Managing Complex Socio-Environmental Systems – An Evolutionary, System-of-Systems Approach

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Department of Civil and Environmental Engineering
Virginia Tech

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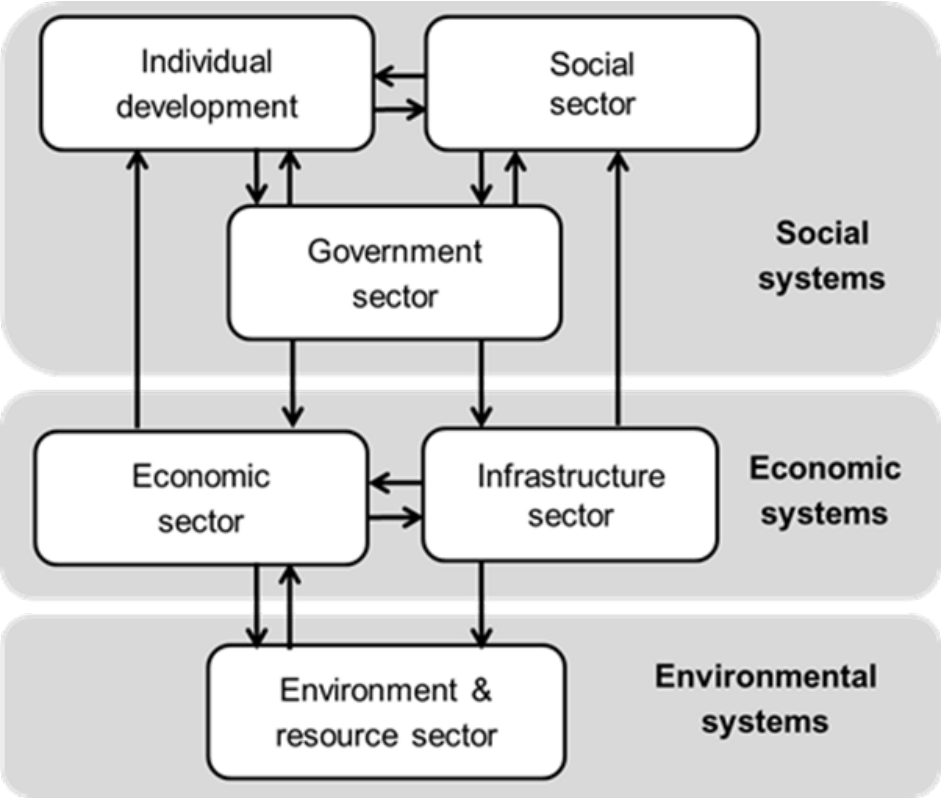
NATIONAL
SOCIO-ENVIRONMENTAL
SYNTHESIS CENTER

Complex socio-environmental problems

Socio-environmental problems
Climate change
Biodiversity loss
Biological invasions
Disease outbreaks
Food/energy/water nexus
Coastal and inland flooding
Interdependent infrastructure systems
Disaster management
Urban planning

- Problems are complex and socio-environmental in the nature of their drivers, interactions and impact
- Often framed in terms of sustainability, resilience or integrated assessment

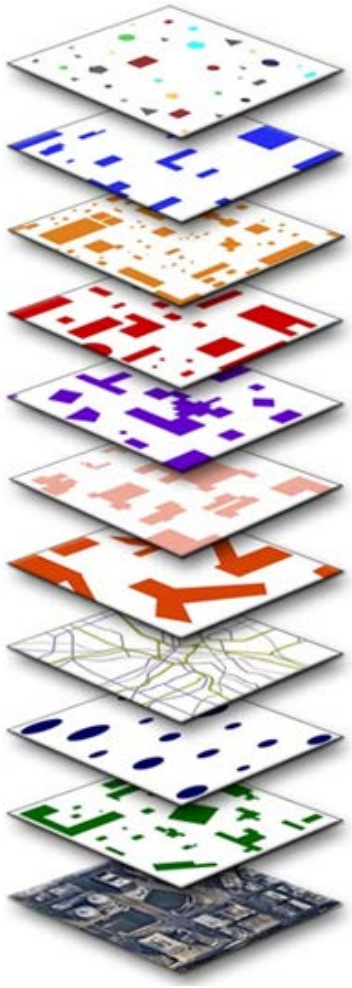
Complex socio-environmental problems



Six sectors of a simple socio-environmental system aggregated into the three classic subsystems of sustainability [Bossel, 2007]

Potential systems
Social systems
Legal systems
Economic systems
Communication
Transportation
Infrastructure
Urban environment
Energy
Climate
Atmosphere
Agriculture
Fisheries
Forestry
Mining and resources
Coastal systems
Oceans
Ecosystems
Watershed
Soil
Land use

Socio-environmental problems involve a system of systems



10 interdependent systems

Each system has many subsystems

The subsystems within a system interact

The systems interact with other systems via the subsystems

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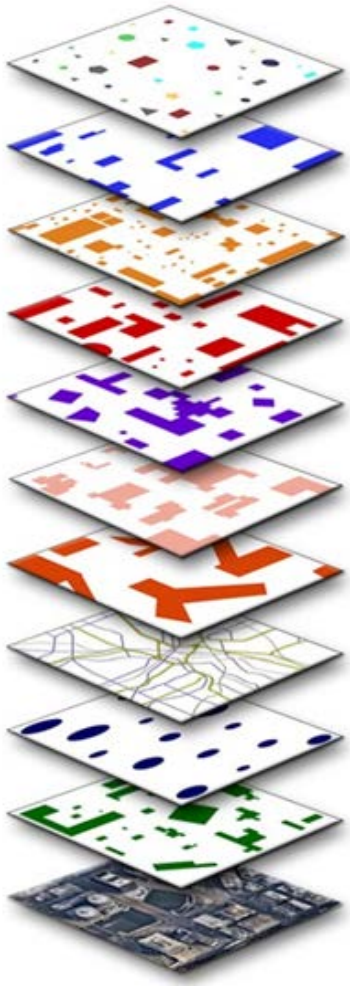


10 interdependent systems

Assume that a socio-environmental problem involves 10 systems each with 100 subsystems

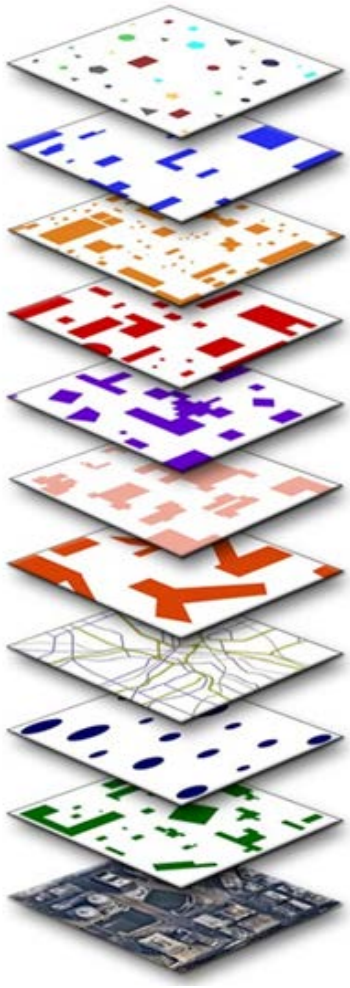
10 x 100 = 1,000 subsystems
implies 500,000 possible connections between all subsystems

Conventional interdisciplinary research studies how 2 or 3 subsystems in 2 or 3 systems interact

It will take thousands of research projects to understand how all subsystems interact …

and we still won't understand how the systems interact!

Socio-environmental problems involve a system of systems

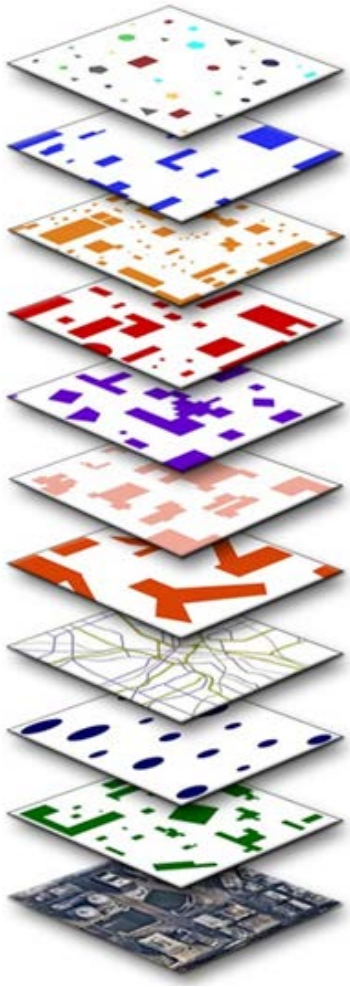


10 interdependent systems

› Some major systemic challenges:

- most disciplines (e.g., hydrology, energy, transportation, ecosystems, agriculture) begin with their own system and then connect to a few other subsystems across a wide range of scales (e.g., local, urban, regional) meaning that there is no systematic basis to compare results to what has been done before
- the dynamics of the other larger systems are almost always ignored
- most socio-environmental problems are intimately related (e.g., climate change; food/energy/water; coastal flooding; urban planning) and cannot be managed independently
- dueling frameworks (e.g., one water; one health; one earth; critical zone observatories; ecosystem services; sustainability; resilience; convergence; smart cities) will result in conflicting policies

Socio-environmental problems involve a system of systems



10 interdependent systems

- It appears that the only way to deal with these systemic challenges is to:
  - divide the world up into systems (e.g., hydrology, energy, transportation, ecosystems, agriculture, economic, social)
  - study and characterize them separately over a range of scales (e.g., local, urban, regional) preferably creating reasonably generic community models
  - systematically re-combine the systems over a range of scales (e.g., local, urban, regional) to simultaneously address a wide range of socio-environmental problems
- Of course, we will never be able to predict the future, but we may be able to manage complex socio-environmental problems more systematically and more comprehensively

A tiered, system-of-systems modeling framework for resolving complex socio-environmental policy issues

› Need a generic framework:

- a component-based, system-of-systems software framework
- a tiered framework with different levels of abstraction
- make robust decisions in the face of deep uncertainty
- integrate multiple knowledge domains and disciplines

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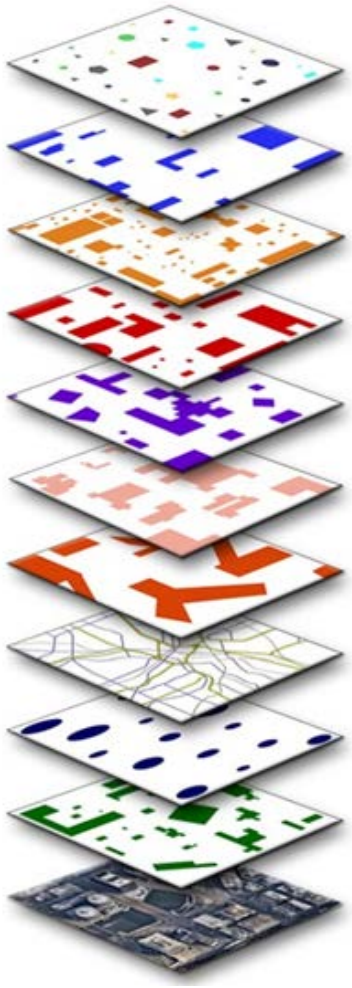
A system-of-systems modeling framework



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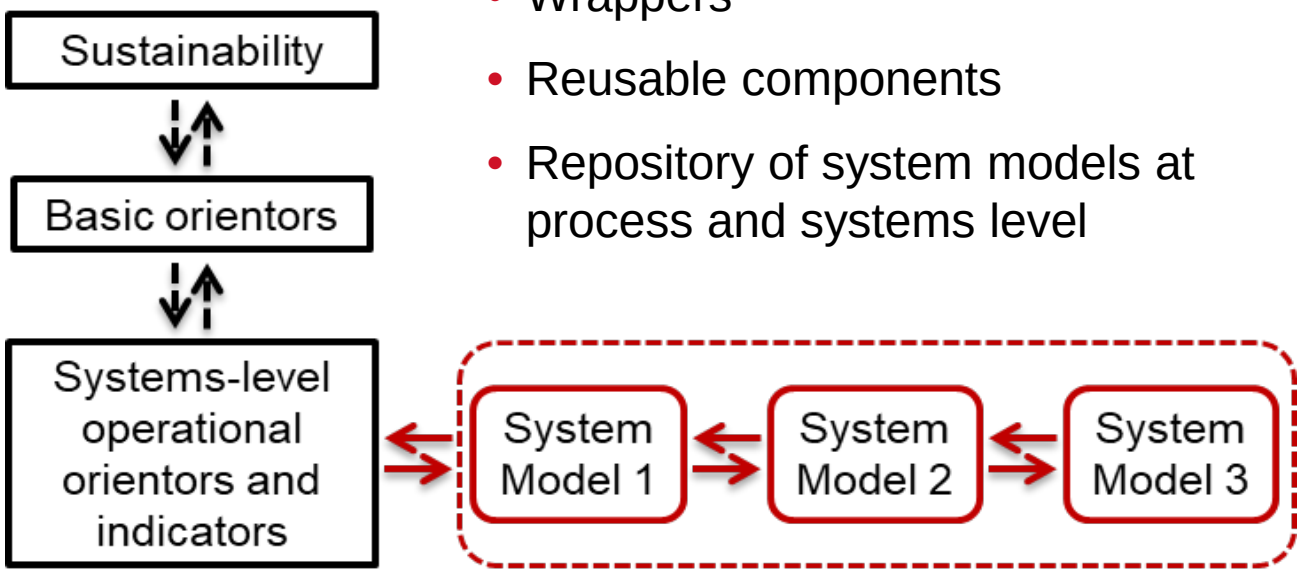
Land use

A component-based, system-of-systems software framework

- Well-established procedures for software frameworks
  - Wrappers
  - Reusable components
  - Repository of system models at process and systems level



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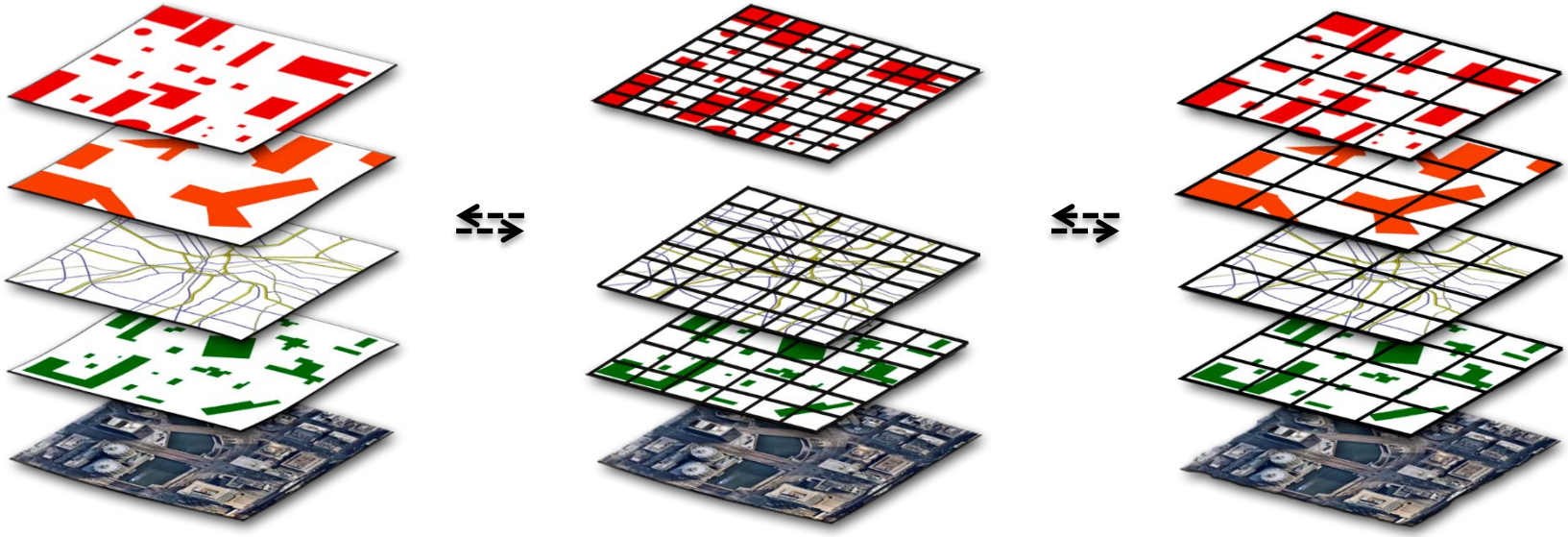
A tiered framework with different levels of abstraction

Geographic Information System

Process Level Models

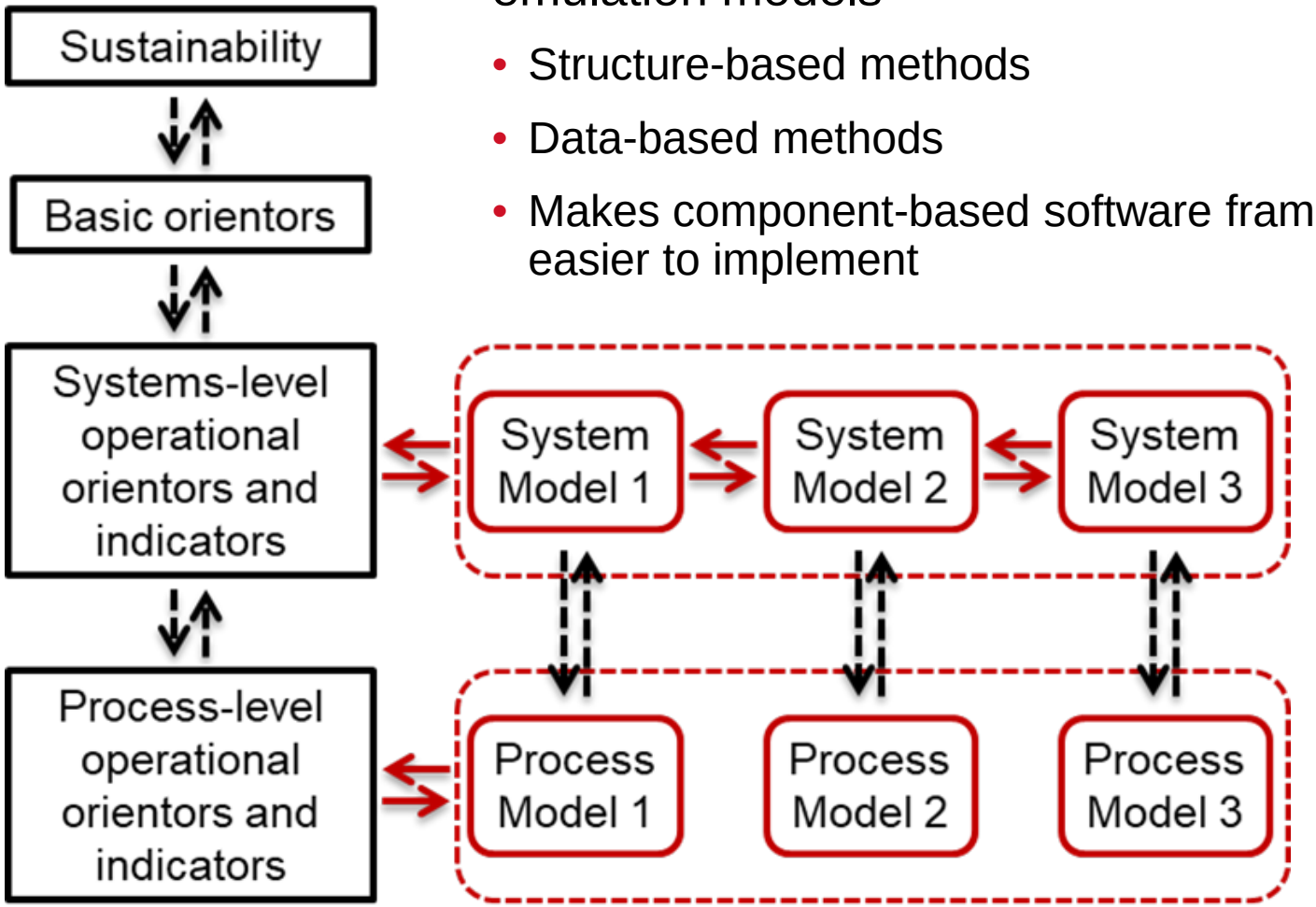
System Level Models



[Fralin Graphic Design]

A tiered framework with different levels of abstraction

- Well-established procedures for developing emulation models
  - Structure-based methods
  - Data-based methods
  - Makes component-based software framework easier to implement



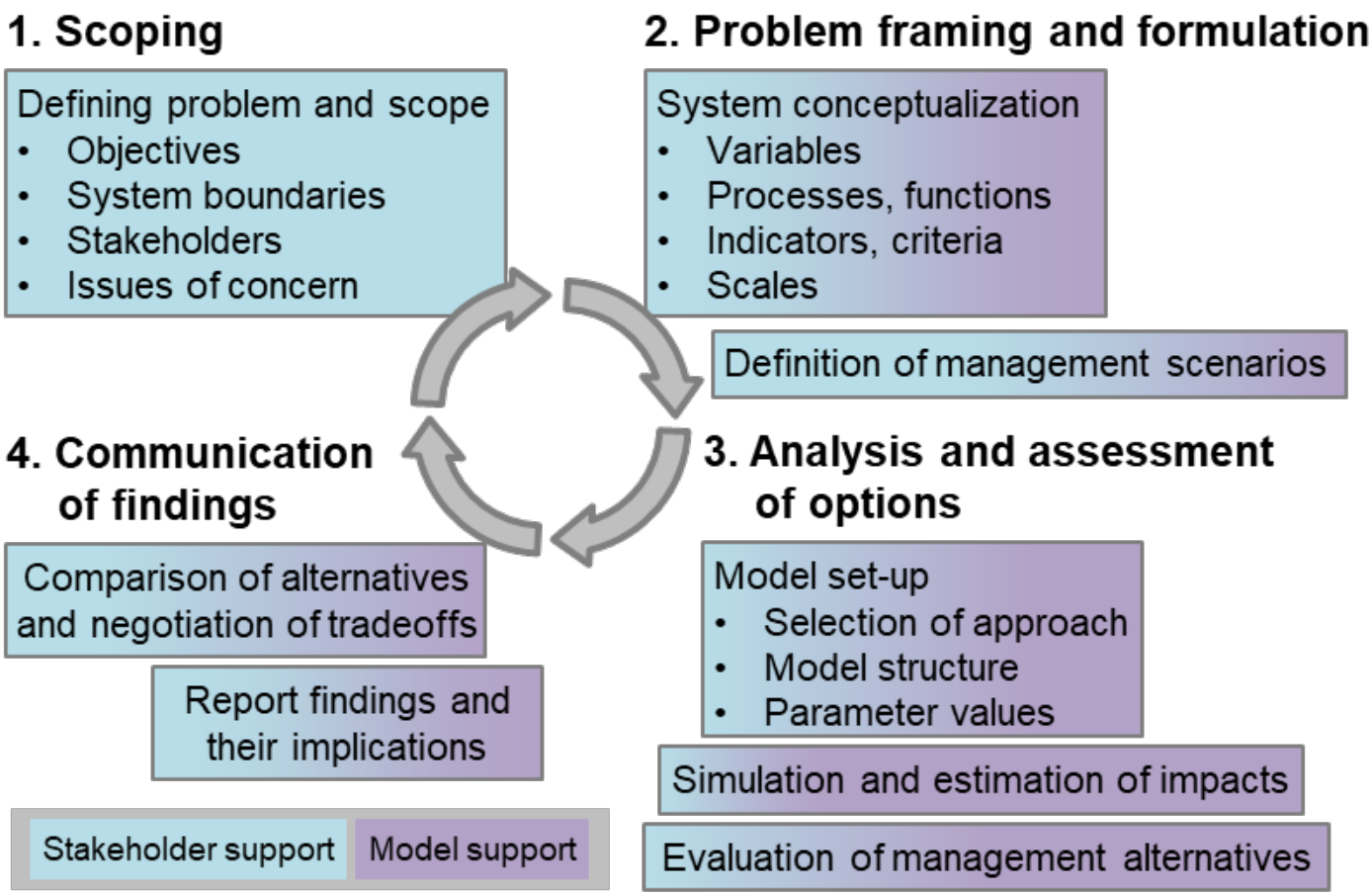
Make robust decisions in face of deep uncertainty

- According to Robert Lempert, deep uncertainty exists when there is "fundamental disagreement about the driving forces that will shape the future, the probability distributions used to represent uncertainty and key variables, and how to value alternative outcomes"
  - Developing emulation models may help reduce uncertainty and will improve system-of-systems model runtimes
  - New multi-objective, robust decision-making (MORDM) strategies are being developed
  - Remember that socio-environmental problems are inherently uncertain

[Lempert, 2002]

Integrate multiple knowledge domains and disciplines

› Use the Integrated Assessment and Modeling methodology

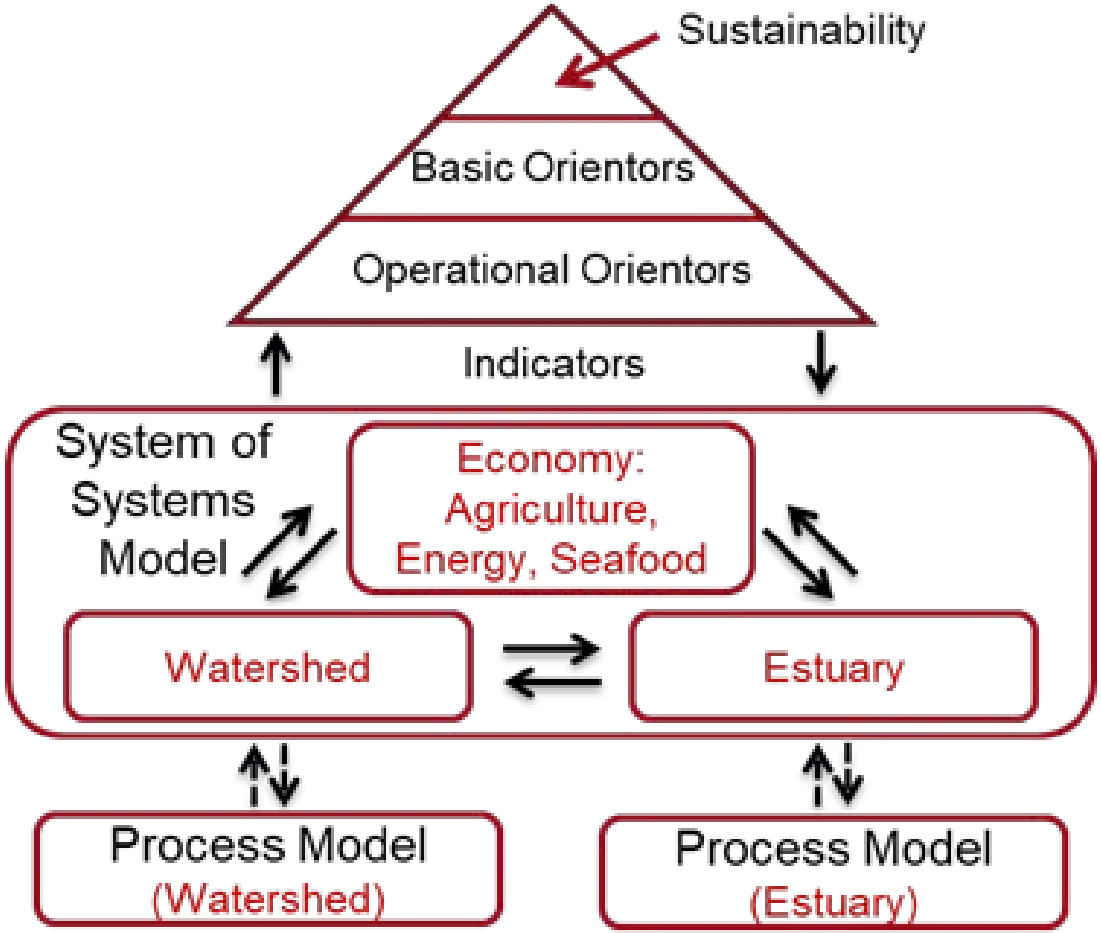


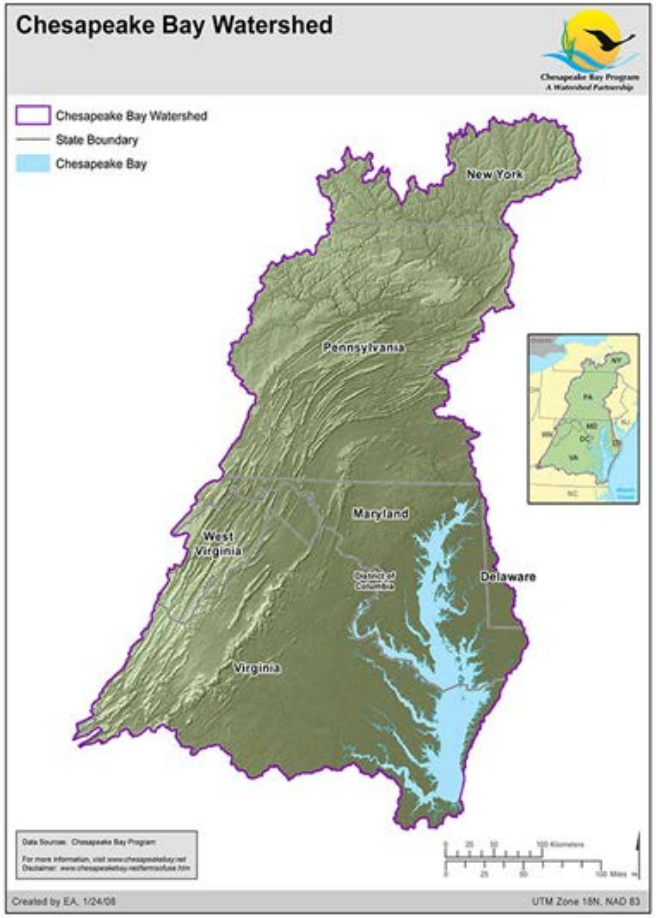
[Hamilton et al., *Environmental Modelling & Software*, 2015]

Integrate multiple knowledge domains and disciplines

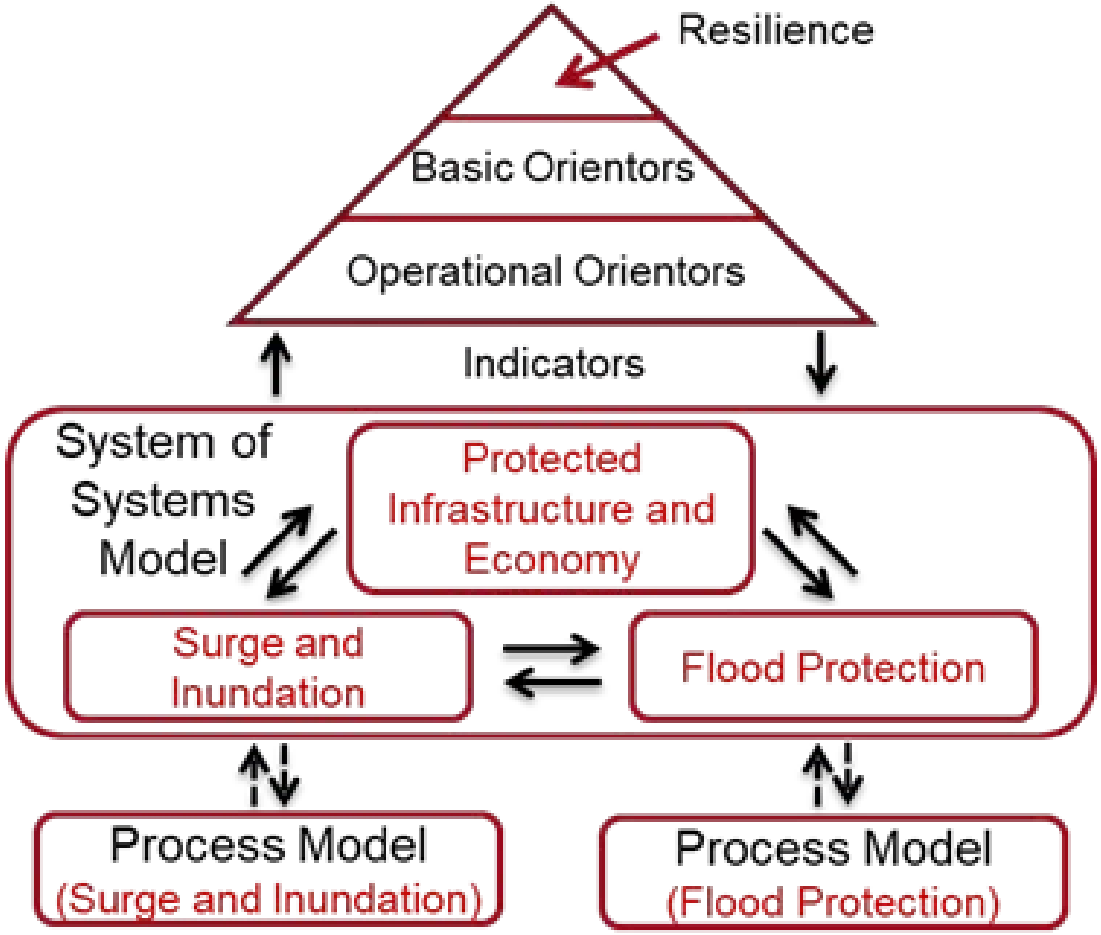
- Neither feasible nor desirable to have everyone working on systems integration
- Add new tracks or minors for "systems" engineers and scientists in relevant disciplines (including social sciences)
- For example, typical tracks in Civil Engineering include:
  - Civil + construction engineering
  - Civil + environmental and water resources engineering
  - Civil + geotechnical engineering
  - Civil + structural and materials engineering
  - Civil + transportation engineering
  - Civil + systems engineering (~5% of all civil engineers?)
- Civil engineering systems experts couple models at the systems level (working with systems experts from other disciplines) and facilitate two-way communication between the process experts at the process level and the systems experts at the systems level

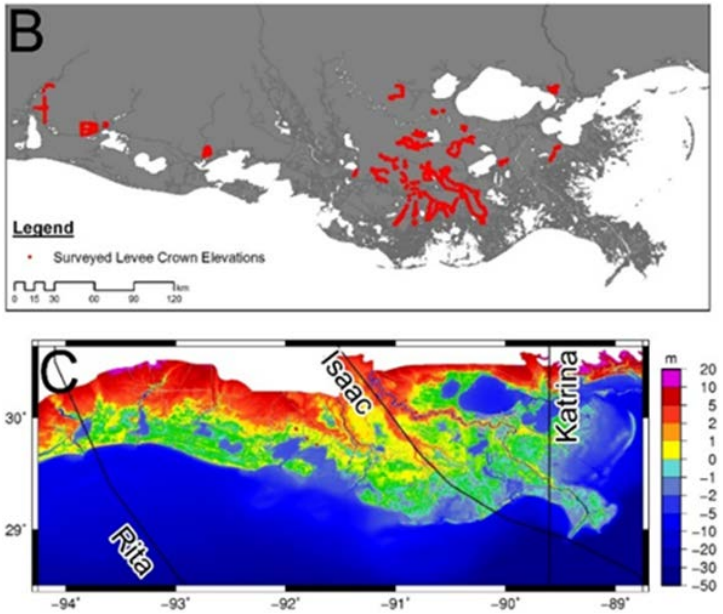
Example – sustainable food, energy, water





Example – resilience to coastal flooding





Environmental Modelling and Software 112 (2019) 82–94

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

A tiered, system-of-systems modeling framework for resolving complex socio-environmental policy issues

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ARTICLE INFO

Keywords:
Deep uncertainty
Integrated assessment
Resilience
Stakeholders
Sustainability
Systemic

ABSTRACT

Many of the world's greatest challenges are complex socio-environmental problems, often framed in terms of integrated assessment, resilience or sustainability. To resolve any of these challenges, it is essential to elicit and integrate knowledge across a range of systems, informing the design of solutions that take into account the complex and uncertain nature of the individual systems and their interrelationships. To meet this scientific challenge, we propose a tiered, system-of-systems modeling framework with these elements: a component-based, software framework that couples a wide range of relevant systems using a modular, system-of-systems structure; a tiered structure with different levels of abstraction that spans bottom-up and top-down approaches; the ability to inform robust decisions in the face of deep uncertainty; and the systematic integration of multiple knowledge domains and disciplines. We illustrate the application of the framework, and identify research and education initiatives that are needed to facilitate its development and implementation.

SESYNC Pursuit Project

Simultaneously managing scale and uncertainty using innovative software concepts in a tiered, system-of-systems modeling framework

SESYNC

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SOCIO-ENVIRONMENTAL
SYNTHESIS CENTER

[www.sesync.org/project/propose-a-pursuit/simultaneously-managing-scale-and-uncertainty-using-innovative-software]

NSF ERC Planning Grant

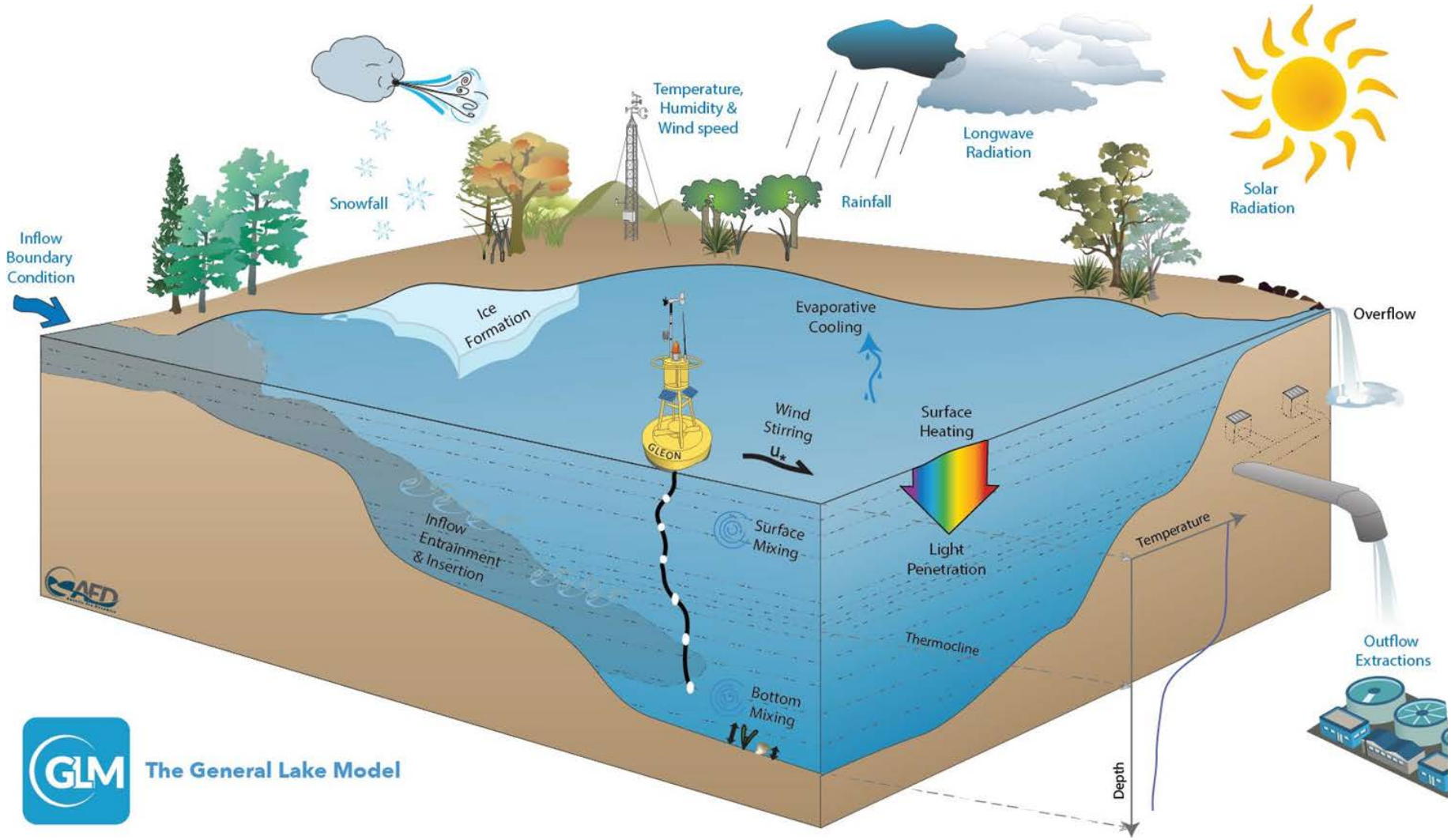
Managing complex socio-environmental problems using a generic, tiered system-of-systems (GTSoS) modeling and data-science framework

[https://nsf.gov/awardsearch/showAward?AWD_ID=1937012&HistoricalAwards=false]

SESYNC + NSF workshops

Workshop (Workshop Leads)	Workshop Location and Date
Satellite Workshop #1 (Tony Jakeman + John Little)	First Regional Conference on Environmental Modelling & Software (iEMSs 2019), Nanjing, China, May 2019
Satellite Workshop #2 (Rose Wang + Bill Grant)	The International Society for Ecological Modelling Global Conference (ISEM 2019), Salzburg, Austria, Oct 2019
SESYNC Workshop #1 (John Little + Rose Wang + Sondoss Elsawah as facilitator)	Annapolis, MD, USA, Oct 2019
Satellite Workshop #3 (Tony Jakeman + Saman Razavi)	Ninth International Conference on Sensitivity Analysis of Model Output (SAMO 2019), Barcelona, Spain, Oct 2019
Satellite Workshop #4 (Alexey Voinov + Sondoss Elsawah)	The 23rd International Conference on Modelling and Simulation (MODSIM 2019), Canberra, Australia, Dec 2019
SESYNC Workshop #2 (John Little + Rose Wang + Sondoss Elsawah as facilitator)	Annapolis, MD, USA, Mar 2020
NSF ERC Planning Grant Workshop	Blacksburg, VA, USA, Summer 2020
SESYNC Workshop #3 (John Little + Rose Wang + Sondoss Elsawah as facilitator)	Annapolis, MD, USA, Sep 2020

Community model example (GLM)



[Hipsey et al., 2014; http://aed.see.uwa.edu.au/research/models/GLM]

Community model example (CMAQ)

Review of the Governing Equations, Computational Algorithms, and Other Components of the Models-3 Community Multiscale Air Quality (CMAQ) Modeling System

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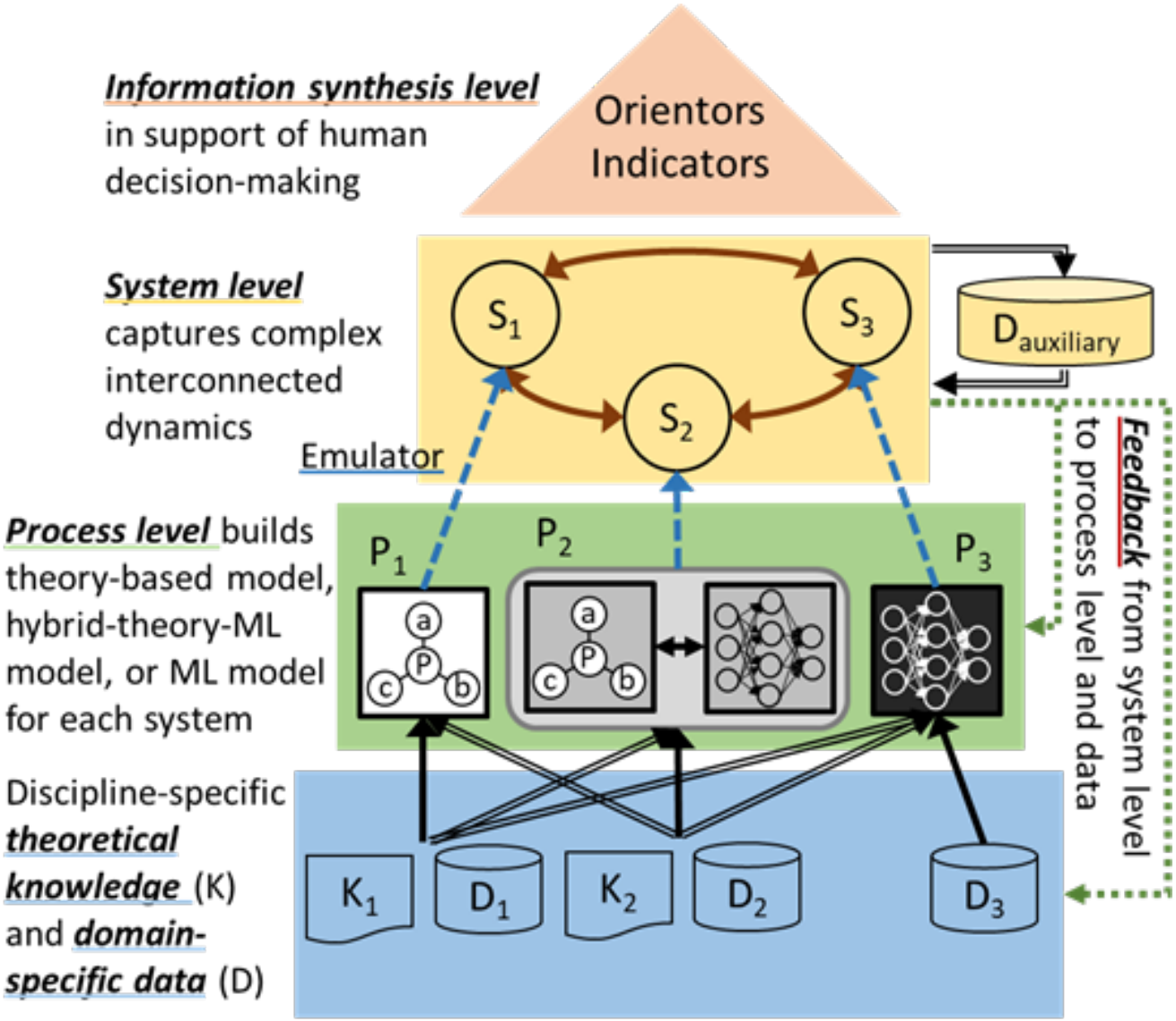
Kenneth L. Schere[2]

Atmospheric Sciences Modeling Division,
Air Resources Laboratory,
National Oceanic and Atmospheric Administration,
Research Triangle Park, NC 27711

This article describes the governing equations, computational algorithms, and other components entering into the Community Multiscale Air Quality (CMAQ) modeling system. This system has been designed to approach air quality as a whole by including state-of-the-science capabilities for modeling multiple air quality issues, including tropospheric ozone, fine particles, acid deposition, and visibility degradation. CMAQ was also designed to have multiscale capabilities so that separate models were not needed for urban and regional scale air quality modeling. By making CMAQ a modeling system that addresses multiple pollutants and different spatial scales, it has a "one-atmosphere" perspective that combines the efforts of the scientific community. To implement multiscale capabilities in CMAQ, several issues (such as scalable atmospheric dynamics and generalized coordinates), which depend on the desired model resolution, are addressed. A set of governing equations for compressible nonhydrostatic atmospheres is available to better resolve atmospheric dynamics at smaller scales. Because CMAQ is designed to handle scale-dependent meteorological formulations and a large amount of flexibility, its governing equations are expressed in a generalized coordinate system. This approach

Managing complex socio-environmental problems using a generic, tiered system-of-systems modeling and data-science framework



The GTSoS ERC will resolve several families of socio-environmental problems at the local, urban or regional scale

Managing complex socio-environmental problems using a generic, tiered system-of-systems modeling and data-science framework

Example socio-environmental problems
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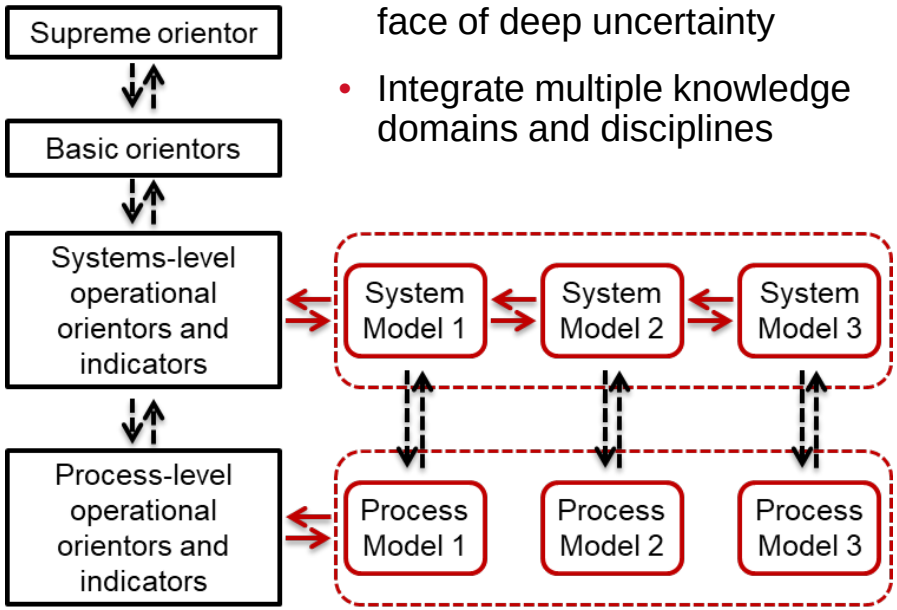
Disaster management
Urban planning

Example supreme orientors
Sustainability
Resilience
Human health
Ecosystem health

Generic framework at regional scale

- Component-based, system-of-systems software framework
- Tiered framework with different levels of abstraction
- Make robust decisions in the face of deep uncertainty
- Integrate multiple knowledge domains and disciplines



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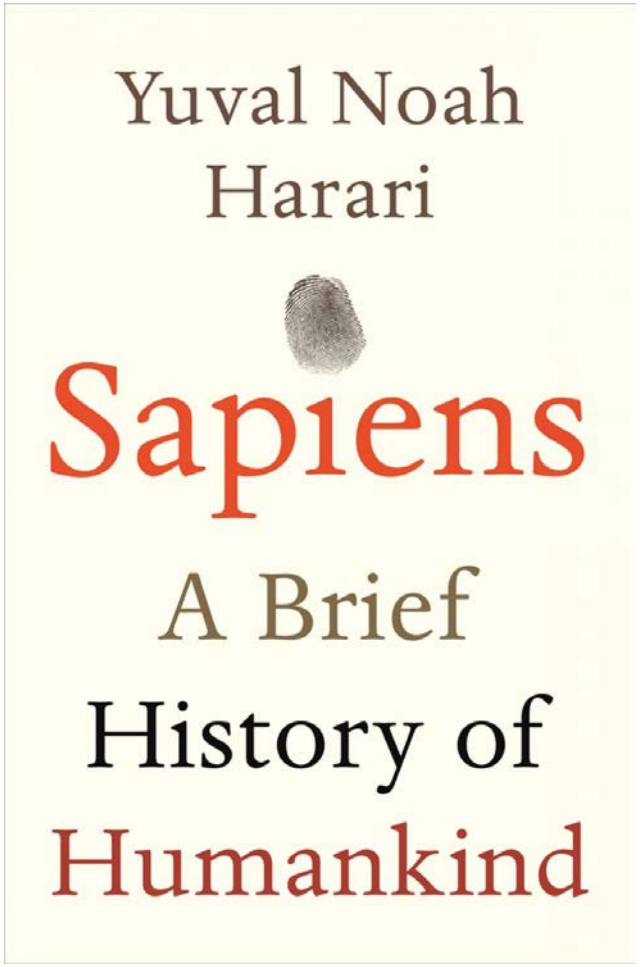
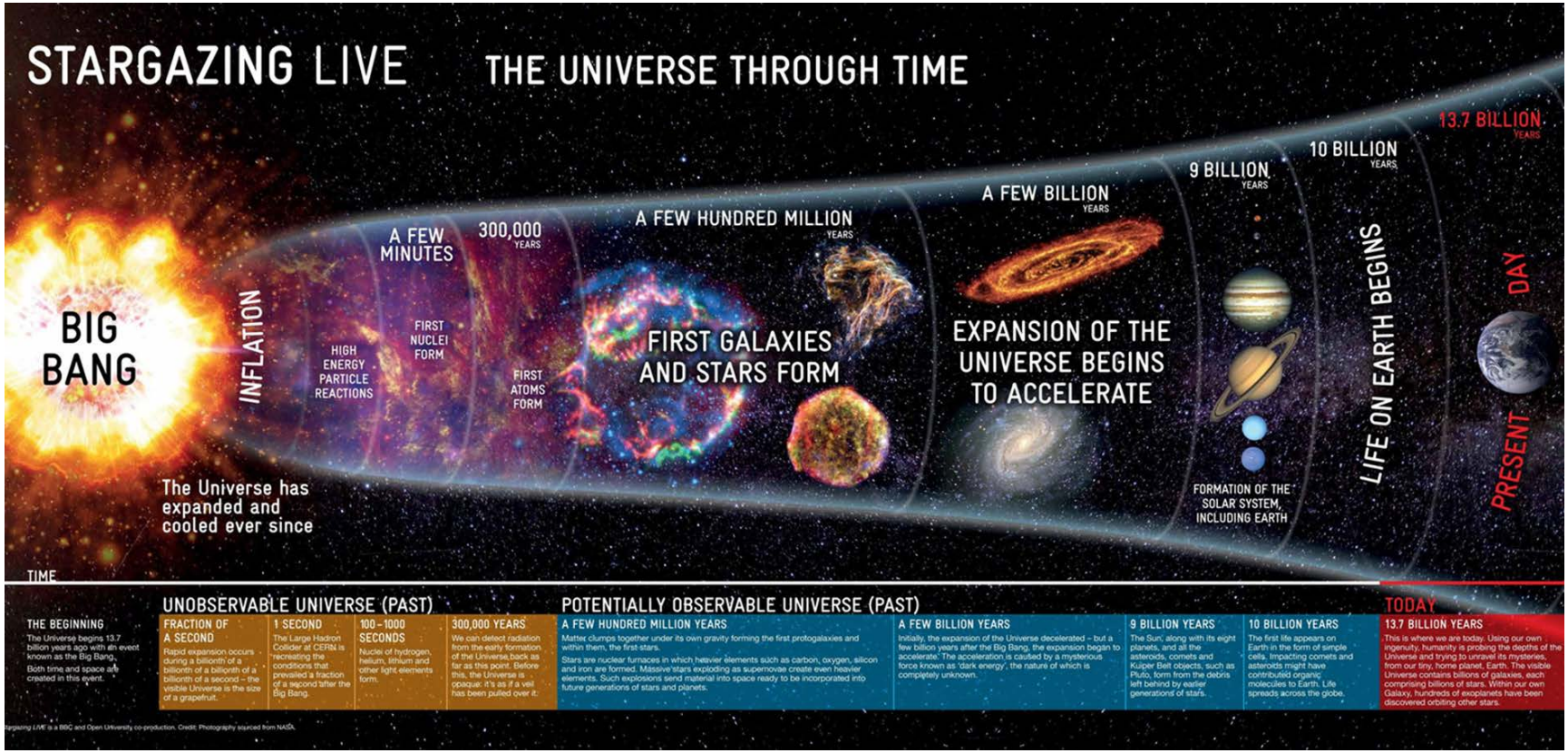
What about social systems?



Period	Years ago
The universe	~13,800,000,000
The solar system	~4,500,000,000
Life on earth	~3,800,000,000
Early humans	~6,000,000
Cognitive revolution	~200,000
Agricultural revolution	~10,000
Scientific revolution	~500
Industrial revolution	~300

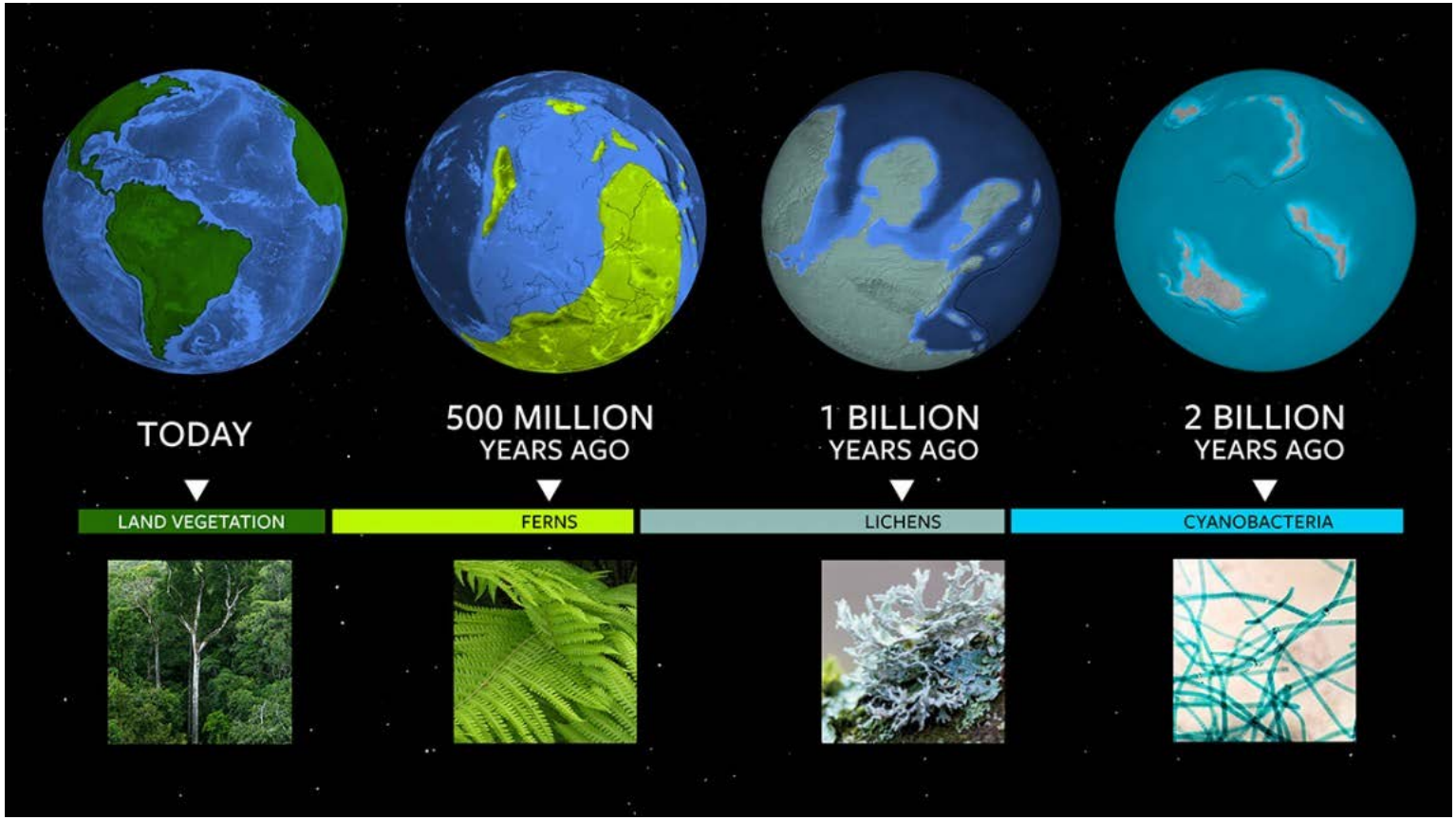
[Christian, 2018; Harari, 2015; LeDoux 2019; Volk 2017]

Period	Years ago
The **universe** begins with the big bang and the formation of stars.	~13,800,000,000
The **solar system** forms resulting in the sun and the earth.	~4,500,000,000



[www.infograde s.com/science-infographics/the-universe-through-time]

Period	Years ago
Life on earth emerges initiating biological evolution and resulting in ecosystems and the biosphere, as well as ocean, water, air, soil and climate systems. The first large organisms in the biosphere evolve, followed by the extinction of the dinosaurs, and the evolution of mammals.	~3,800,000,000



[www.space.com/alien-life-search-expanded-photosynthesis-signatures.html]

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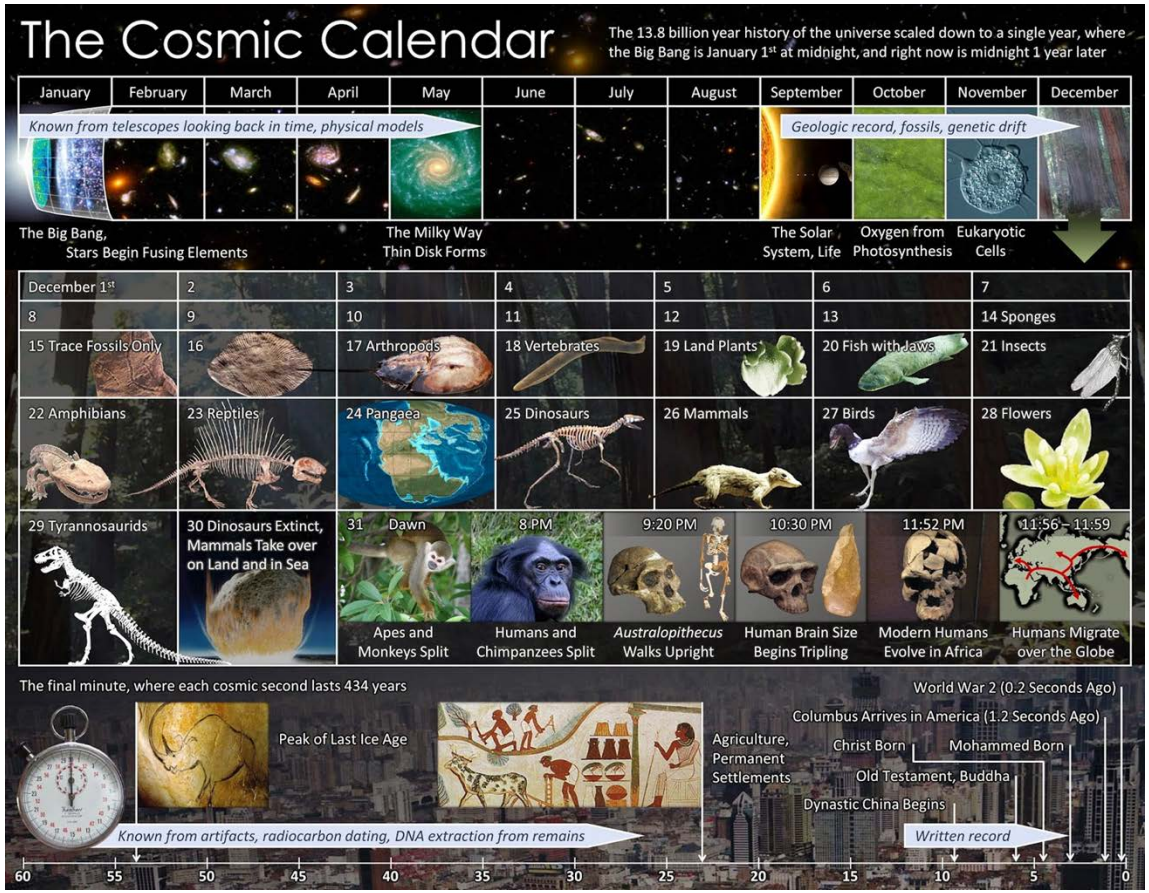
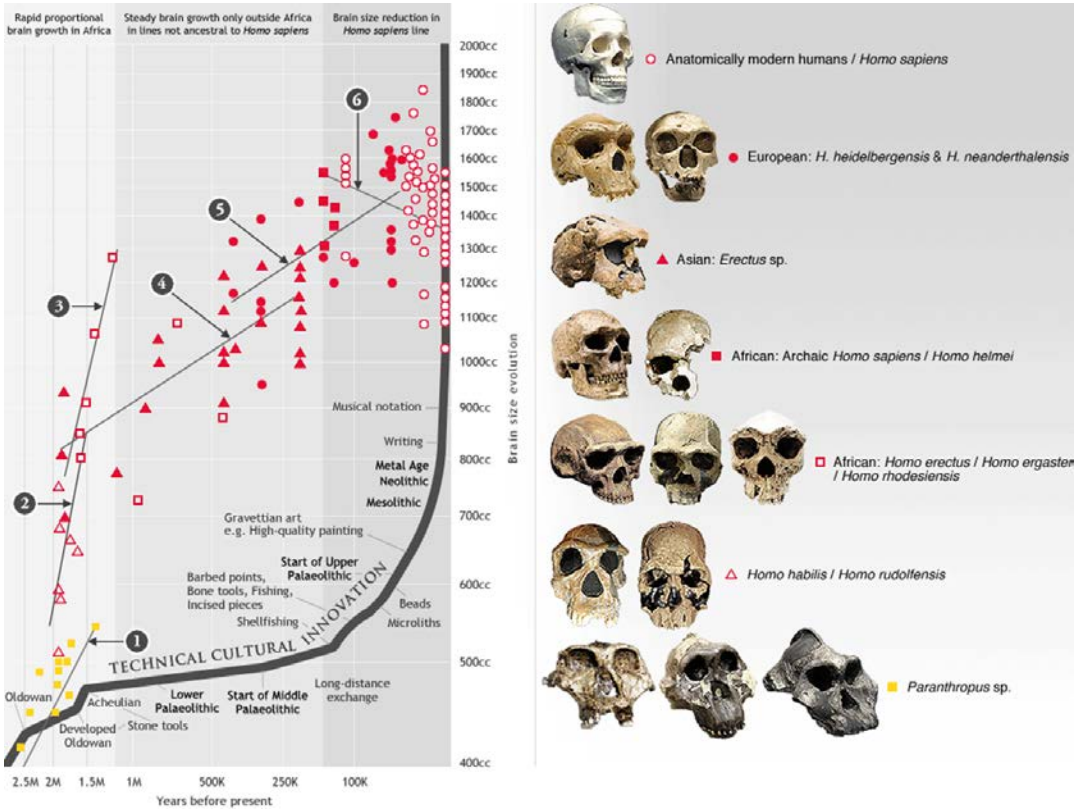


[https://en.wikipedia.org/wiki/Cosmic_Calendar]

Period	Years ago
Early humans separate from the apes and continue evolving leading to *Homo erectus* and the hunter gatherers. *Homo sapiens* evolve (~200,000 years ago) with an accelerating rate of cultural evolution, which is facilitated by fire, cooking, and communication. Several waves of migration out of Africa take place, with the eventual population of all major continents.	~6,000,000

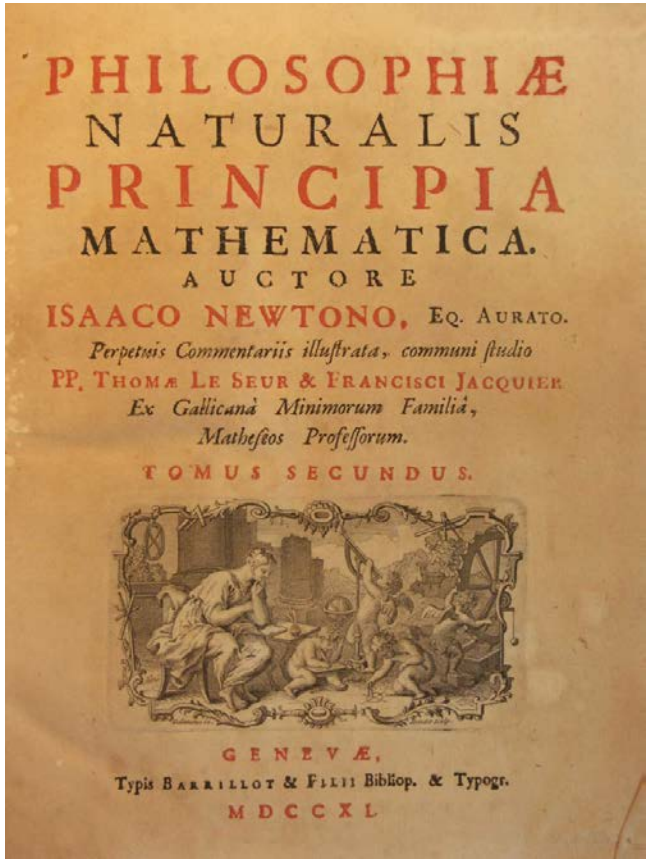


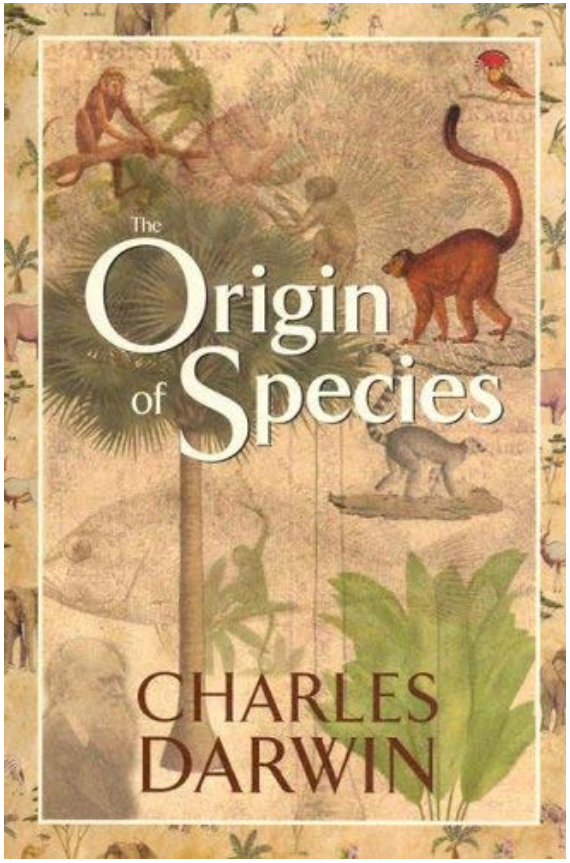
[www.bradshawfoundation.com/origins; hunter-gatherers.org]

Period	Years ago
The **agricultural revolution** leads to villages, towns, cities and agrarian civilizations, with domestication of crops and animals, and the associated disease, as well as the emergence of war and organized religion.	~10,000

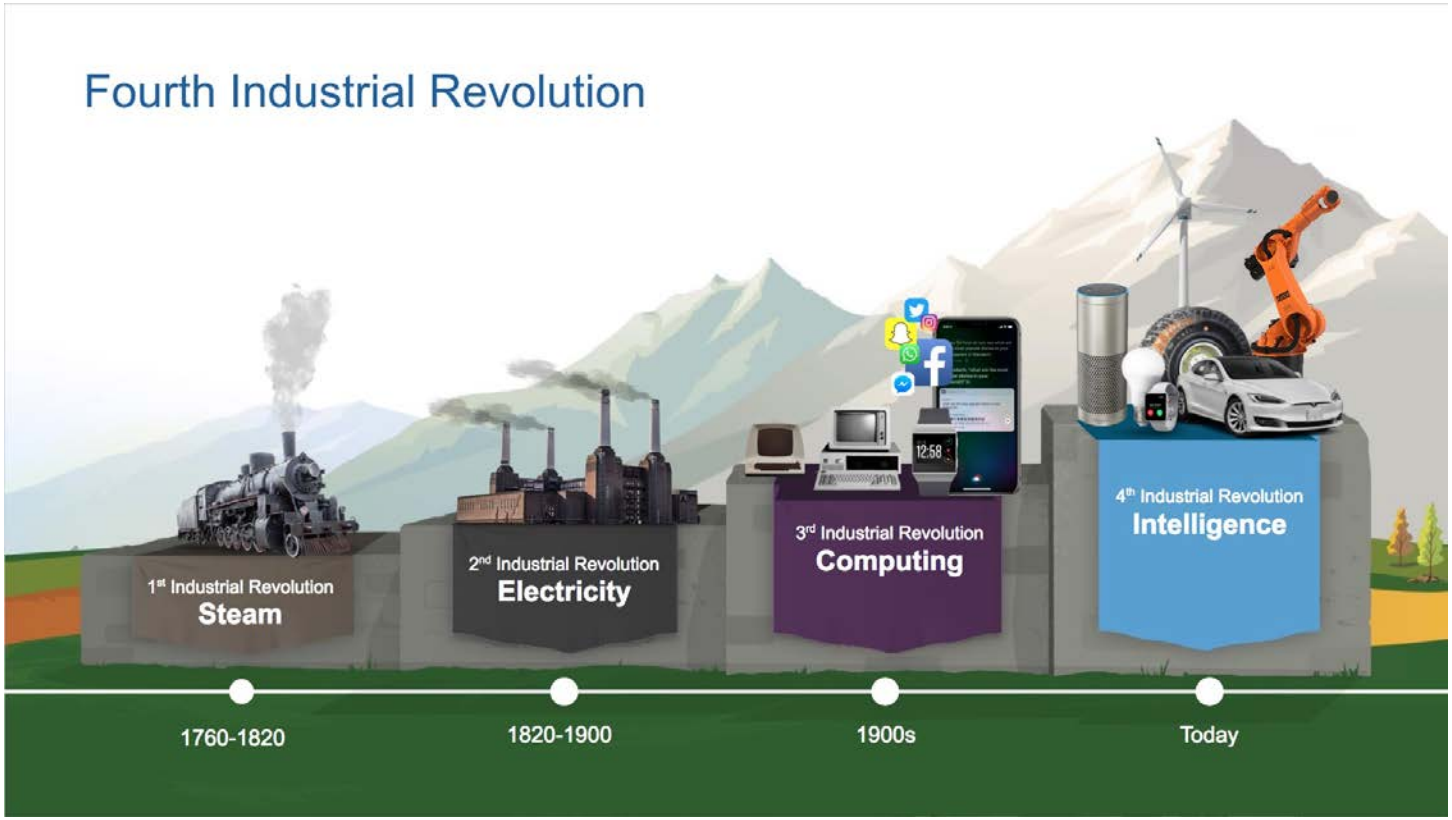
[www.ancient-origins.net/history-important-events/neolithic-revolution-0010298]

Period	Years ago
The **scientific revolution** begins as world zones are linked through trade, transportation and economic systems, with increasing development of mining, resource and energy systems.	~500



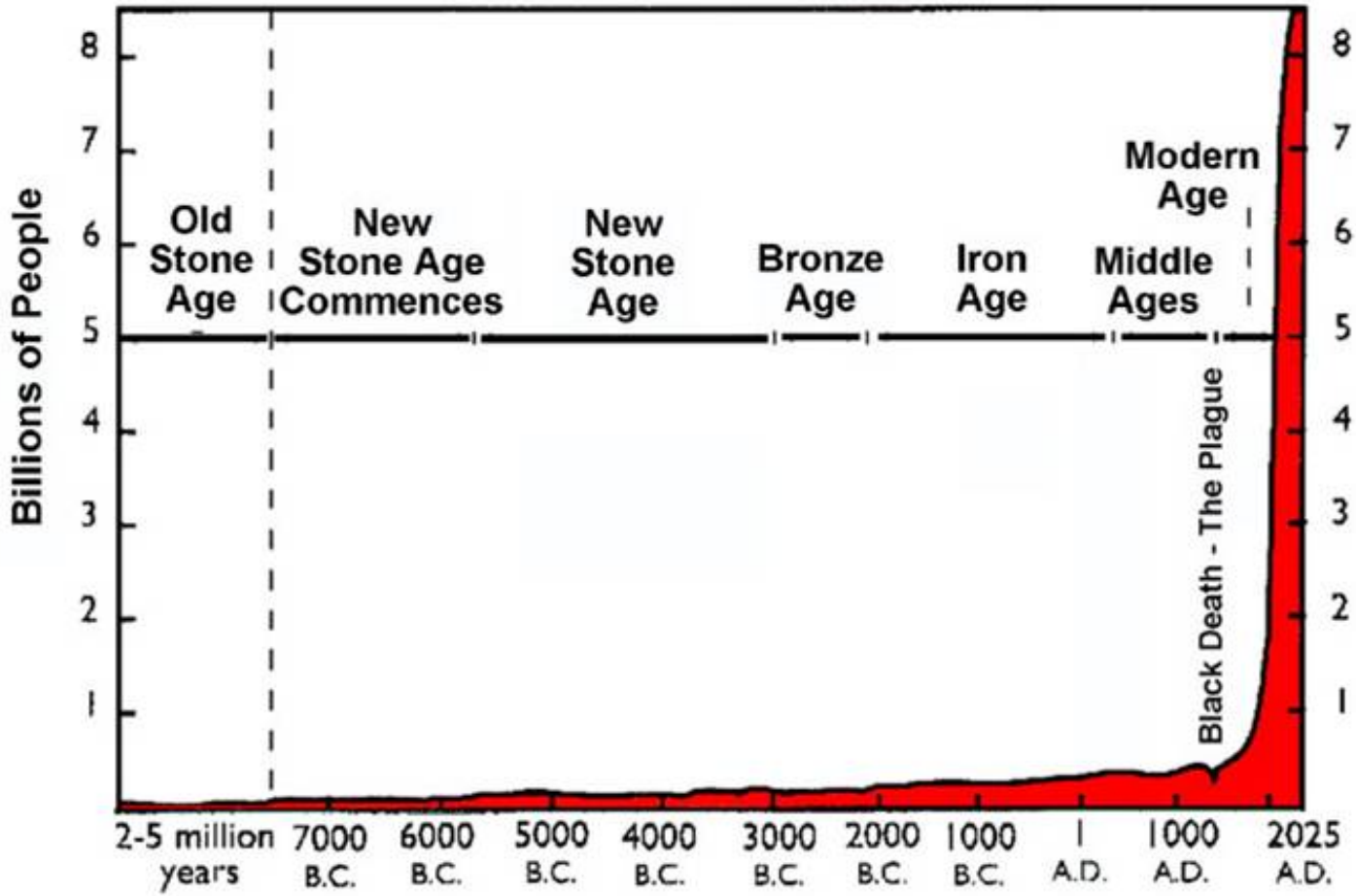


Period	Years ago
The **industrial revolution** is catalyzed by fossil fuels and causes the great acceleration, resulting in urbanization and increasingly sophisticated infrastructure, education, social systems, and the digitalization and computerization of science and society.	~300



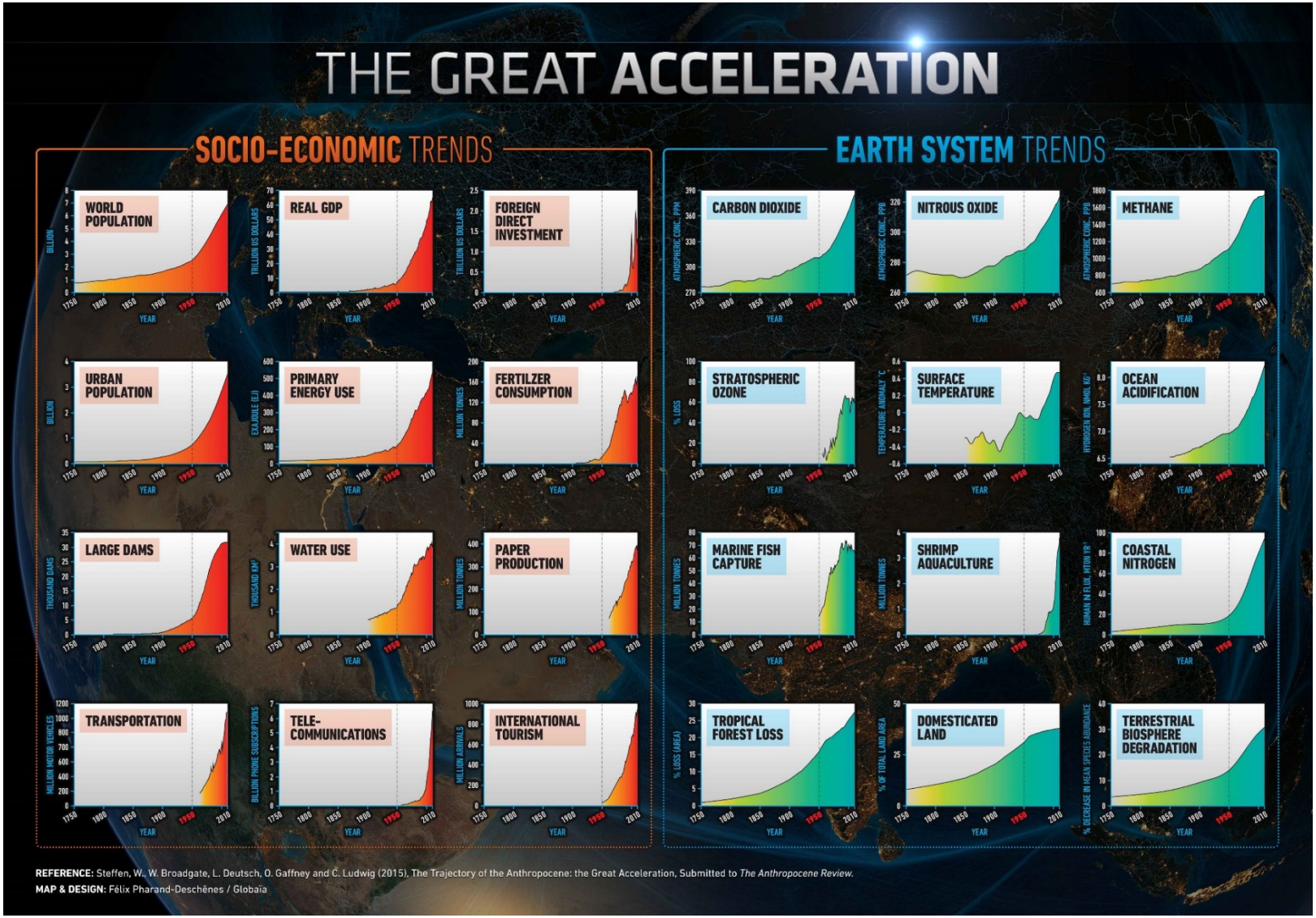
[https://medium.com/salesforce-ux/]

World Population Growth Through History



From "World Population: Toward the Next Century," copyright 1994 by the Population Reference Bureau

The trajectory of the Anthropocene …

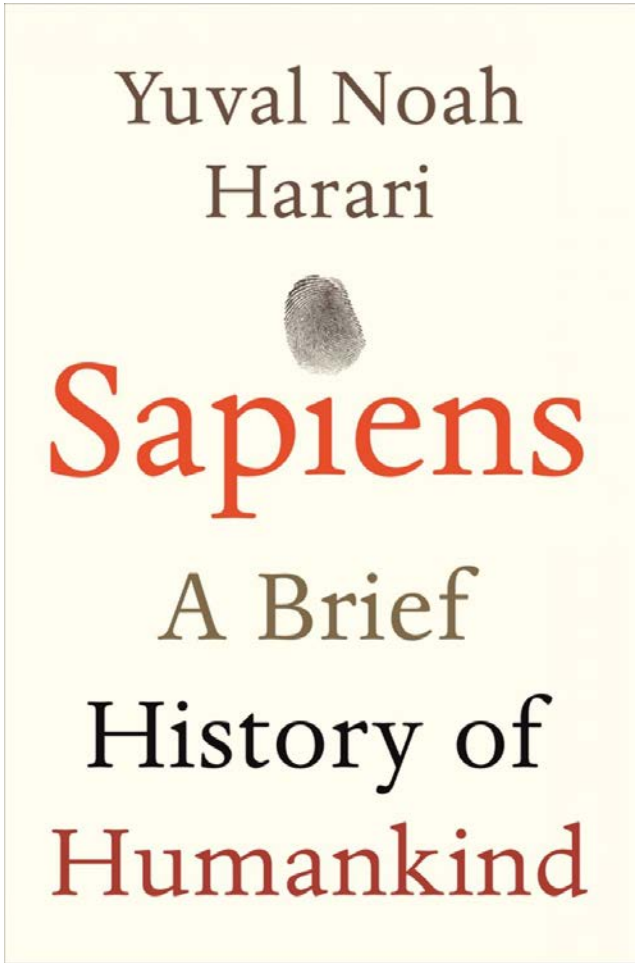


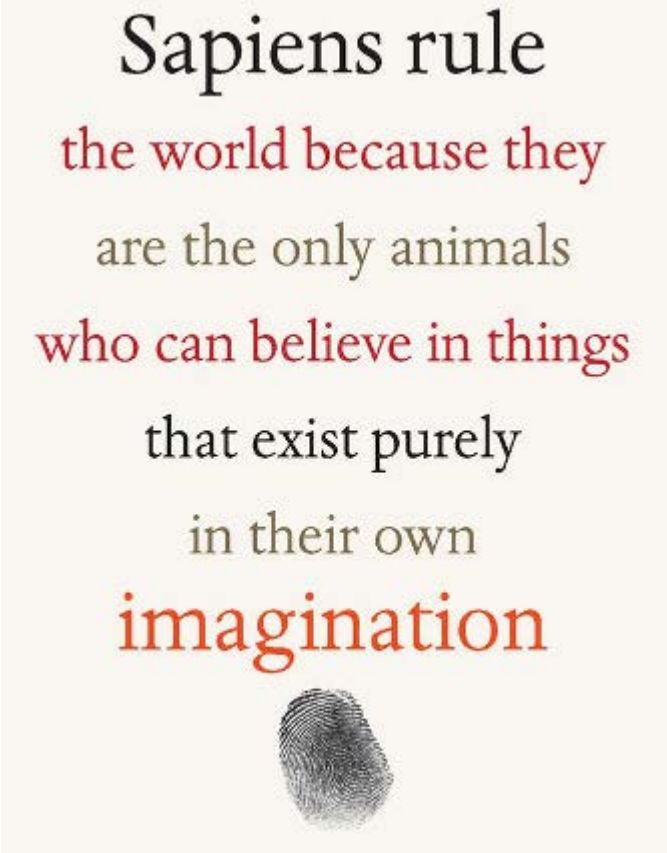
[Steffen et al., 2015]

An evolutionary, system-of-systems approach

Following the evolution of *Homo sapiens*, human cooperation accelerated the emergence of new social, economic and technical systems, while allowing humans to strongly influence existing earth, climate and ecosystems, resulting in the emergence of a globally-connected system of complex, socio-environmental systems.

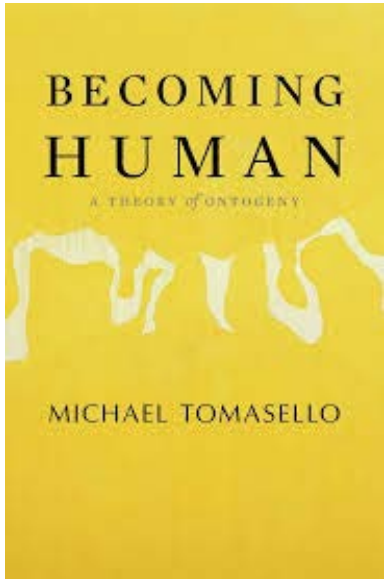
Humans – A brief history

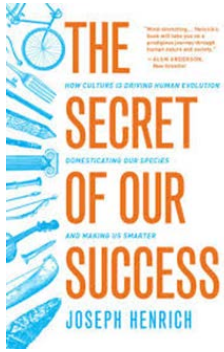


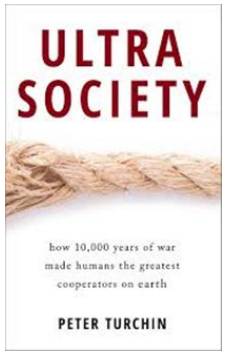


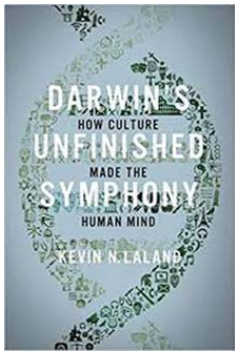
Cultural evolution

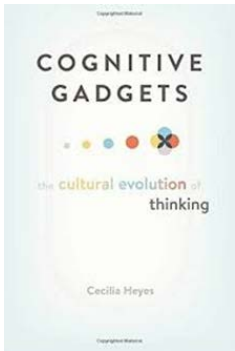
- The members of a cultural group coordinate with one another in the context of self-created cooperative structures (conventions, norms and institutions) and relate to one another based on cooperative motives (trust, commitment and fairness).
- The members of the group pass along skills and knowledge to succeeding generations via cultural learning (active instruction and conformist learning) causing cultural practices and products to evolve.
- Almost all of our most remarkable achievements – from steam engines to higher mathematics – are due to the unique ways in which individuals cooperate, both in the moment and over historical time.









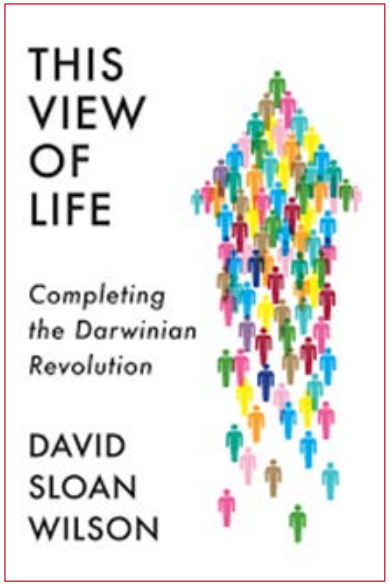


Evolution of groups

- According to D. S. Wilson, human behavior can really only be understood in the context of groups.

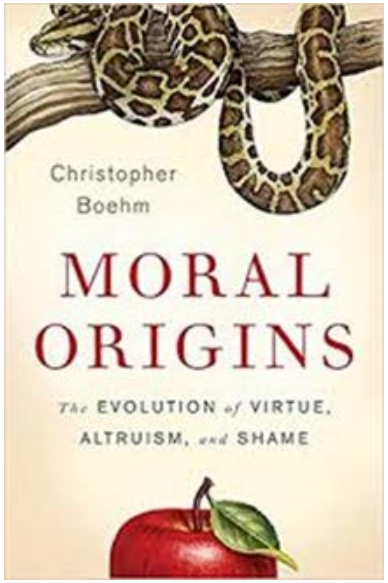
- A quote from D. S. Wilson and E. O. Wilson:
- "Selfishness beats altruism within groups. Altruistic groups beat selfish groups. Everything else is commentary."

- We can understand human behavior by moving from groups to individuals, as well as from groups to multicellular society.



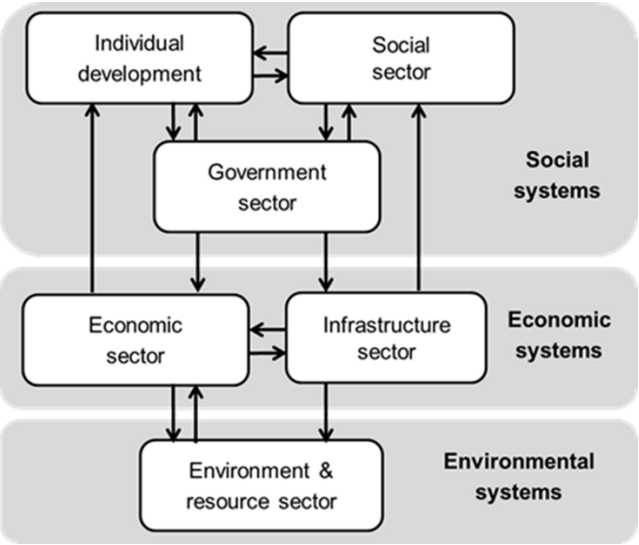
An evolutionary, system-of-systems approach

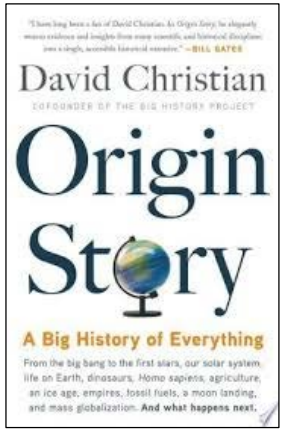
- When considering complex socio-environmental problems, cultural evolution must be the dominant social force because it was the evolutionary mechanism that resulted in the emergence of the globally-connected system of complex, socio-environmental systems.
- Other strong forces govern human behavior, but tend to be moderated by cultural evolution.
- For example, Boehm showed that for groups to function effectively, social norms are used to suppress selfish individual behavior.



An evolutionary, system-of-systems approach

- If this evolutionary, system-of-systems approach proves viable, we could use cultural evolution and niche construction as causal mechanisms in an interacting social network that connects other systems.
- Human behavior would be represented as the central social system in our system of socio-environmental systems (but need to revise the schematic).
- As with other systems, we would start with a fairly simple representation of social systems and then add other aspects of human behavior to make them increasingly realistic.

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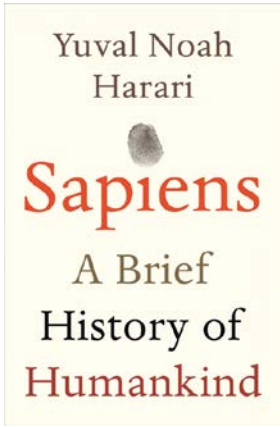
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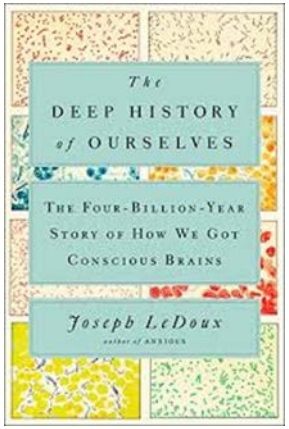
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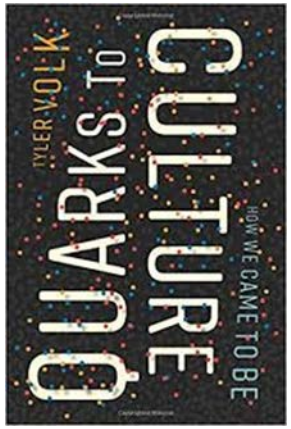
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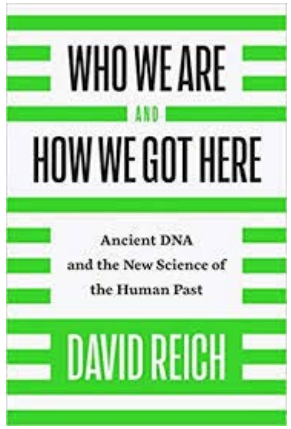
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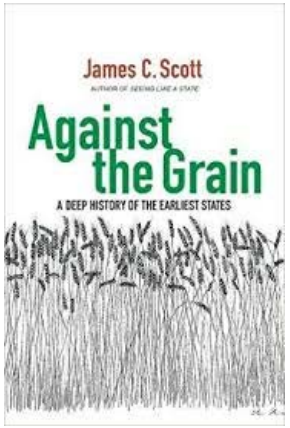
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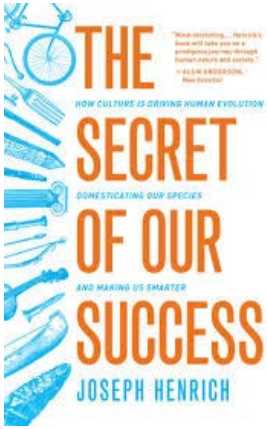
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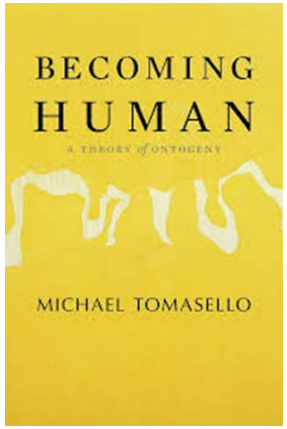
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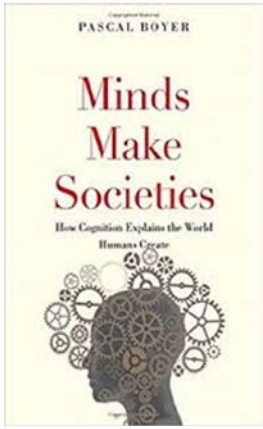
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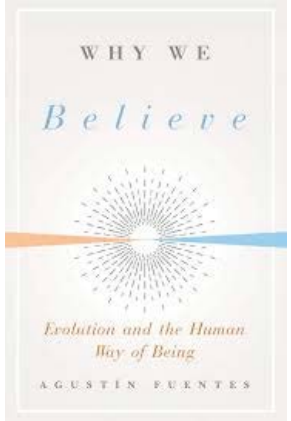
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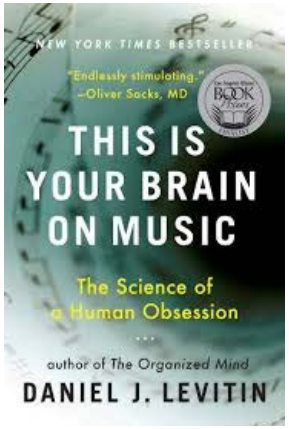
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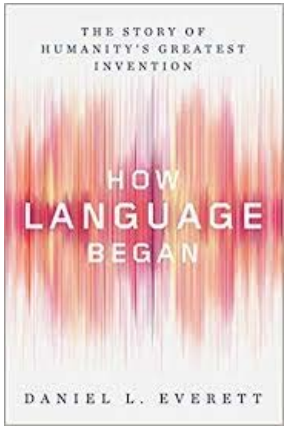
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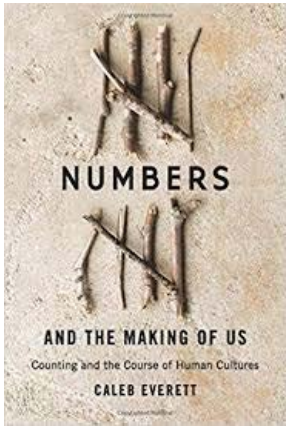
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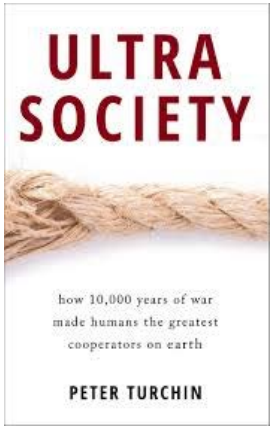
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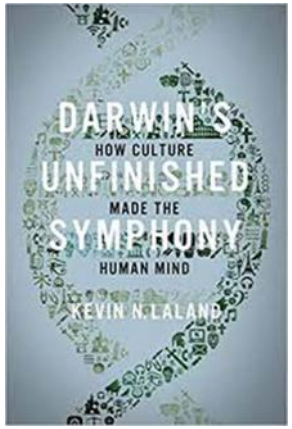
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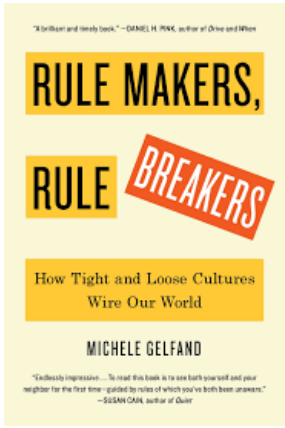
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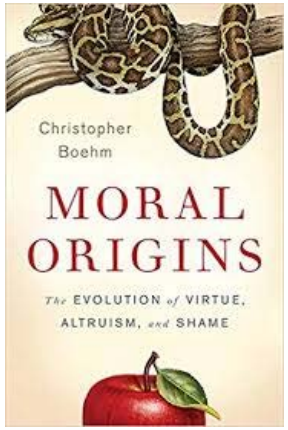
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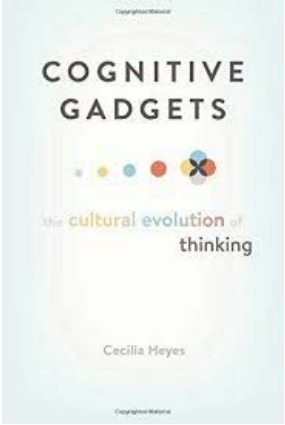
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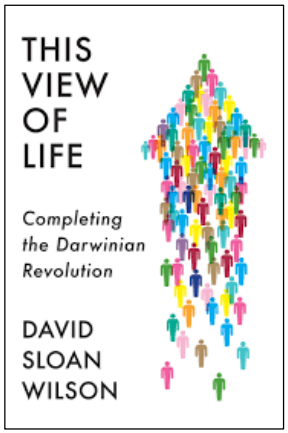
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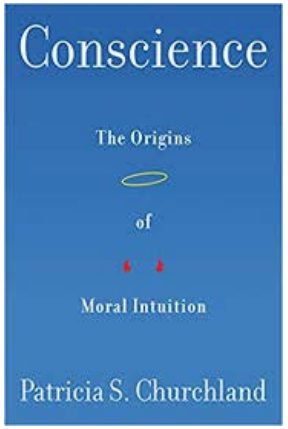
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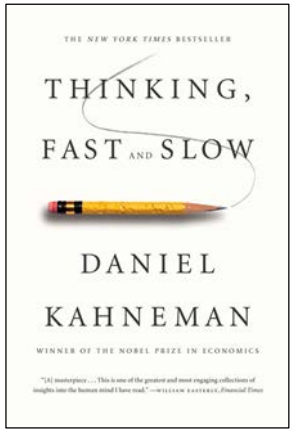
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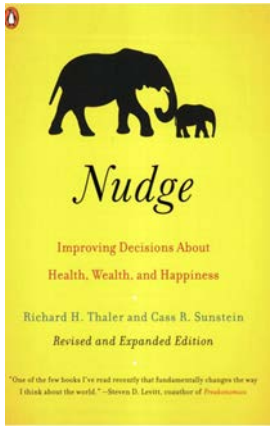
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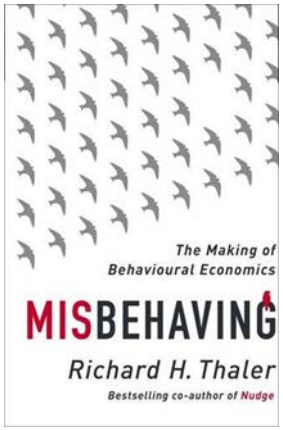
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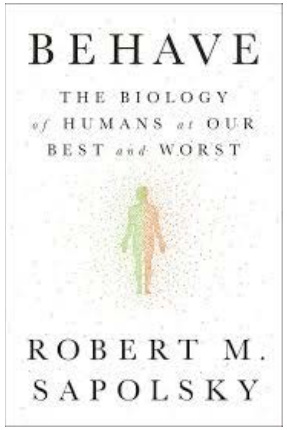
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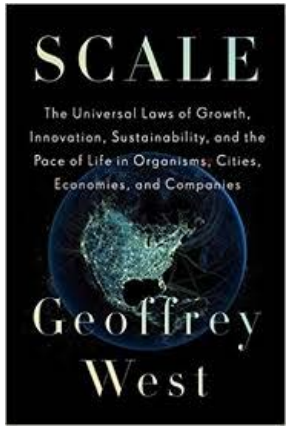
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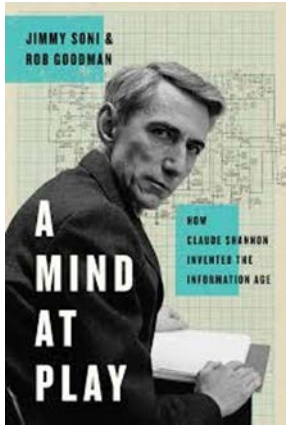
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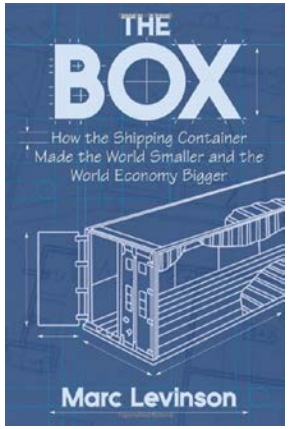
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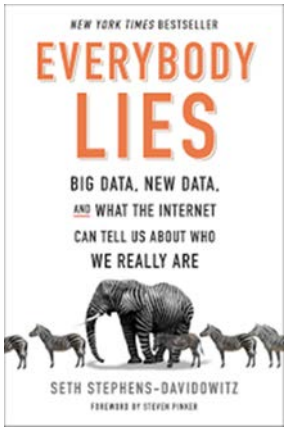
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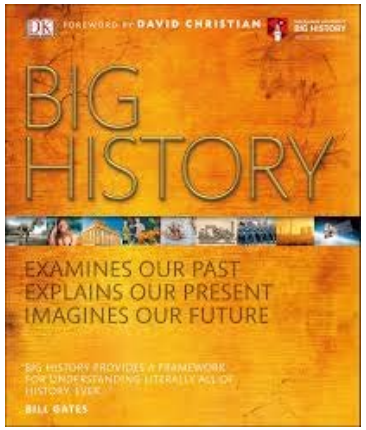
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Managing Complex Socio-Environmental Systems – An Evolutionary, System-of-Systems Approach

John Little
Department of Civil and Environmental Engineering
Virginia Tech

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