Economic Co-operation and Development (OECD) in Paris, France (2014); and a Humboldt Fellowship at the Dresden University of Technology, Germany (2018-2020).

This *Atlas* was made possible by an amazing team effort: David K. Kloster, Caellaigh Klemz, Medina Sydykanova, Todd N. Theriault, and Michael Ginda diligently worked on copyright acquisition; Perla Brown patiently designed all custom figures; Todd N. Theriault rigorously compiled references; Gordana Jelisijevic professionally performed all copyediting; and Tracey L. Theriault designed the elegant and effective layout and book cover. Gita D. Manaktala, Erika Barrios, and Yasuyo Iguchi at MIT Press ingeniously mastered the many complexities involved in publishing this *Atlas* series.

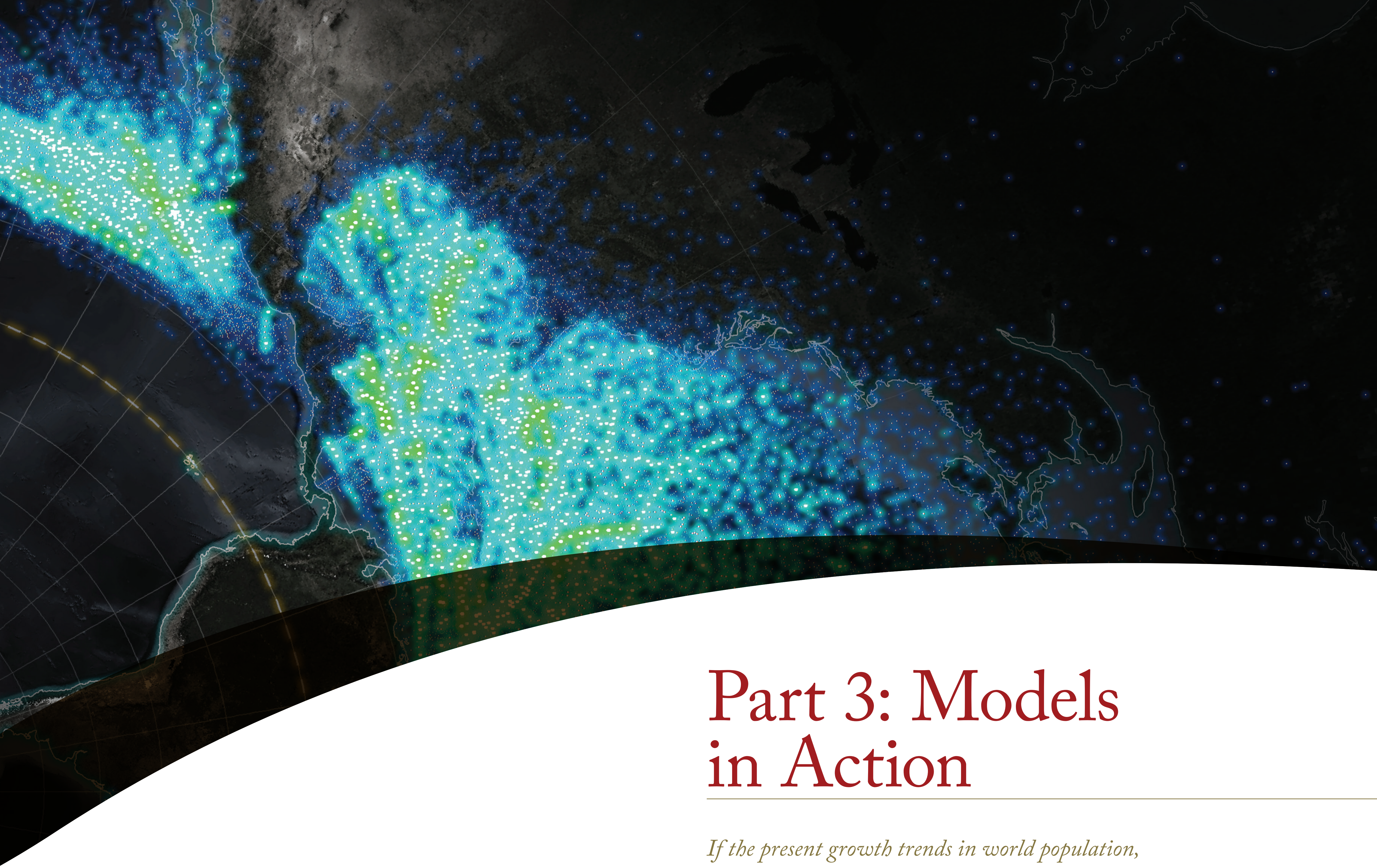
I would like to express my gratitude to the extraordinary team at CNS for providing a rich and supportive environment for testing and discussing models on team formation, resource allocation, and communication streamlining in a professional setting.

Last but not least, I thank my family for letting me explore models in personal decision-making—from picking winning recipes, to reviewing colleges for our daughters and comparing career trajectories, to making resource investment decisions.

This *Atlas* trilogy would not have been possible without the extensive professional and social support I received from colleagues, friends, and extended family—my sincere thanks go to you all.

15th International Conference on Scientometrics & Informetrics, Boğaziçi University, Istanbul, Turkey

Modeling and Visualizing Science and Technology Developments, Sackler Colloquium, Beckman Center, Irvine, CA



Part 3: Models in Action

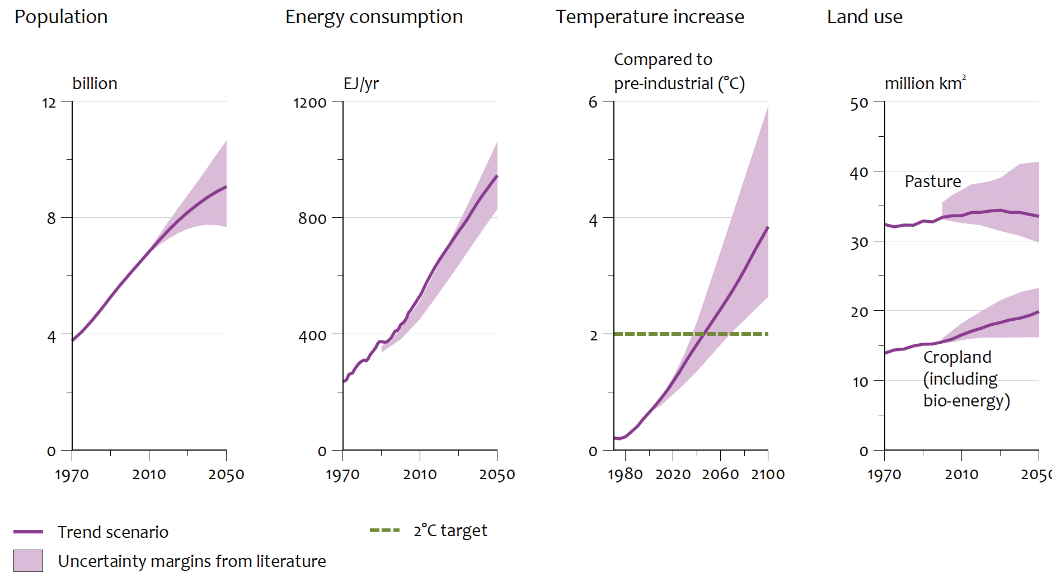
If the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years. The most probable result will be a rather sudden and uncontrollable decline in both population and industrial capacity.

Donella H. Meadows, Jørgen Randers, and Dennis L. Meadows

Model Substrates Overview

Fundamental constraints on an individual's or nation's future development include human resources (e.g., health and education), natural resources (e.g., water, food, and energy), climate and weather (e.g., affecting air quality and flooding), transportation (e.g., access to oceans, geospatial distance to major industrial centers, street and air traffic networks, price of postage), digitization (e.g., availability of compute power, computers, Internet, or phones), and urbanization (e.g., smart city development). This and the subsequent six spreads discuss the impact of these systemic constraints on the future of education, scientific and technological advance, and policy decision-making.

We all breathe the same air and drink the same water. There are no boundaries when it comes to the environment. The sooner we learn to survive on the mother earth, the better.
Bruce Sanchez

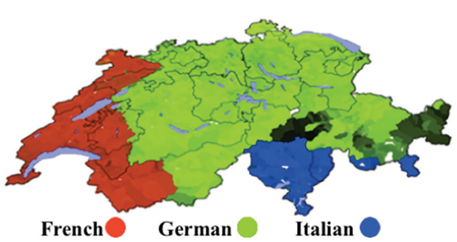


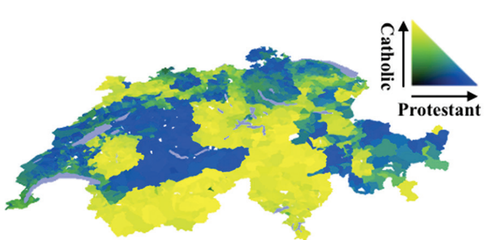
Constraints and Substrates

Natural, social, legal, and other constraints have a major impact on how past, present, and future developments unfold. When designing models or using model results, it is important to keep local and global constraints and their likely evolution in mind. For example, it makes little sense to build the best educational institution in an area that might soon be flooded due to climate change.

One way to introduce external constraints into system models is via substrates (also called base maps or reference systems, which are discussed in *Atlas of Knowledge*, **page 25**). Constraints become the reference system, and system dynamics (e.g., the evolution of author nodes and co-authorship links) can be represented as a data overlay.

For instance, if the number of scientific collaborations and citations is correlated with the number of face-to-face interactions, then the model could use a car, train, or air transportation network as a substrate. Analogously, a geospatial map might help indicate geographical features that likely impact system evolution.





Recent work by Alex Rutherford and colleagues entitled "Good Fences: The Importance of Setting Boundaries for Peaceful Coexistence" showcases how mountain ranges impact the diffusion and retention of language and culture. The paper features the two maps below left that show Switzerland's 2000 census proportion of linguistic groups (top) and Catholics and Protestants (bottom). Their findings indicate that mountains and lakes impact not only the delineation of linguistic areas and religious beliefs, but also whether peace or violence reigns among various groups (see also **Managing Risks, page 174**). Their model correctly predicts where peace prevails amid diversity, due to well-defined topographical and political boundaries.

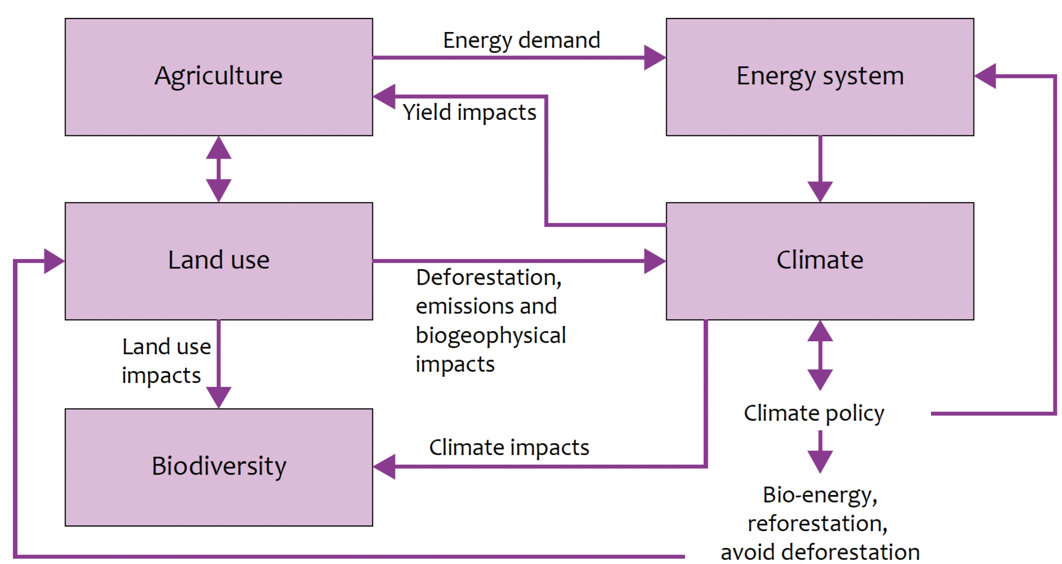
Research by Shahar Ronen and colleagues demonstrates the influence of language on the visibility and possible impact of its speakers. The authors examined three global language networks using book translations, multiple language editions of Wikipedia, and Twitter (see the figures in **Topical Models, page 69**). The nodes in those networks represent languages, and the links denote which languages are co-spoken. Results show that English is a global hub; intermediate hub languages include Spanish, German, French, Russian, Portuguese, and Chinese. Languages with high centrality in the network contribute to the visibility of its speakers and the global popularity of the cultural content they produce.

Börner and colleagues mapped evolving citation networks for the top 500 most-cited U.S. research institutions, showing spatiotemporal changes over a 20-year time span. Surprisingly, the introduction of the Internet did not affect the distance over which information diffuses, as manifested by citation links.

Trends and Interdependencies

Constraints are interdependent (e.g., due to human behavior, culture, and the environment), and their interdependencies need to be understood in order to improve outcomes.

Growing within Limits, a 2009 report by PBL Netherlands Environmental Assessment Agency, features global trends in human population, energy consumption, temperature increase, and land use—as shown in the four graphs at top right. The report argues that "business as usual" could severely threaten the sustainability of human life on Earth, and that intelligent steps must be taken to counteract current trends in climate change and biodiversity loss. It highlights the importance of policy packages for establishing and implementing a green economy with zero-carbon energy options, improved energy efficiency and agricultural yields, better-conserved ecosystems, and healthy lifestyles. Effective policies require a deep understanding of relevant, interlinked complex systems; agreement on long-term targets; and strict regulations to ensure that targets are reached in a timely fashion. The report argues that models can be applied to predict the likely impact of policy changes. As one example, it features the conceptual model below (see also **page 5** and **Model Visualization, page 20**), which shows five relevant system components—agriculture, land use, biodiversity, energy, and climate—and their interlinkages. Climate policy changes are likely to affect any of the five systems. Similarly, changes in land use tend to impact all other components.



PLANETARY BOUNDARIES				
Earth-system process	Parameters	Proposed boundary	Current status	Pre-industrial value
Climate change	(i) Atmospheric carbon dioxide concentration (parts per million by volume)	350	387	280
	(ii) Change in radiative forcing (watts per metre squared)	1	1.5	0
Rate of biodiversity loss	Extinction rate (number of species per million species per year)	10	>100	0.1–1
Nitrogen cycle (part of a boundary with the phosphorus cycle)	Amount of N_2 removed from the atmosphere for human use (millions of tonnes per year)	35	121	0
Phosphorus cycle (part of a boundary with the nitrogen cycle)	Quantity of P flowing into the oceans (millions of tonnes per year)	11	8.5–9.5	~1
Stratospheric ozone depletion	Concentration of ozone (Dobson unit)	276	283	290
Ocean acidification	Global mean saturation state of aragonite in surface sea water	2.75	2.90	3.44
Global freshwater use	Consumption of freshwater by humans (km^3 per year)	4,000	2,600	415
Change in land use	Percentage of global land cover converted to cropland	15	11.7	Low
Atmospheric aerosol loading	Overall particulate concentration in the atmosphere, on a regional basis		To be determined	
Chemical pollution	For example, amount emitted to, or concentration of persistent organic pollutants, plastics, endocrine disrupters, heavy metals and nuclear waste in, the global environment, or the effects on ecosystem and functioning of Earth system thereof		To be determined	

Planetary Operating Boundaries

Many subsystems of Earth show emergent behavior that is difficult to understand and predict. Most react in a nonlinear and often abrupt way; small changes in input variables, such as temperature changes, can lead to tipping points, with potentially irreversible system state changes (see **pages 14–15**).

Work on "planetary boundaries" aims to identify the key components of Earth and a safe operating space for each. A specific focus is the identification of threshold levels for key variables, which if crossed lead to the failure of important subsystem components or to new system states with potentially disastrous consequences for the human population.

The table above shows the boundaries for 10 important process components, which are listed in the first column. Proposed parameters and their boundaries, current status, and preindustrial values are subsequently provided. A red-hued background is used for the top three process components (in contrast to the surrounding pale green) to emphasize their current status has crossed the proposed boundary and is higher than during preindustrial times. Values for atmospheric aerosol loading and chemical pollution are yet to be determined.

Six Substrates That Impact Future Developments

The subsequent six spreads introduce six sociotechnical subsystems that have a major impact on future developments in ESTP. The subsystems provide important constraints, or substrates, that must be considered when developing models.

Population: Health and Education

Population health and education impact which workforce is available to teach the next generation, advance science, or develop and implement new technologies. The expertise, knowledge, and attitudes of citizens influence which policies are developed and adopted; those policies in turn impact population demographics, health, and literacy (see the **Micro** to **Macro** spreads on **Policy—pages 80, 88,** and **96**).

Natural Resources: Water, Food, and Energy

Natural resources, such as water, food, and energy, have wide-ranging effects on ESTP developments. For example, water shortages might lead to innovation in desalination; natural gas limits might cause investments in sustainable energy.

Climate and Weather: Pollution and Flooding

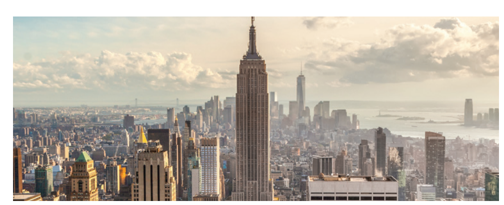
Climate and weather impact, for instance, which land areas might soon be flooded or which cities suffer pollution that compromises the health and cognitive abilities of citizens.

Transportation: Land, Maritime, and Air

Transportation infrastructure—the coverage and quality of land, maritime, and air transport routes—dictates where and how fast people and goods may travel, yet it thereby also influences potential disease transmission.

Digitization: Computing and Communication

Digitization refers to storing, computing, and communicating data, knowledge, and expertise. It makes it possible to combine human and machine intelligence to arrive at desirable futures; different scenarios are explored in the film *Humanexus*, which animates human communication through the ages amid three projections into futures that may or may not be desirable.



Urbanization: Segregation and Migration

Urbanization leads to hyperconnected cities that attract talent and resources, and efficiently develop new ideas and products. Smart cities manage to address such stresses as homelessness or the loss of family cohesiveness.

Population: Health and Education

Population size, demographics, health, and education have a major impact on the wealth and happiness of a region or country. The stage of "peak child" was reached in 2018; since then, the number of children born per year has been decreasing. However, people are living longer, healthier lives, leading to both an aging population and a continuing population increase. Conversely, accelerated lifestyles over the last 100 years have resulted in greater stress and associated illnesses. Providing education and workforce training for increasingly sophisticated work opportunities whose skill requirements are rapidly changing presents abundant challenges.

Anyone who believes exponential growth can go on forever in a finite world is either a madman or an economist.

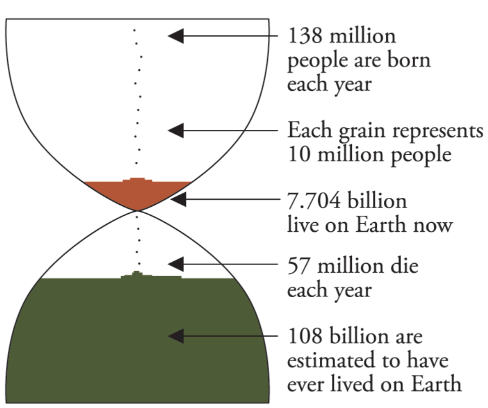
Kenneth Boulding

Population and Demographics

Atlas of Science (**pages 2–3**) opens with a graph that shows the enormous increase in world population from 1,000,000 BC to the projected time of AD 2200. Considerable population increase has occurred in just the last two centuries, from 1 billion people in 1800 to 7.8 billion people in 2020.

The *Hourglass of Life* image below uses 2019 data to show the number of people born per year, the number currently living (in brown), the number of deaths, and the total number of people estimated to have ever lived on Earth (in green). The 2020 daily averages of 380,000 births and 160,000 deaths translate to a population increase of about 220,000 per day.

The United Nations *World Population Prospects* 2019 provides past, present, and predicted future data for total fertility. The three maps at right show medium fertility rates at the country level for time periods starting in 1950, 2020, and 2095. Countries shown in dark red have an average of eight or more live births per woman; those in yellow have three; and those in dark blue have two or less. Over the 150 years covered, fertility rates appear to decrease drastically, with most countries expected to have a rate of no more than two births per woman by 2100.



Despite the decrease in the number of children being born, there is a steady increase in population due to increasing life expectancy (see **Health** below), which causes substantial changes in demographics (see **Demography of the World Population from 1950 to 2100** and **Demographic Transition in Five Stages** on the opposite page).

Human migration has been rapidly and in some cases substantially changing national population rates and demographics. Estimates by the United Nations indicate that about 70.8 million people left their home countries because of conflict or persecution at the end of 2018. Flow maps of human migration can be found in *Atlas of Knowledge* (**page 18**, lower left; and **page 55**, top right).

Health

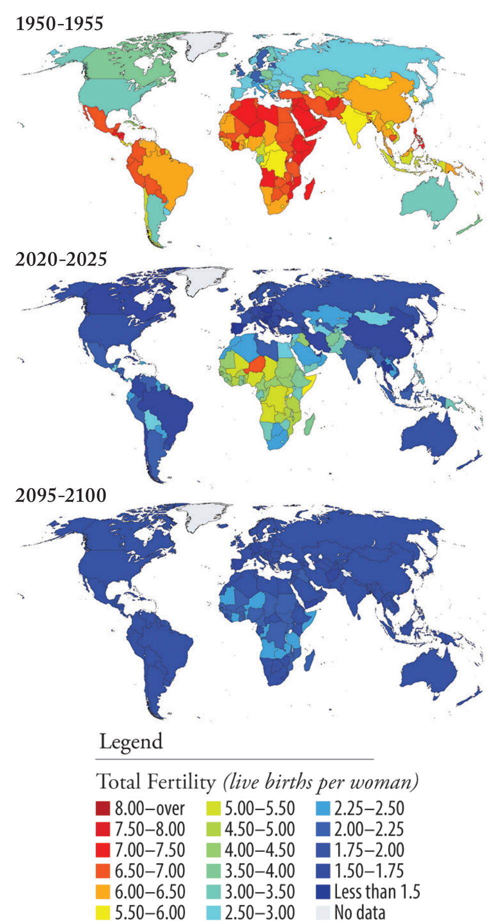
The last 20 years have seen a steady increase in life expectancy. In fact, the record female life expectancy has been increasing every 30 years by 7 years; concretely, that means every new generation (if born 30 years later) is likely to live 7 years longer than the preceding one (see also **Broken Limits to Life Expectancy, page 80**). Most children born since 2000 in countries with long life expectancies will live to celebrate their 100th birthday.

According to Kaare Christensen and colleagues, "The remarkable gain of about 30 years in life expectancy in Western Europe, the USA, Canada, Australia, and New Zealand—and even larger gains in Japan and some western European countries, such as Spain and Italy—stands out as one of the most important accomplishments of the 20th century."

Life expectancy is strongly impacted by intrinsic and extrinsic factors, or nature and nurture (see **Population Health and Life Expectancy** on the opposite page). Genetic predispositions make certain diseases more or less likely. A well-balanced lifestyle—comprising proper nutrition, exercise, sufficient sleep, and rich social networks—typically leads to a longer life with stronger physical and cognitive health.

Work by James H. Fowler and Nicholas A. Christakis shows how people embedded in family and social networks may share similar (over)eating and smoking behaviors, as well as levels of happiness.

Importantly, the health of a population has a major impact on the economic prosperity of a nation, as the disease burden caused by significant illness (e.g., depression, obesity, cancer) can be substantial.



A healthy workforce is able to learn, innovate, and produce more than a workforce that is sick at home. Poor health and unhealthy behaviors can also cause educational setbacks or interference with schooling, which ultimately impacts educational outcomes such as requisite skills and expertise.

Education

Education refers to the instruction and acquisition of core knowledge, skills, and values. Learning, both academic and experiential, can take place in formal or informal settings—from classrooms and seminar halls, to museums and parks, to homeschooling.

Atlas of Science (**page 25**) discussed H. G. Wells's 1938 estimation that it would take 2,400 hours of education (6 hours a week, times 40 weeks per year, times 10 years) to teach common citizens what they should know to live productive lives. Children born after 2000 in developed countries likely spent 10 times as many hours in formal education, followed by ever more hours in on-the-job training and continuous re- and upskilling efforts.

With tens of millions of workers whose jobs are being transformed by artificial intelligence (AI) and automation in the U.S. alone, lifelong learning has never been more important and valuable to employers and employees. In addition to technical skills, 21st-century social skills (including social and emotional intelligence) are just as important, as many major S&T and societal challenges require efficient teamwork.

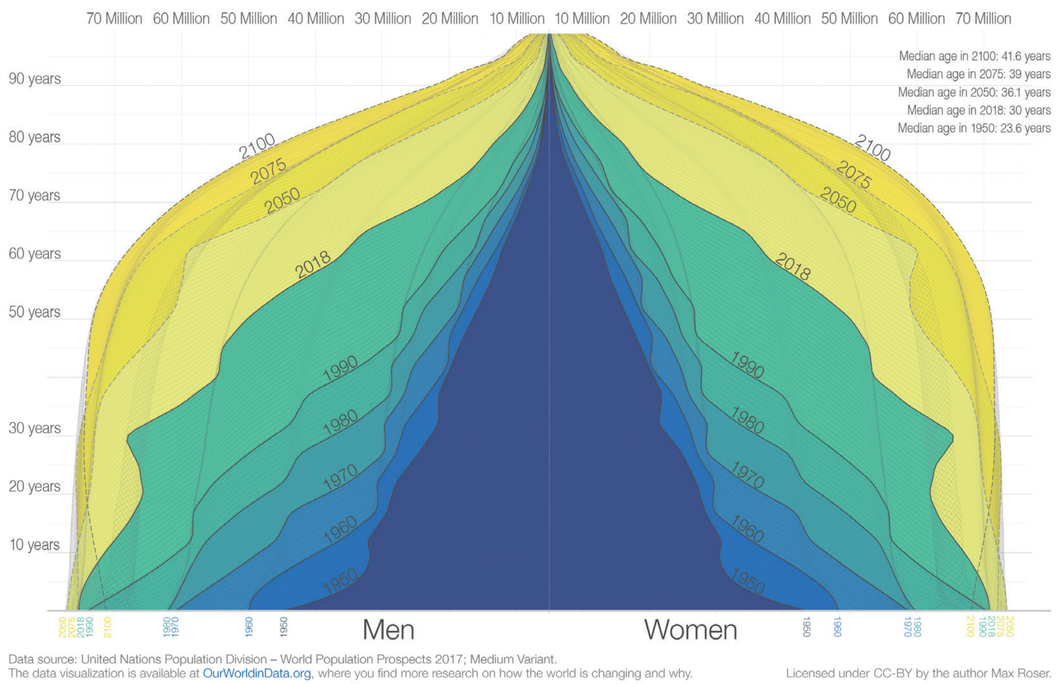
Students and current employees need to understand, for instance, which types of jobs will exist in the near future, which colleges offer a future-proof and efficient education, and what kinds of skills are required for a given dream job (see **Micro: Education, page 74**).

Education decision-makers need to understand changes in the landscape of public and private universities; they need to apply new theories of learning to design and deliver ever more effective teaching and learning experiences—in classrooms and online (see **Meso: Education, page 82**).

At the macro scale, skill indicators need to be understood, while discrepancies between academia, industry, and education (i.e., new insights derived from scholarly research vs. job skills that industry demands vs. material taught in classrooms) must also be overcome (see **Macro: Education, page 90**).

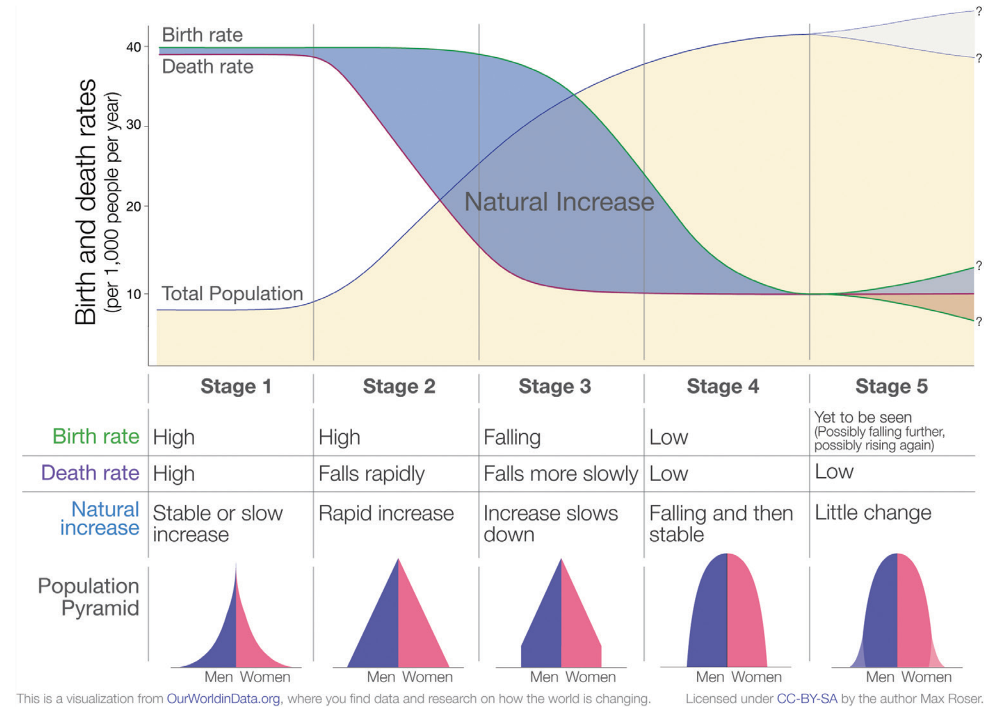
Demography of the World Population from 1950 to 2100

Population pyramids represent the distribution of age groups in a population. If a population is shown to be rapidly growing, the graph looks like a pyramid; if aging, like a mound. The total area size corresponds to the number of people alive. The graph below shows the worldwide aging demographics and population increase over 150 years.



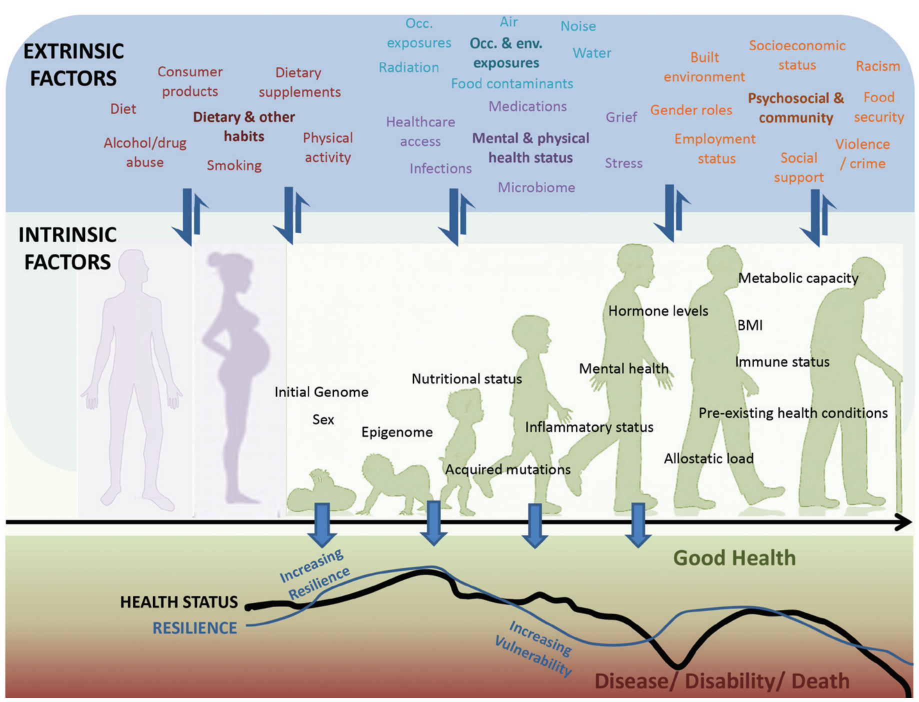
Demographic Transition in Five Stages

This demographic transition model is based on European data. It predicts that all countries follow a trajectory from low economic growth with high birth and death rates (Stage 1), via increasing economic capabilities with high birth rates and decreasing death rates, to high economic power with low birth and death rates (Stage 5).



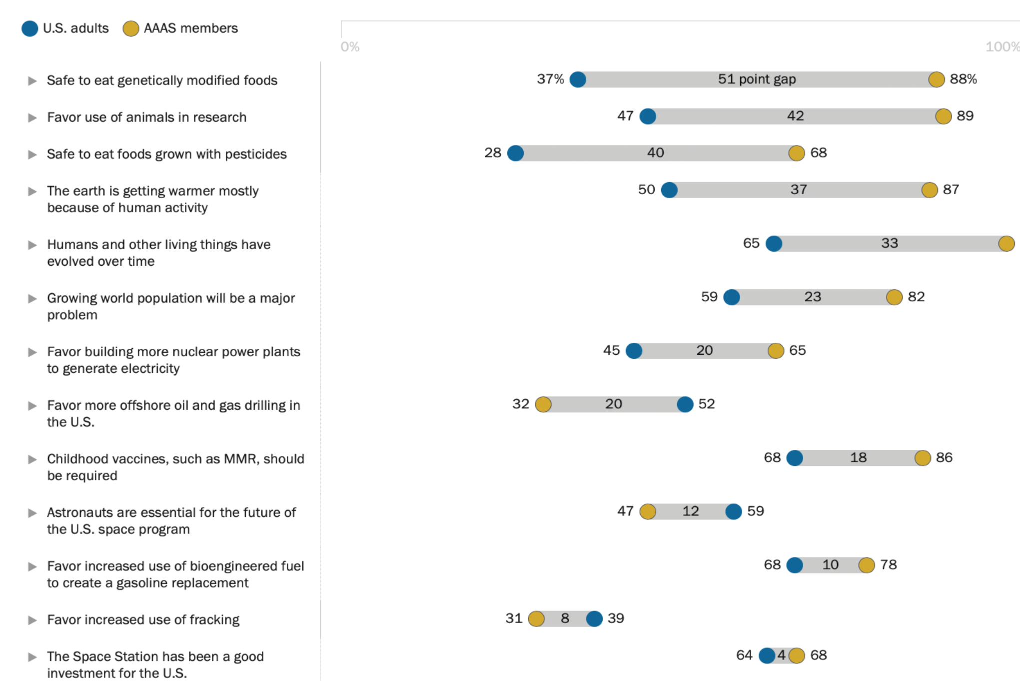
Population Health and Life Expectancy

The graph below lists extrinsic and intrinsic factors and their impact on health status (black line) and resilience (blue line) over a human's lifetime. Extrinsic factors are color-coded and grouped by four main types. Both types of factors impact physical and mental health, disease susceptibility, disability probability, and death.



Major Gaps in Views: The Public vs. Scientists on Key Issues

Literacy includes scientific literacy. The graph below shows how U.S. adults in general (blue dots) and the American Association for the Advancement of Science (AAAS) community in particular (gold dots) hold vastly differing opinions on scientific issues. Of particular note is the top response indicating a 51% gap in views on genetically modified foods.



Natural Resources: Water, Food, and Energy

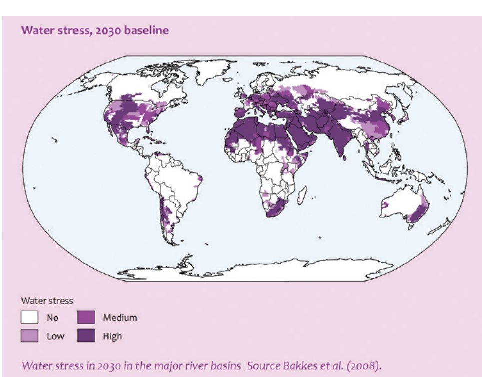
Population growth results in a growing demand for primary resources such as water, food, and energy. Progress in science and technology has led to increased efficiencies in harnessing those resources, albeit within definite limits (see **Planetary Operating Boundaries, page 55**). The World Economic Forum has identified freshwater scarcity as the most critical risk, since it threatens the viability of the global economy, the environment, and human lives. Given the long-standing threats (over more than a century) of falling water tables, climate change, and various forms of water pollution, half the world's population could be living in areas with severe water stress by 2030, according to the Organisation for Economic Co-operation and Development (OECD).

Eat food. Not too much. Mostly plants.
Michael Pollan

Water

Water covers about three-quarters of the planet. The oceans contain enough water to fill a cube of about 1,000 km^3. Only 2.5% of all water is freshwater. Two-thirds of that freshwater is trapped in glaciers and ice caps. Nonfrozen freshwater, the remaining one-third, is very unevenly distributed around Earth.

Agriculture accounts for about 70% of water usage worldwide. Climate change impacts the hydrologic cycle, leading to reduced precipitation and greater water scarcity. Many regions are experiencing water stress, namely increasing drought, causing major economic risks and higher poverty levels. That trend is expected to continue. The map below by Jan A. Bakkes and colleagues features an overlay of water stress predicted for 2030 in major river basins; highly stressed areas, rendered in dark purple, include most of Europe and the U.S., and all of India.



Water stress in 2030 in the major river basins Source Bakkes et al. (2008).

Balancing water needs for humans and nature is critical, especially in vulnerable areas.

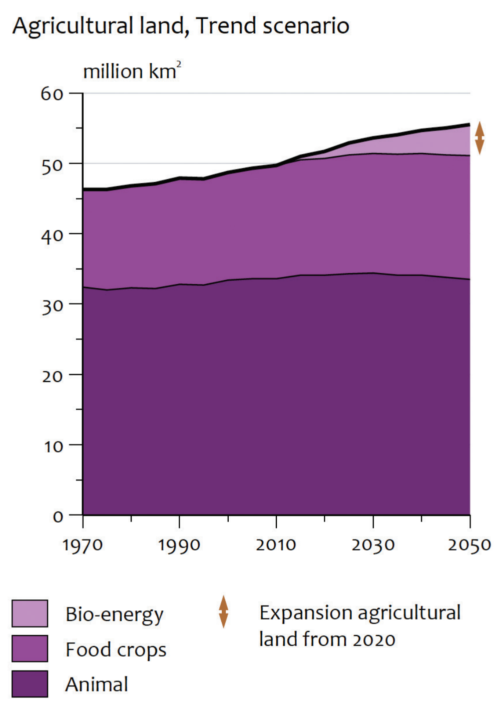
Food

According to PBL Netherlands Environmental Assessment Agency, about three Earths are needed to provide a Dutch standard of living for everyone, given current food processes and efficiencies.

The graph below visualizes predictions by PBL, within a 1970–2050 time frame, regarding the likely expansion of agricultural land as of 2020. In addition, more than half of all land appears to be used for animal production, and a much smaller but increasing amount for bioenergy.

The large environmental footprint of the global food system is causing biodiversity loss, greenhouse gas emissions, water shortages, ecosystem pollution, and land degradation (see **Transformation of the Biosphere** on the opposite page).

Solutions to these challenges include the increased consumption of crickets, for instance, rather than beef and pork, since insect farming requires considerably less feed and water for the same amount of protein (see **A Smarter Way to Utilize Land** at right).

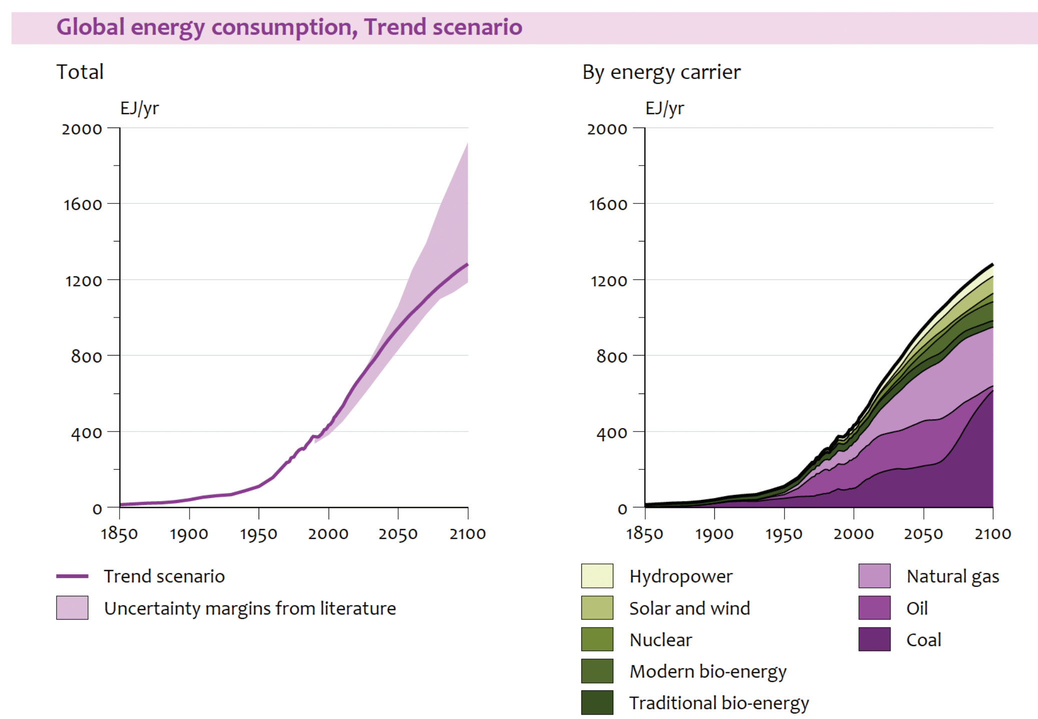


Energy

Access to energy is crucial for improving human development indicators. According to the Millennium Project, there were 1.2 billion people (17% of the world) living without electricity in 2014. An additional 2.4 billion people will be added to the world's population by 2050. Thus, to provide energy globally by 2050, electrical production capacity needs to be added for billions of people—ideally while decommissioning aging nuclear power plants and replacing or retrofitting fossil fuel plants.

In addition, peak oil will soon be reached (see **The Oil Age: World Oil Production from 1859 to 2050** in *Atlas of Science*, **page 148**), meaning that we have used up nearly half of all the available oil on the planet. Fortunately, technology is advancing quickly, making it possible to replace gasoline car fuel with hydrogen, electric, and other more sustainable kinds of fuel.

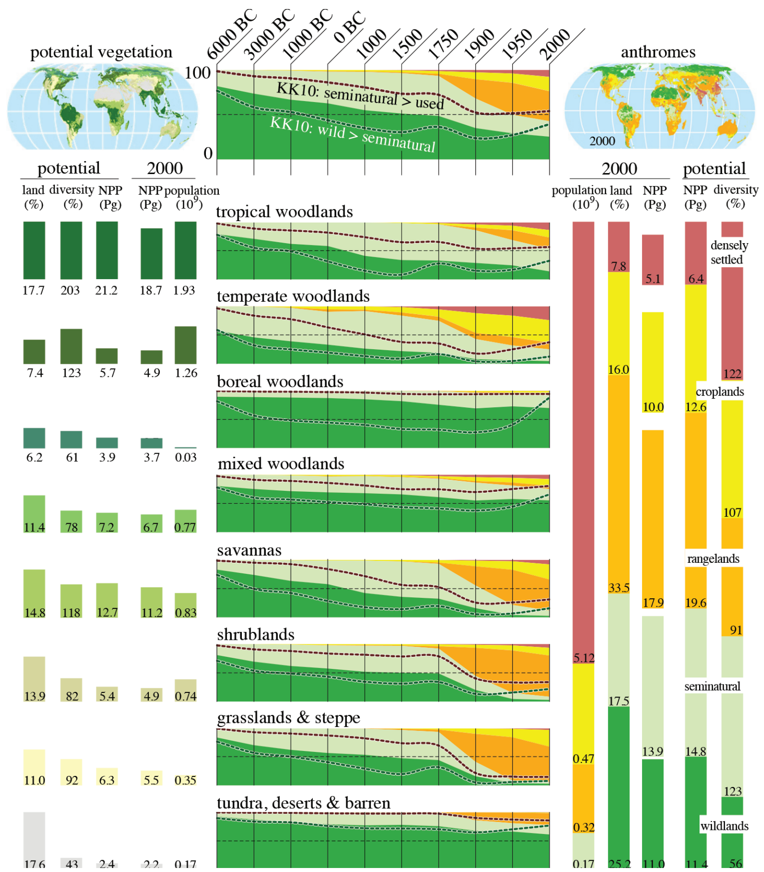
Global energy consumption projections by Detlef van Vuuren and colleagues and the Intergovernmental Panel on Climate Change (IPCC) are given below. The left graph shows the predicted trend scenario for global energy consumption, with uncertainty margins. The right graph features the same scenario via energy type—with oil decreasing, but coal and natural gas usage increasing. Sustainable energy sources (rendered in green) are also increasing to almost one-quarter of total consumption. For an alternative prediction of increases in renewable energy, see **Projected Nonhydropower Renewable Electricity Generation for 2010–2035** on the opposite page. In 2019, the top three countries in primary energy consumption were China with 141.7 exajoules (EJ), the United States with 116.58 EJ, and India with 34.06 EJ; see **Estimated U.S. Energy Consumption in 2019** on the opposite page.



Transformation of the Biosphere

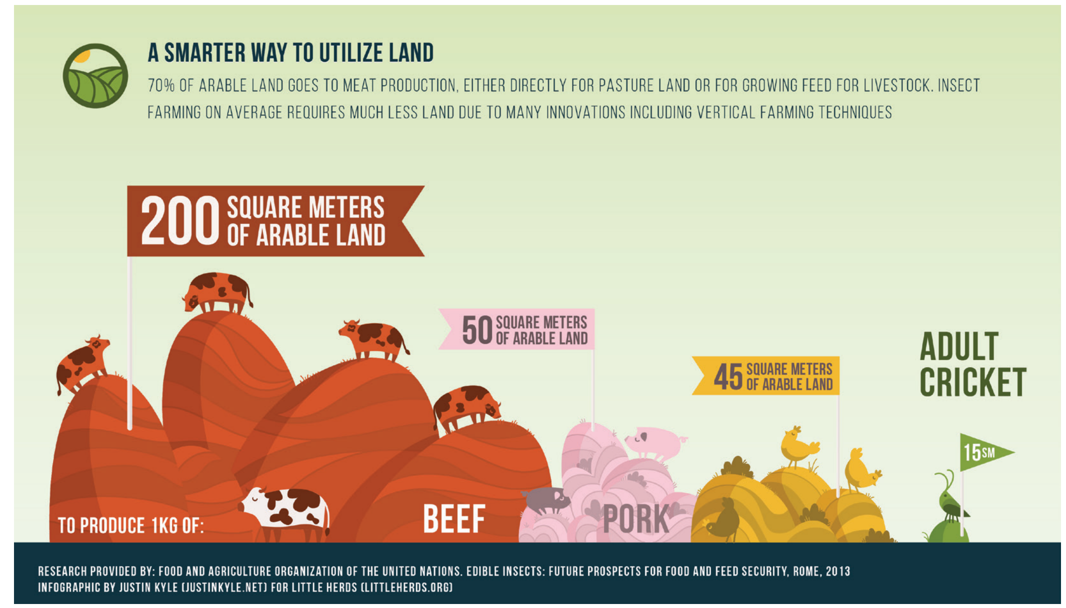
Human activity has significantly altered almost all of the Earth's system components: the atmosphere, hydrosphere, lithosphere, and biosphere. It has transformed most of the biosphere to anthropogenic biomes, or anthromes, with most of the changes happening over the last century—as can be seen in the figure at right of major transformations from 6000 BC to 2000 CE.

What results are novel ecological patterns and processes that have irreversibly altered the terrestrial biosphere. It is important to ensure that the Earth's system components can continue to support human life.



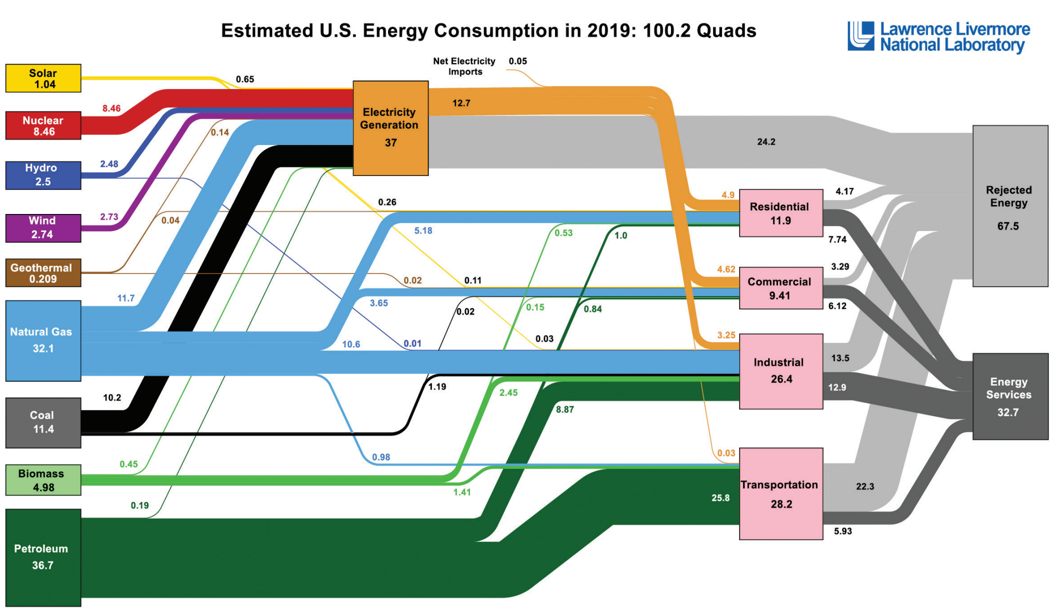
A Smarter Way to Utilize Land

As previously mentioned, a significant percentage of land is used for meat production. The infographic below compares the number of square meters of arable land required to produce 1 kg of beef, pork, chicken, or adult cricket meat. Using only 15 square meters, crickets are the clear winner. Other advantages include the fact that crickets are rich in proteins; contain twice the amount of iron as spinach; have similar amounts of omega-3 fatty acids as fish; and release 99% less greenhouse gases than cows. Finally, 80% of a cricket is edible, compared to 55% of a chicken and 40% of a pig or cow.



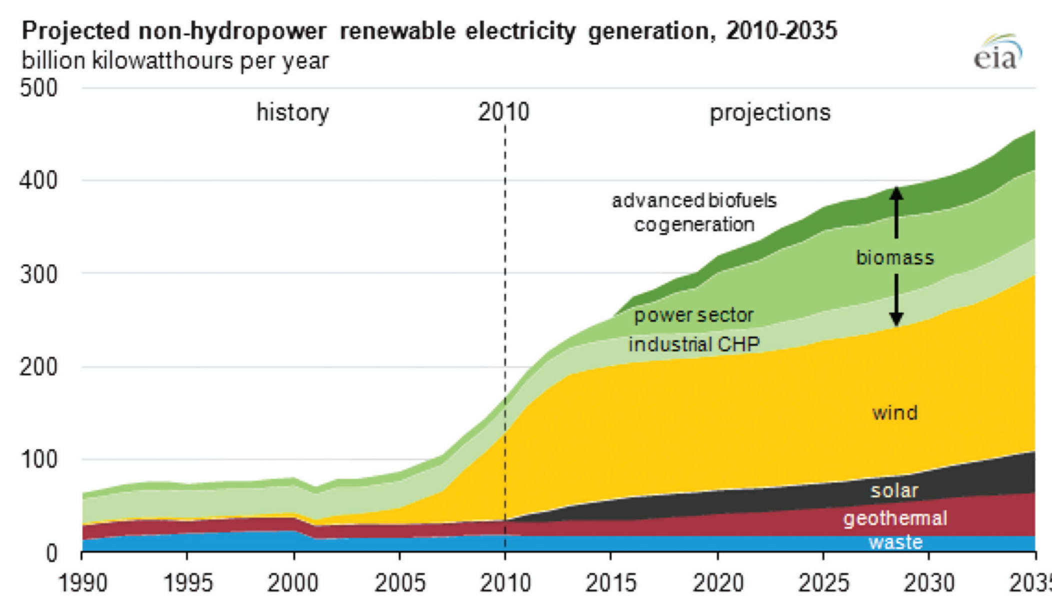
Estimated U.S. Energy Consumption in 2019

Each year, Lawrence Livermore National Laboratory (LLNL) publishes a Sankey diagram that shows U.S. energy production and usage. In 2019, Americans used 100.2 quadrillion BTUs (British thermal units, or quads; 3,400 BTUs are equivalent to about 1 kilowatt-hour or 3,600,000 joules). The different energy sources are labeled on the left, with four types of usage (residential, commercial, industrial, and transportation) indicated in the pink boxes, and the percentages of rejected energy (i.e., energy losses due to waste heat) culminating in gray boxes on the right. Due to independent rounding, the totals do not necessarily equal the sum of the components shown.



Projected Nonhydropower Renewable Electricity Generation for 2010–2035

The graph below shows predicted increases in renewable U.S. energy by the Energy Information Administration (EIA). Data prior to 2010 is measured, while data after 2010 is predicted through 2035. Thus, about 450 billion kilowatt hours will likely be generated in 2035, corresponding to 1.53 quadrillion BTUs, or about 1.5% of the total U.S. energy consumption in 2019.



Climate and Weather: Pollution and Flooding

Climate and weather models are critical for disaster prevention and management, electrical utilities and energy, agriculture, construction, transport, health, recreation and tourism, and water resource planning. While weather cannot be forecast reliably beyond 15 days, climate models can be used to understand long-term trends. Access to high-quality data, scalable models, and computing infrastructures, in addition to visualizations and moderators that help translate model results to relevant stakeholders, is key for successful model applications.

When strong winds blow, don't build walls, but rather windmills ... turn every bit of adversity into fuel for improvement.
Nassim Taleb

Weather

As of 2019, there were more than 10,000 land weather stations around the globe, with observations (e.g., temperature, wind speed, and air pressure) updated at least every three hours. Measurements are processed by computers and used in predictive models to compute how weather might change in both the short term (e.g., within 30 minutes) and long term (e.g., droughts can be forecast several months in advance). Meteorologists then interpret model results based on their knowledge of local conditions and needs, and communicate the results to the general public.

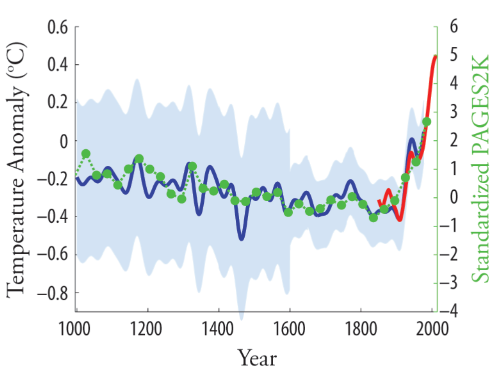
Climate

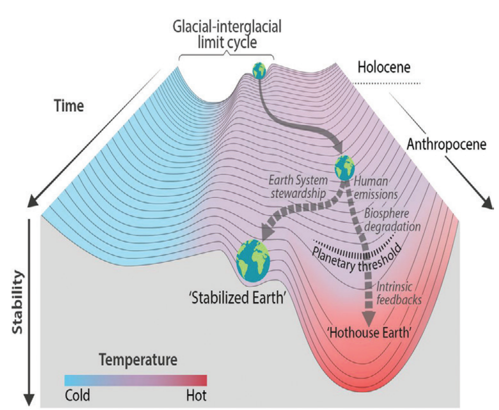
Using data from ice core readings, it is possible to derive mean annual surface temperature variations over the northern hemisphere for the last 1,000 years. When plotted, the so-called "hockey stick" graph has the trajectory of an upturned hockey blade. The red line indicates the start of industrialization. As there is no precedence for the current acceleration of global warming on our planet, we are yet to see which species will be able to adapt quickly enough to survive.

The rapid increase in average temperatures causes many other undesirable effects, such as melting ice caps, flooding, and increased net radiation. Sea ice and snow help reflect much of the solar radiation; however, thin ice is less reflective, allowing more sunlight to be absorbed by the ocean, which in turn warms the ocean and melts the ice faster—a fatal feedback cycle. Climate change also causes increased rainfall in some regions, which can result in the overgrowth of certain dense vegetation that leads to rodent abundance and the potential spread of more disease.

Climate Feedback Cycles on the opposite page shows a graph from the *Global Outlook for Ice & Snow* (2007). Climate change science aims to understand the net effect of such cycles and other similarly complex interactions.

Will Steffen and team have explored the state space trajectory of the Earth system, from the Holocene to the much hotter Anthropocene, as shown in the figure below. They argue that a fork exists in the trajectory, with one path leading to a *Stabilized Earth*, and the other crossing a planetary climate threshold and leading to an irreversible *Hothouse Earth*, in which global average temperatures exceed those of any interglacial period of the past 1.2 million years.





Flooding

Increased temperatures lead to melting ice caps and glaciers as well as associated increased flooding risks (see **Hurricane Katrina Predictions** and **Sea Level Rise Viewer** on the opposite page). The resulting risks are severe, affecting farm land, industrial buildings, and many residential homes. In Ocean City, New Jersey, alone, there are thousands of residential homes worth billions combined that could be at risk of routine flooding by 2050.

If global carbon emissions continue at the current rate, then about one in 40 people worldwide will be living in a place at risk of regular flooding by the end of the century. The Netherlands, with more than 40% of its area at risk, also has the world's most advanced levee system to greatly reduce that risk. In the United States, if no action is taken, about 3.1 million people may face regular flooding.

Pollution

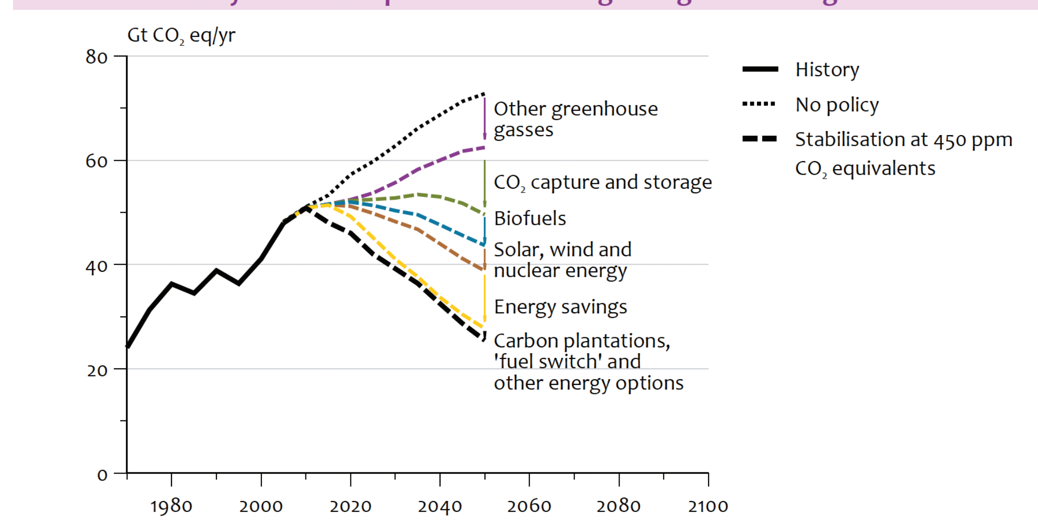
Pollution refers to adding harmful gases, particulates, or biological molecules to an environment. Some substances can be poisonous, while others might have major health impacts.

According to the World Health Organization (WHO), air pollution such as that caused by cars and factories affects nine out of 10 people and kills an estimated seven million people each year.

A recent study by researchers at the International Food Policy Research Institute (IFPRI) examined the impact of air pollution on cognition in China, using data from the national China Family Panel Studies longitudinal survey. From 2010 through 2014, the survey collected cognitive test scores of nearly 32,000 people over the age of 10. That data was compared to the exposure of the same people to short- and long-term air pollution. Results showed that both verbal and math scores decreased with increasing cumulative air pollution exposure; a steeper decline was noted for verbal scores. The study predicts that if the annual mean concentration of particulate matter smaller than 10 µm was reduced to the 50 µg/m^3, then test scores could increase from the median to the 63rd percentile for verbal and the 58th percentile for math test scores.

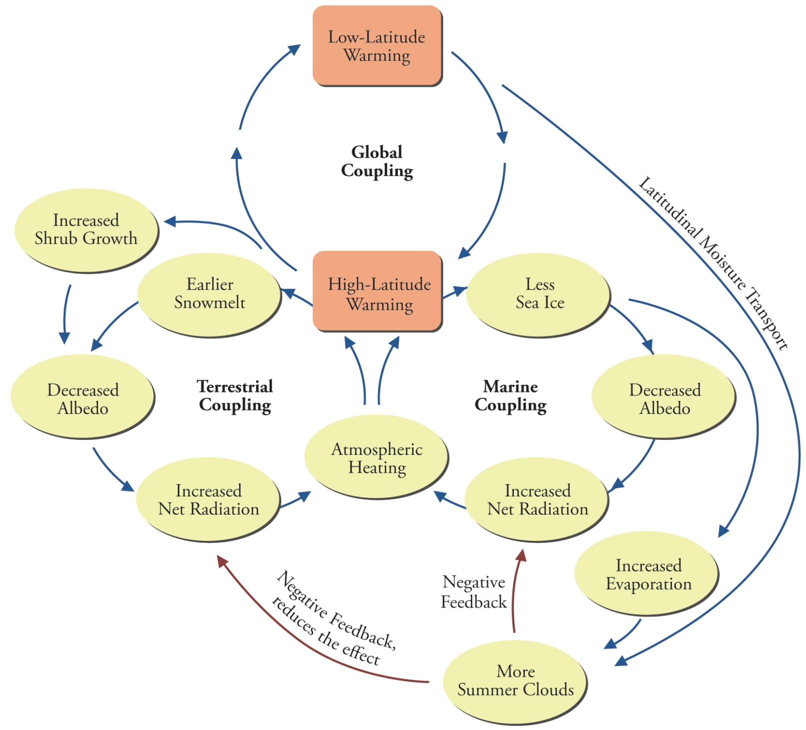
With the physical and mental health of so many people at stake, it is imperative that pollution be reduced worldwide. The graph below shows how different reduction measures can be combined to achieve desirable emissions reductions. While the black dotted line indicates no policy change, the black dashed line denotes a stabilization at 450 ppm CO_2 equivalents per year.

Contribution by reduction options to stabilise global greenhouse gas emissions



Climate Feedback Cycles

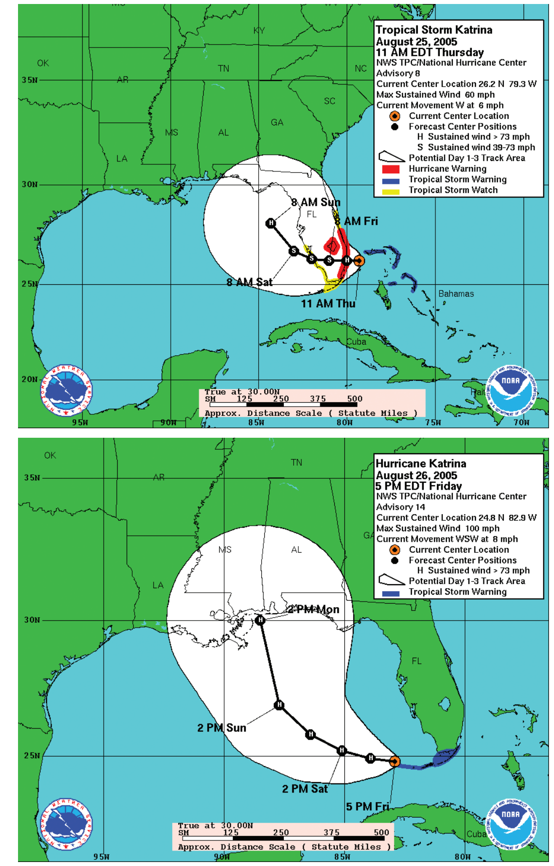
This causal graph from the *Global Outlook for Ice & Snow* (2007) shows the impact of atmospheric heating on decreasing sea ice, earlier snowmelt, and increasing shrub growth, all of which in turn decreases the diffuse reflection of solar radiation as compared to total solar radiation (called albedo), leading to further atmospheric heating. The *Global Coupling* feedback cycle on top aims to capture the interplay between *Low-Latitude Warming and High-Latitude Warming.*

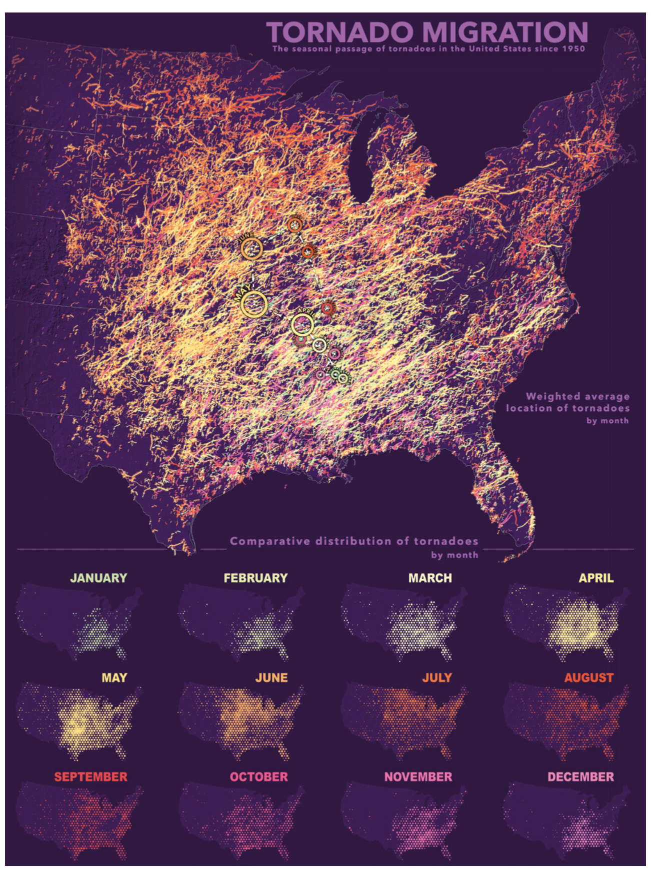


Hurricane Katrina Predictions

Hurricane Katrina struck the Gulf Coast in the early morning of August 29, 2005. It proved to be one of the deadliest hurricanes on record, with an estimated 1,800 lives lost and millions of homes destroyed.

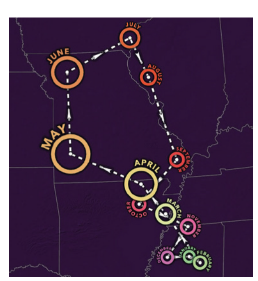
The two-part figure at right is from the Tropical Prediction Center (TPC) of the National Weather Service (NWS). It shows early prediction of the hurricane center, movement, and potential attack area for the first three days, as of the morning of August 25 (top) and the afternoon of August 26 (bottom). Although initial storm trajectory predictions differed from later predictions, they nevertheless helped inform evacuation and rescue operations.





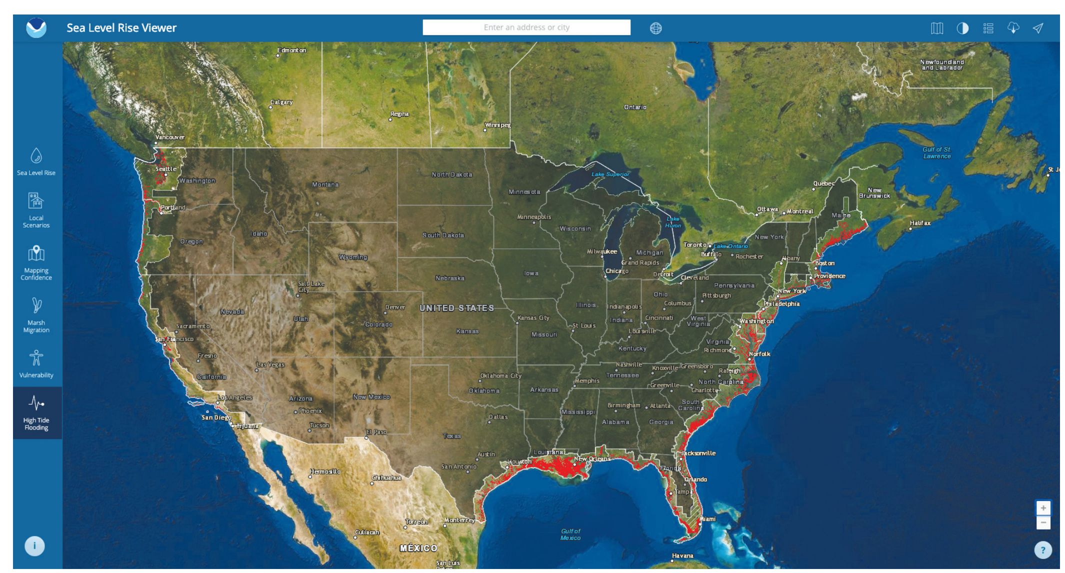
U.S. Tornado Tracks for 1950–2011

This figure shows 56 years of U.S. tornado tracks, created with data provided by the National Oceanic and Atmospheric Administration (NOAA). Lines connect the start and end points of tracks. Line brightness reflects the severity of storms according to F-scale, with brighter strokes representing more-violent storms. The top map shows the weighted average location of tornadoes, color-coded by month, plus an overlay diagram of the weighted mean center movement (see the zoom below). The 12 maps below show the distribution of tornadoes per month.



Sea Level Rise Viewer

The figure below is from a model and interactive data visualization developed by the Office for Coastal Management at NOAA. The model helps users explore the risks of sea level rise, storm surge, and flooding along the coastal United States. Users can simulate inundation associated with one to six feet of sea level rise likely at high tide. Home and business owners as well as community planners can use the tool to identify flood-prone locations in their area and to make more-informed decisions when it comes to (re)building houses and cities in more-resilient ways. Links to relevant videos and interactive visualizations are provided in **References & Credits** (page 180).



Transportation: Land, Maritime, and Air

The topology of road and airport networks has a major impact on how diseases spread, people migrate, and ideas diffuse (see **Network Models, page 46**). A robust transportation infrastructure, access to rivers and oceans, and proximity to airport hubs are opportunity enablers. Traffic throughput and logistic efficiency are valuable for converting spatial advantages into strong social and business networks, economic prosperity, and desirable futures.

Infrastructure is destiny: Follow the supply lines … to see where the future flows.
Kevin Kelly

Land

Space matters significantly, and transportation networks impact how entities diffuse. The map of third-century transportation routes featured in **ORBIS** (see **page 154**) helps answer why London could not become one of the capitals of the Roman Empire. Taking into account speed, cost, and the seasonal availability of transportation, the map shows how London was simply too expensive to reach, too far away, and impossible to access in the depths of winter.

The introduction of new transportation systems—from the invention of the wheel, to sea vessels, all road transport, and ultimately modern spacecraft—typically results in accelerated transportation time (see **Shrinking of Our Planet** in *Atlas of Knowledge*, **page 82**).

The first electric vehicles (EVs) became available in the U.S. in 1980. The above photo of a car being charged is from 1905. As of 2018, one million EVs are on U.S. roads. CNN predicts that by 2040, more than half of all new cars will be electric. Airline companies are working to develop smaller, point-to-point airplanes for personal use, which differ from the current spoke-hub, commercial airflight distribution paradigm.

Oceans

Old maritime maps—with illustrated ocean currents, winds, and antiquated continents (see examples in *Atlas of Science* on **pages 78, 80**, and **82**)—vary considerably from today's standard maps.

The global ship routes map at right was designed by Ben Schmidt, using shipping logs from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS). Examination of the four maps reveals the development of global trade and modern sea lanes over time (from before 1860 to 2000), particularly the increase in transpacific and Suez Canal trade.

In 2020, more than 50,000 merchant ships are operating in the oceans, according to the International Chamber of Shipping. Currently (2017–2020), the largest container ship is 399.87 meters long, 58.8 meters wide, and 32.5 meters deep, with a carrying capacity of 21,413 TEU (where 1 TEU equals a standard 20-foot shipping container).

The widespread usage of standardized 20- and 40-foot shipping containers, carrying material goods across oceans and over land, has enabled modularization, standardization, and optimization of logistics around the globe. In 2020, large container ships transport nearly 90% of all nonbulk cargo worldwide.

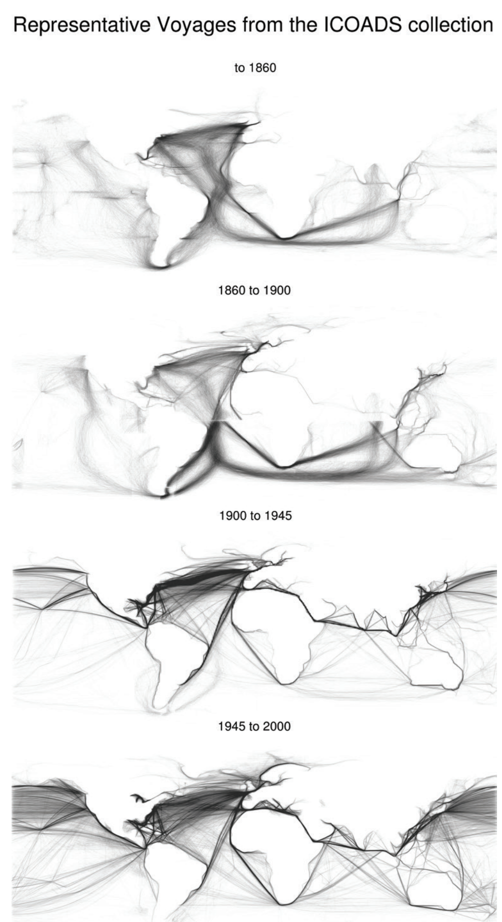
Rivers

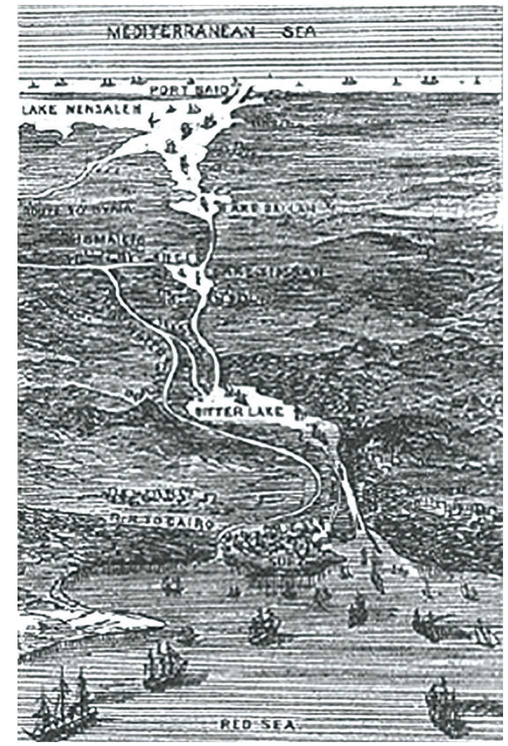
River waterway transportation is an efficient mode of transporting goods, with lower greenhouse gas emissions when compared to road and rail transport. Container ships and ferries require deep, open waterways and shipping ports for safe navigational access, ensured by measures such as dredging, water level management, channelization, and riverbank reinforcement.

Cargo shipped from Northeast Asia to the U.S. East Coast generally passes through either the Suez or Panama Canal. The former connects the Red Sea to the Mediterranean, saving ships the long route around Africa (see the vintage map at top right); the latter allows for passage via Central America, rather than around South America.

The 193 km-long Suez Canal (opened for traffic in 1869) is at sea level and requires continuous sand dredging. The 65 km-long Panama Canal (opened in 1914) was cut through mountains and requires locks to raise ships during their journey. The opening of the canals led to a major shift in international ship traffic, which can be seen in the below figure—in the *1900 to 1945* map image relative to the two pre-1900 images above it.

Another example for exploration is the comprehensive map in **The Mideast: Transport Routes, Electricity, and Pipelines** on the opposite page.





Air

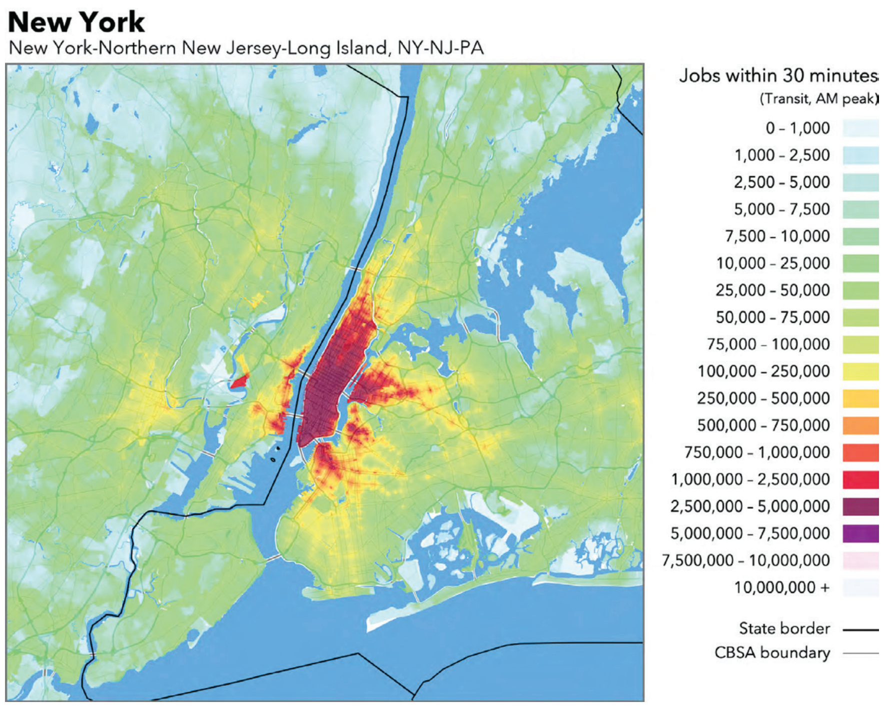
In 1914, the world's first scheduled passenger airboat service started operation between St. Petersburg and Tampa, Florida. As of 2020, there are more than 360 commercial airlines worldwide, offering a global capacity of 106 million seats and connecting about 22,000 city pairs via regular flight services.

Airline traffic maps show the increase of air traffic over time, the cyclic nature of daily flights, and major airline traffic routes. Air traffic networks help transport passengers and goods; they spread news, knowledge, and innovation (yet also potentially diseases) from one urban hub to the next and outwards from each. While street networks have a Gaussian node-degree distribution, airline networks exhibit a power-law distribution (see **Network Models, page 46**; and *Atlas of Knowledge*, **page 60**).

With global airline traffic heavily impacted by COVID-19, capacity decreased to 49 million within 10 weeks in 2020. Consequently, reduced air and land traffic led to major drops in emission pollution (see **Nitrogen Dioxide Emissions Drop Over Italy** on the opposite page).

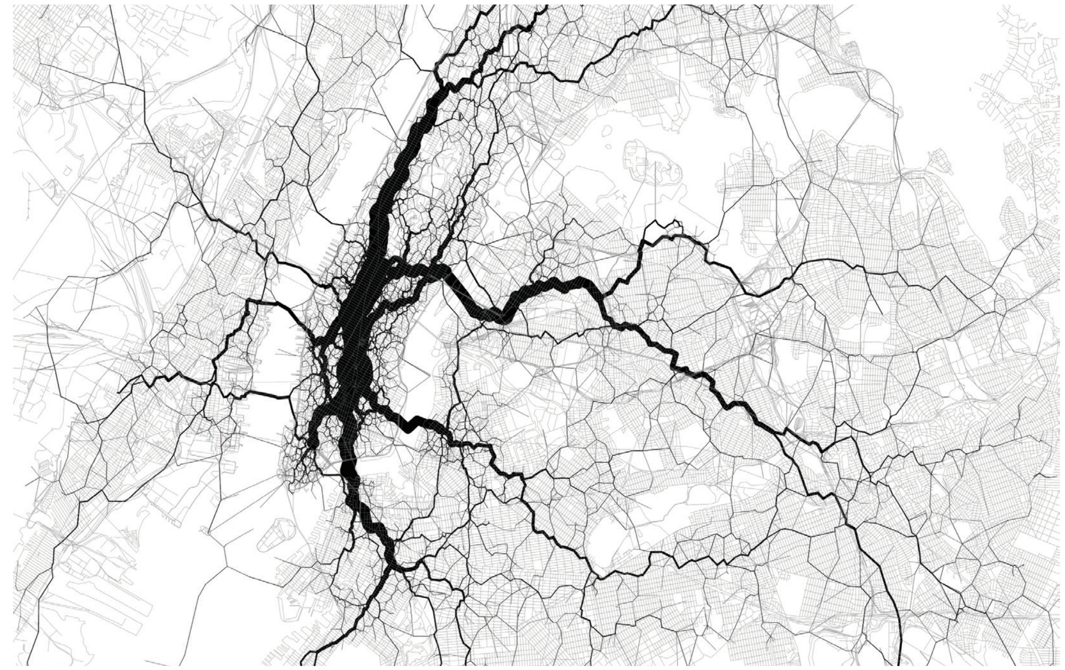
Jobs Within 30 Minutes of New York City

Andrew Owen and colleagues from the Accessibility Observatory, a program of the Center for Transportation Studies at the University of Minnesota, examined the accessibility of jobs via public transit in the most populous U.S. metropolitan areas. New York was identified as the area with the greatest accessibility to jobs.



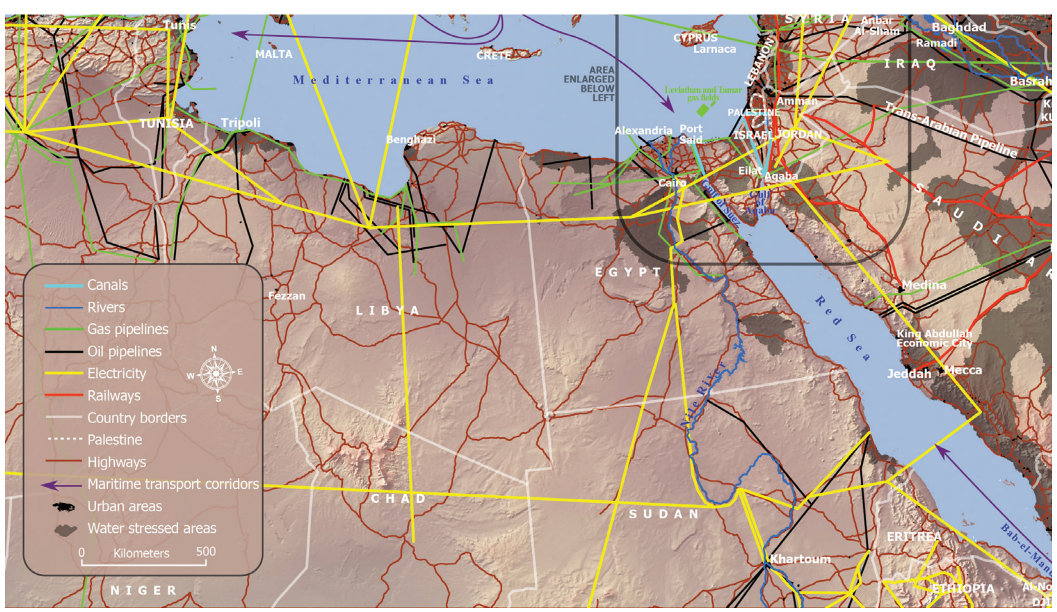
New York City Traffic Map Based on Geotagged Tweets

Eric Fischer used geotagged tweets to create maps of major cities. The New York City map below shows highly trafficked thoroughfares and places where people tend to concentrate. Manhattan is at the heart of this network, connected to surrounding areas via subway lines, bridges, and roads. These new kinds of maps can be used to create smarter cities and more-effective transit routes.



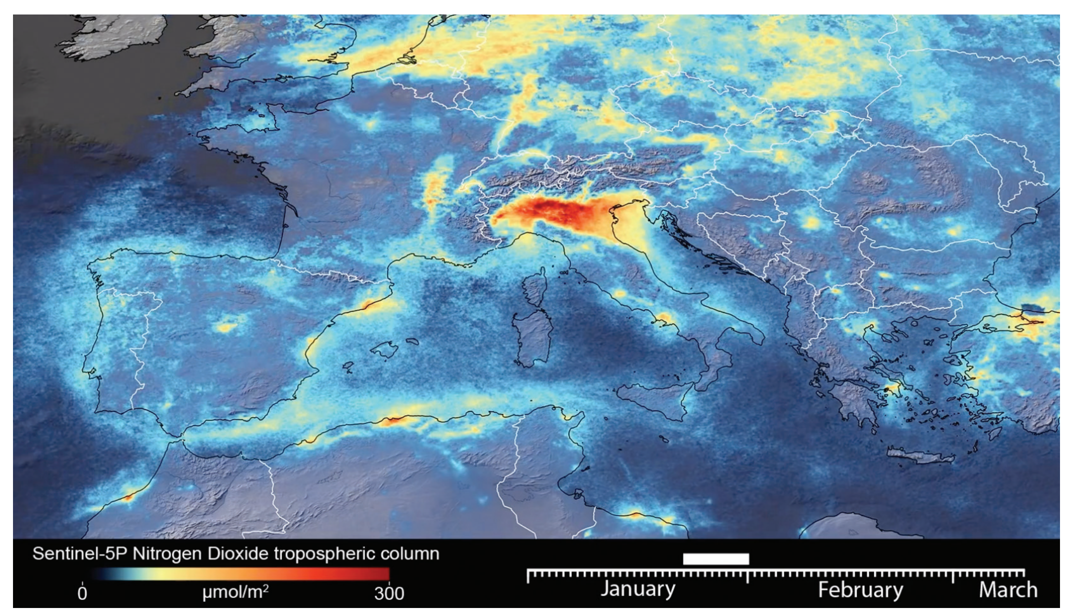
The Mideast: Transport Routes, Electricity, and Pipelines

In his 2016 book *Connectography*, Parag Khanna argues for maps that show connectivity rather than division. The Mideast map below shows current, half-built, and potential transportation routes (canals, rivers, railways, and highways), electric networks, and pipelines (gas and oil), in addition to urban areas. Ideally, water- and energy-stressed zones can be interconnected with affluent areas via an infrastructure that supports job creation, product diversification, and political stabilization.



Nitrogen Dioxide Emissions Drop Over Italy

In March 2020, the European Space Agency (ESA) published an animation of satellite imagery from the Copernicus Sentinel-5P satellite for the two-month period of January 1 to March 11, 2020, using a 10-day moving average. The map imagery below shows the decline of air pollutants in Europe. Filmed during Italy's nationwide lockdown to prevent the spread of COVID-19, the reduction in traffic and industrial activities led to reduced nitrogen dioxide concentrations, particularly visible in northern Italy (red area in map image). The associated video link is given in **References & Credits, page 180**.



Digitization: Computing and Communication

In the information age, indispensable assets include data, knowledge, and expertise. People are increasingly hyperconnected to others, as well as AI, in both personal and professional life. Many individuals and industries are developing and serving intangible products that “cannot be touched.” Intangible industries work differently than tangible industries—they have different dynamics for product values (initial software development is expensive but future copies of the software are virtually free), competition, risk, and stock market value.

If infrastructure is required for an industrial economy, then we could say that cyberinfrastructure is required for a knowledge economy.
Daniel E. Atkins

Digitization

In former times, information was scarce, precious, and frequently not shared. In the information age, data is vast and often readily available online, but it must be mined to extract knowledge. Digital information conservation is nontrivial, and keeping multiple copies is beneficial—a principle upheld by David S. H. Rosenthal’s Lots of Copies Keep Stuff Safe (LOCKSS) program at Stanford University.

The digital era has impacted almost every aspect of life, in every nation and culture—from consuming the news online rather than via newspapers, formerly the norm (see the mid-twentieth-century photo below of New York City commuters); to communicating extensively via cell or smartphone with friends, family, and colleagues (see the 2010 photo above of such a moment on the metro in Seoul, Korea); to performing nearly any form of modern work.

In fact, technology and communication infrastructure usage by humans and machines generates massive volumes of rich data. The 2012 *Digital Universe* study by the EMC Corporation predicted a tenfold increase of digital data between 2013 and 2020—from 4.4 trillion to 44 trillion gigabytes.

The International Data Corporation (IDC) predicts that the number of devices or things (cars, houses, etc.) connected to and communicating via the

Internet will grow from 14 billion, or 2% of the world’s data, to 32 billion in 2020, or 10% of the world’s data.

The *Digital Futures Final Report: A Journey into 2050 Visions and Policy Challenges* by the European Commission predicts that “by 2050, a new form of human (a trans-human) will emerge, where ICTs and bio-medicine will fundamentally improve the human condition and greatly enhance human intellectual, physical, and psychological capacities.” A discussion of this human-machine symbiosis crowdsourced intelligence can be found in **Modeling Opportunities (page 170)**.

Computing

Accelerating progress in bandwidth, data storage, and computation has made possible ever-faster and more-connected computing devices and infrastructures, which can subsequently be used to design the next generation of increasingly efficient computing and communication.

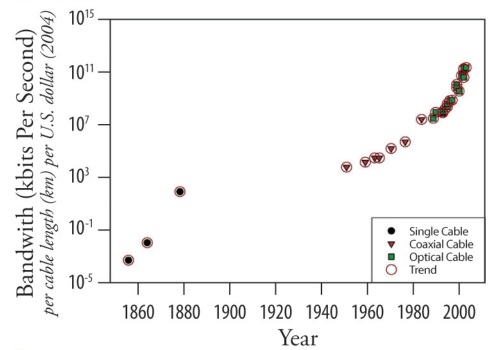
The three graphs at right plot key operation and functional performance metrics for progress in information technology (IT). The middle graph measures data storage as the amount of information (in megabits) per unit cost; the top graph is bandwidth (in kilobits per second) per cable length (in kilometers) per unit cost; and the bottom graph is computation as calculations (in million instructions per second, or MIPS) per unit cost. All unit costs are in 2004 U.S. dollars.

For bandwidth, single cable was initially used, then coaxial cable, and finally optical cable—leading to a millionfold increase over 60 years.

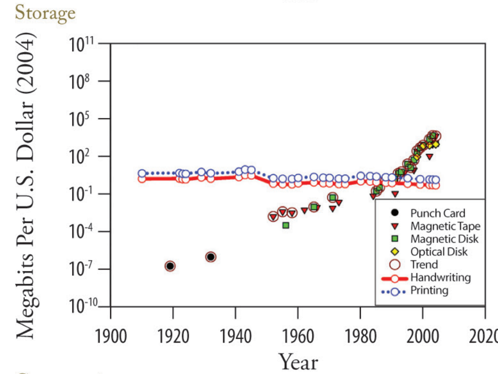
For storage, punch cards were first used for many years, and then replaced by magnetic tapes and disks, and finally optical disks. Storage capacity measures for handwriting (in red) and printing (in blue) are given for comparison.

Computing started with mechanical calculators (which had surpassed manual calculation by hand—the red reference point at lower left) and then continued via vacuum tube computers, transistor-based integrated circuit (IC) computers, and finally today’s devices and supercomputers.

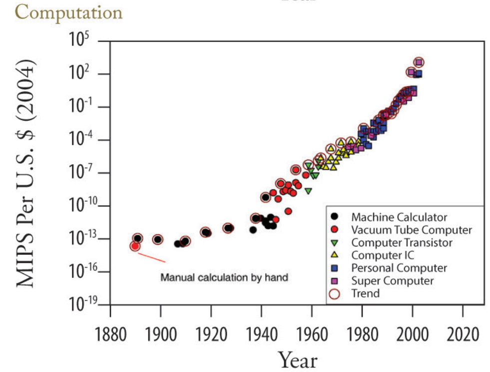
Bandwidth



Storage



Computation



Bandwidth per U.S. dollar is shown on top; single cable was initially used, then coaxial cable, then optical cable—leading to a millionfold increase over 60 years.

Storage in megabits per U.S. dollar is given in the middle. Punch cards were used initially (and for many years) but replaced by magnetic tapes and disks, then optical disks. Storage capacity for handwriting (in red) and printing (blue) are given for comparison.

Computing costs in MIPS per U.S. dollar are shown on bottom, starting with mechanical calculators that surpassed manual calculation by hand (red reference point), via vacuum tube computers, transistor-based on integrated circuit (IC) computers, to personal and super computers.

Communication

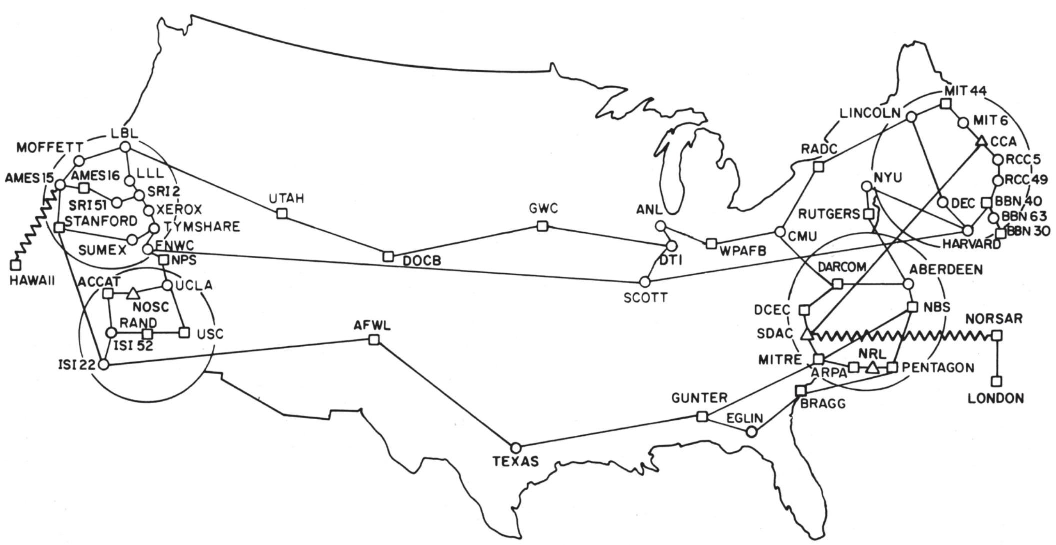
The accelerating pace of change in transportation and communication infrastructures was captured in graphs in *Atlas of Science* (**page 7**) that show the number of passenger miles for different means of transportation, and the increase in usage of different means of communication (from telegraph messages to radio, television, cell phones, and the Internet).

A map of the Advanced Research Projects Agency Network (ARPANET) in December 1978 is shown on the opposite page. In 1989, Tim Berners-Lee proposed the basic idea behind the World Wide Web (see **Visionary Approaches** in *Atlas of Science*, **page 20**). A map of the global Internet in 2011—only 22 years later—can be seen in *Atlas of Knowledge* (**page 13**). In 2020, more than 50% of the world’s population has access to the Internet.

As discussed in **Network Models** (**page 46**), the structure of networks has a major impact on how information and news are diffused. In fact, details about community structure and/or the backbones of communication networks can be used to predict which information will spread virally—independent of message content. The results are relevant for online marketing via social media, or for political elections. One example is the visualization in **Britain Segregation by Phone Traffic** (**page 67**). Also see *Atlas of Knowledge* (**pages 156–157**) for the 2010 Facebook social graph with no coverage for China, and Olivier H. Beauchesne’s *Map of Scientific Collaborations from 2005 to 2009*.

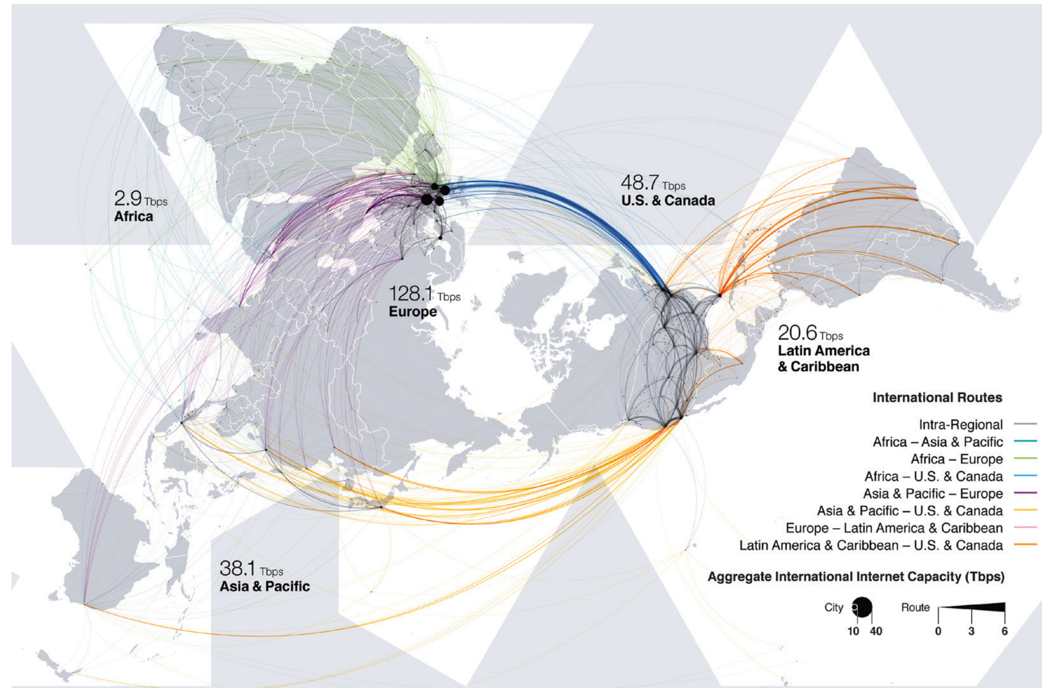
ARPANET Geographic Map, December 1978

In 1969, the Defense Advanced Research Projects Agency (DARPA) sponsored the start of ARPANET as an experimental network to interconnect heterogeneous computers, so that data, hardware, and software resources could be shared. In 1978, it was run as an operational resource-sharing intercomputer network, interlinking U.S. computers with those in Norway and England. In the figure below, circles indicate interface message processors (IMPs); squares denote terminal interface message processors (TIMs).



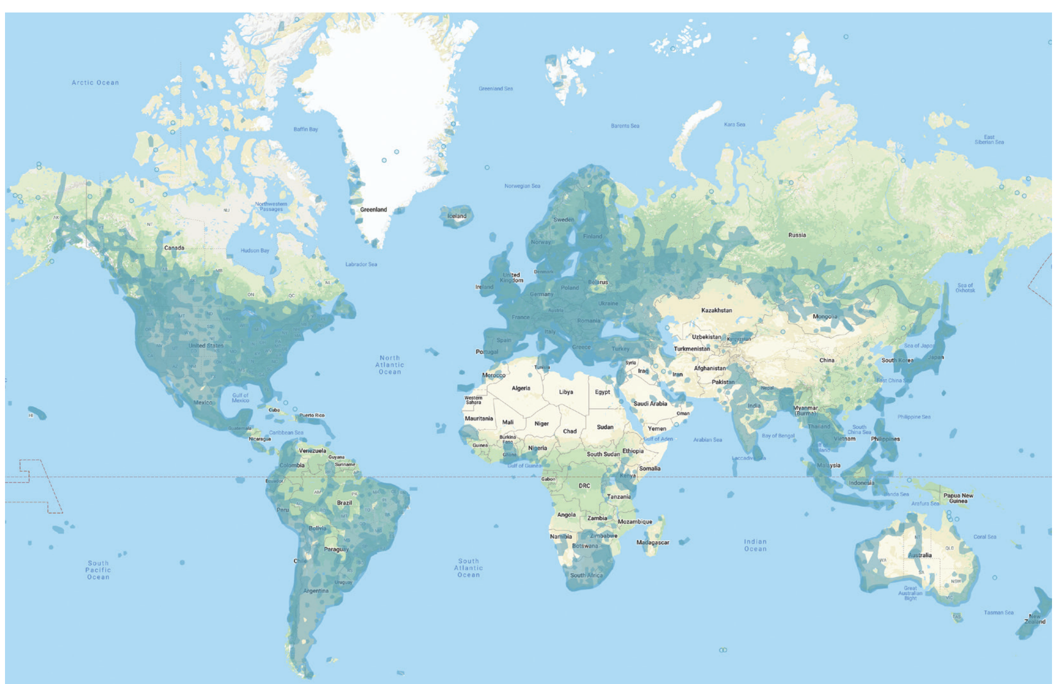
International Internet Cable Routes and Capacity

The map below from Parag Khanna's book *Connectography* shows how global data flows are expanding and accelerating over time. The aggregate Internet capacity is given in terabytes per second (Tbps). Europe has a capacity of 128.1 Tbps—far ahead of the rest of the world.



Where Google Street View Is Available

Access to the Internet is significant, as is access to data and services. The map below shows (via blue overlay) the areas where Google Street View is available. Since launching the service in 2007, the Google team has taken more than 80 billion photos in 85 countries, covering more than 10 million miles of roads.



Anthropocene Animation

The short film *Welcome to the Anthropocene* showcases how our species has transformed planet Earth. The three-minute animation was commissioned by the London 2012 "Planet Under Pressure" conference. A composite of data visualizations from the start of the Industrial Revolution to modern times—of evolving cities, roads, railways, pipelines, cables, shipping lanes, and finally the weblike Internet—shows humans' gradual planetary impact. The graph in the still image below shows time on the x-axis, and a rotating set of key parameters on the y-axis, including population, energy use, GDP, urbanization, fertilizer use, deforestation, and biodiversity loss. A link to the animation is provided in **References & Credits** (**page 180**).

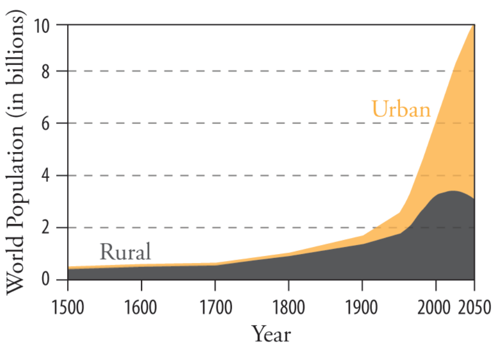
Urbanization: Segregation and Migration

The electrical network erased the boundaries between day and night, and opened up the evening to commerce and social activities. The highway network revolutionized how and where people choose to live and work. A 2014 study by the McKinsey Global Institute (MGI)—of the global flows of goods, services, finance, and people, coupled with the underlying flows of data and communication—shows the benefits and risks of our global connectedness in this digital age. As cities continue to attract talent, money, and ideas from around the world, they create more jobs and wealth in the process.

If you are not actively creating cultures of inclusion, then by default, you are creating cultures of exclusion.
Linda J. Burrs

Urbanization

As of 2014, 3.9 billion people were living in an urban environment—an eightfold increase since 1950. By 2045, more than 6 billion of the world's population will be living in urban areas, as the graph below shows. Massive investments in infrastructure and new technologies will be necessary to support that change.



One reason for the rapid increase in urbanization is the fact that the size of cities proportionately corresponds to qualities such as social connectivity, efficiency, productivity, and innovation—all of which scale superlinearly with population density.

Urbanization decreases costs; it is far more expensive to provide water, energy, and the Internet to a given number of remote houses as compared to the same number of apartments in a skyscraper. Cities also speed up transportation—particularly when public transportation is efficiently used and individual car traffic is reduced.

U.S. population changes from 2000 to 2010 can be plotted to reveal so-called "growth rings," or suburbs expanding on the outskirts of cities. Declining "urban dead zones" at the urban centers might eventually experience resurgent growth. Parag Khanna's book *Connectography* discusses the likely future of urban development, a reversal wherein cities might become suburbs of megacities.

The map below compares the top 15 megacities in 2018 (black circles) with the top 15 in 2035 (orange circles). While cities like Tokyo and Delhi simply grow in size—with Delhi expected to have the greatest population (43 million) by 2035—there are new megacities evolving, like Lagos and Kinshasa, and others gradually leaving the top 15, such as Osaka and Istanbul.

The process of urbanization will need to be monitored closely and modeled in detail to support data-driven decision-making and the proactive management of sustainable growth, while ensuring adequate access to housing, water, and energy for all citizens. All of the resulting factors—both positive (e.g., efficiencies gained from serving more-concentrated populations) and negative (e.g., homelessness, loss of family cohesiveness, and the stresses that enhance the need for mental health services)—will need to be addressed.

Top-15 Megacities

Segregation

Segregation refers to the separation of humans into groups (e.g., based on interests, ethnicity or race) and the consequent impact on daily life (e.g., when selecting a new home or neighborhood, attending school, or using public transportation).

Our preferences regarding whom we choose to do business with, talk to, or spend time with, and how often, can now be captured and modeled using the movement of banknotes, phone traffic, and other geospatially explicit data. Exemplary studies and results are shown on the opposite page, in **"Money-in-Motion" Map of America** and **Britain Segregation by Phone Traffic**.

In **Cellular Automata (page 40)**, we introduced Schelling's segregation model, which uses an agent-based approach to illustrate how individual preferences regarding neighbors can lead to city-wide segregation patterns. Erez Hatna and Itzhak Benenson extended the model to explain integration alongside segregation in the Mideast cities of Yaffo and Ramle. Their work shows that neighbors are selected or determined according to not only religion and ethnicity, but also income and education levels. For example, low-income Jews and Arabs might become neighbors by default, merely due to limited resources. However, affluent neighborhoods were found to be generally more tolerant and therefore less segregated; in contrast, poor households were found to be generally less tolerant and thus more segregated.

The United States is a nation of immigrants, with a complex history of two and a half centuries of migration, conflict, and prosperity. *National Geographic* used the 2010 U.S. census data to map racial diversity, distribution, and population density—one visualization from that series is the **U.S. Racial Dot Map** on the opposite page.

Mobility and Migration

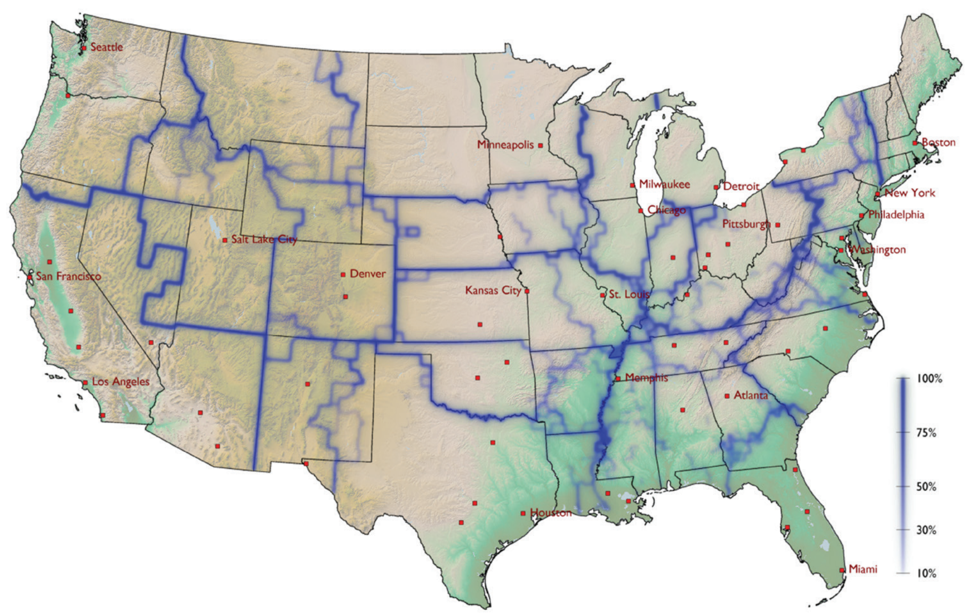
Human mobility is beneficial for individuals, regions, countries, and the world. It expands people's horizons, helps diffuse knowledge and innovations, and provides collaboration and business opportunities. Countries with open borders that welcome emigrants tend to be richer culturally (in terms of architecture, the arts, cuisine, etc.) and economically (as global expertise can be hired, shortcomings in labor can be quickly resolved, and global market opportunities can be efficiently harnessed). As many developed countries are aging (with more people living longer while fewer children are born), they need young and industrious immigrants who can support the increasing elderly population and contribute otherwise to society.

Khanna's map in **Connectography: Migration** on the opposite page shows just how much we all are connected, and the large numbers of emigrants working outside of their home countries. The top four countries with the highest number of emigrants are indicated by green markers; India is number one, followed by Mexico, China, and the Philippines.

Human mobility patterns and preferences can also be studied using data collected in virtual worlds. Michael Szell, Roberta Sinatra, and colleagues studied the online mobility of players of a self-developed massive multiplayer game. They found that at short time scales, player movement is constrained not only by physical distances but also by the presence of socioeconomic areas. Over long time scales, the precise time order of visited locations matters increasingly and shapes the individuals' trajectories. This mobility model can be used to predict future trends, identify resource gaps, and stress-test different scenarios using the metaphor of a "social petri dish."

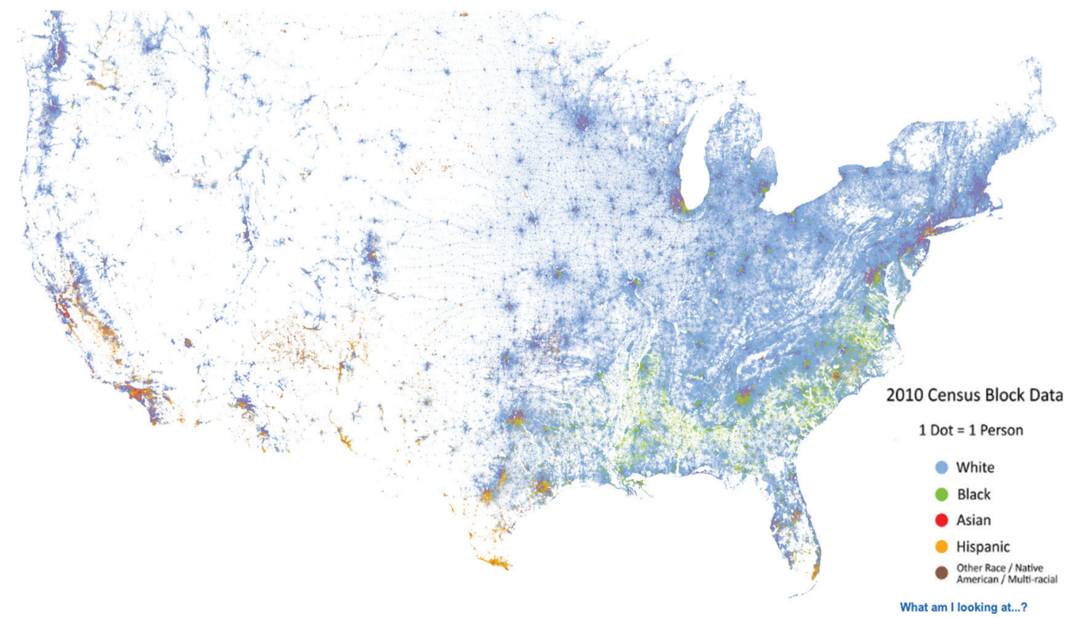
“Money-in-Motion” Map of America

Dirk Brockmann and colleagues used data on the movement of banknotes (1,033,095 reports describing the movement of 464,670 bills) to design the map below. Using “money-in-motion” as one proxy for how people connect, they identified virtual borders (blue lines) that money rarely crosses. For example, Kansas City and St. Louis appear to draw money mostly to themselves, which effectively creates an absence of movement and thus a border between them. In contrast, the area that includes Missouri, Kansas, Oklahoma, and Arkansas, for instance, forms an effective money-sharing community.



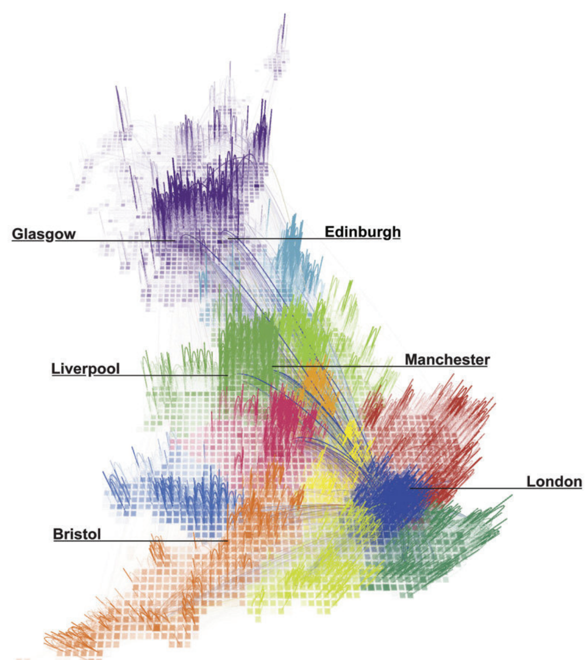
U.S. Racial Dot Map

The map below uses 2010 U.S. census data to show the geographic distribution, population density, and racial and ethnic diversity for 11,155,486 census blocks. Each of the 308,745,538 dots represents one person. Every person is placed randomly within the census block in which they resided during the census. Each dot is color-coded according to race and ethnicity. While the dot patterns and concentrations indicate population density, the color patterns help communicate which cities and geospatial regionals are most diverse or segregated.



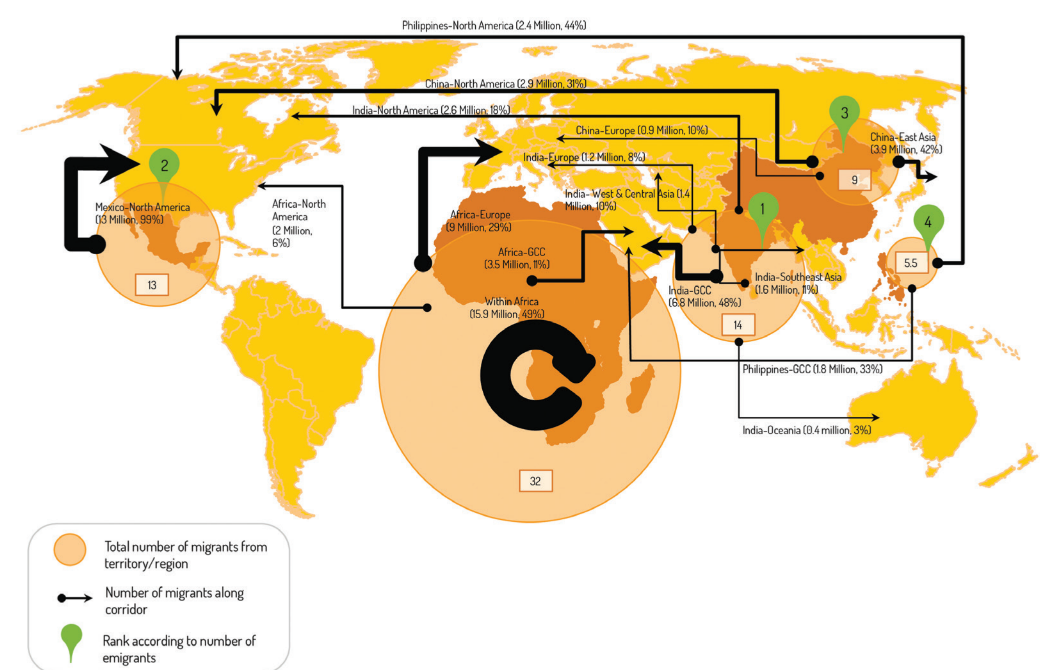
Britain Segregation by Phone Traffic

The Bartlett Centre for Advanced Spatial Analysis (CASA) worked with Mauro Martino to analyze British phone-call data in order to discern communication traffic patterns and clusters for regions in the United Kingdom. The result is the map below, which shows color-coded, interconnected clusters (e.g., blue calls blue, green calls green, etc.) presenting an alternative geography beyond political boundaries.



Connectography: Migration

Parag Khanna’s map below shows global migration patterns. For instance, the United States is a top destination for migrants from Mexico and other countries; conversely, nine million Americans live and work abroad. Migration across developing countries shows the fastest growth (large arrow above Africa), with many people migrating across Africa, the Middle East, and Asia.



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Group photo courtesy of Katy Börner.

Extracted from Newman 2008.

Extracted from Porter 1939.

Extracted from Nelson 2012.

Extracted from Fischer 2012.

Extracted from Vargic 2014.

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Metropolis image courtesy of Rex Features.

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Open-Loop Control Systems

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Epidemic network graph designed by Katy Börner and Perla Brown.

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Stag Hunt model figure designed by Perla Brown.

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Schematic illustration of diffusion dynamics from Sayama 2015, fig. 13.10.

Spatial function defined over 2D space from Sayama 2015, fig. 13.1.

Gradient field and vector field from Sayama 2015, figs. 13.9, 13.3.

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Network Representations

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Network Topologies

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Node Degree Distributions

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