The Principles of Complexity: Understanding the Hidden Sources of Order

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Inspiring Awe & Wonder

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I. Introduction

Since at least Plato, Western philosophers have attempted to understand how and why life exists. Attempting to understand our place in the web of life has led scientists, and others with a philosophical nature, to live and study among different societies and ecosystems. This drive led Paul Gauguin to depart his native France for Tahiti, where he pondered the question of humanity's place in ecosystems and the reason for our existence in ***D'où Venons Nous, Que Sommes Nous, Où Allons Nous***.

Figure 1. D'ou Venons Nous, Que Sommes Nous, Où Allons Nous, by Gauguin. Considered one of his major masterpieces, this work was Gaugin's meditation on life, painted directly preceding an unsuccessful suicide attempt by the artist.

The procession of life dominates this painting, beginning from the right with birth, to adolescence in the middle, and old age in the left. Within this procession we can see women interacting directly with their local ecosystems—picking fruit and tending to domestic animals, with the volcanic landscape rising from the sea beyond. *Where Do We Come From, What Are We, Where Are We Going* speaks to the questions of humanity's place on earth, questions that were pulling at Gauguin as he painted this, intended to be his final oeuvre (due to an unsuccessful suicide attempt immediately following the completion of the painting). Gauguin lived on, painting more and further exploring the place of people in eco- and social-systems, with this painting setting the stage for exploring the place of humans (Sweetman 1995).

Beyond the world of art and philosophers, complex adaptive system science has aided the pursuit of understanding who we are, where we come from, and where we are going. When *Homo sapiens* spread out of Africa as early as 125,000 years ago, our species began to rapidly modify environments as it encountered them (Bird et al. 2021). While the initial impacts of humans on ecosystems may have been small in scale, focused on the direct impact of a new species arriving in a novel environment, over time human impacts across the globe compounded and intensified (Crabtree, Dunne, and Wood 2021). From these simple antecedents, complex structures and tens of thousands of distinct cultures grew. Yet despite differences among these varying societies across the 510 million square kilometers of land on earth, human action may be in fact subject to unifying principles of organization.

Complex adaptive systems theory can enable an understanding of the myriad ways that humans have shaped the globe and can provide a method for examining such disparate subjects as human mobility (Romanowska et al. 2017), settlements and cities (Bettencourt 2013), and ecosystems (Crabtree, Dunne, and Wood 2021) worldwide. In this review I focus on the ways that complex adaptive systems science has aided our understanding of humanity, lending a unifying theory to the ways that we impact the globe and impact other societies (Sabloff and Sabloff 2018). Often the choices made by individuals and societies have cascading effects, leading naturally to the use of complex adaptive system science to understand culture.

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II. What Is a Complex Adaptive System?

A unified definition is required to understand complex adaptive systems, specifically in a social systems context. Broadly speaking, a complex adaptive system is something that is greater than the sum of its parts that cannot be predicted based merely on the priors of its constituent units. There are actions and interactions among the units that can lead to non-linearities, where a system experiences somewhat unpredictable—and emergent—behavior (Mitchell 2009).

A simple example is a flock of birds. Each individual bird follows its own flying pattern, using sensory cues to help it decide in which direction it will be flying. Yet when birds group together, they form a complex flock, seeming to move as one organism. The same can be observed in fish, migrating ungulates, and even human systems. So, what are the underlying principles that drive a flock to form a whole that is greater than the sum of its individual birds?

Reynolds simulated flocking behavior in his famous "boids" simulation (Reynolds 1987). In this he found that three simple rules would govern the flock to behave in complex murmuration patterns. 1) The birds all head in the same direction. 2) Birds try and maintain the same spacing between themselves and their neighbors. 3) Birds maintain a similar velocity to their neighbors. Via these three simple rules, Reynolds was able to create the flocking patterns we observe in nature.

Flocking and herding behaviors can be seen as a public goods problem, as there are benefits to the group that flocking confer, yet for some individuals flying (or migrating) may be quicker without the cumbersome group. However, clear advantages to the group can be seen from flocking behaviors, namely, predator defense. In many complex systems there are benefits that emerge from the accumulation and interaction of multiple individual strategies.

In sum, in complex adaptive systems simple rules can lead to large, unpredictable behaviors, which frequently can be beneficial to individuals. In social systems we often look to these simple rules. As we shall see below, principles of complex systems guide many social and biological systems, from allometric scaling to the growth of hierarchy.

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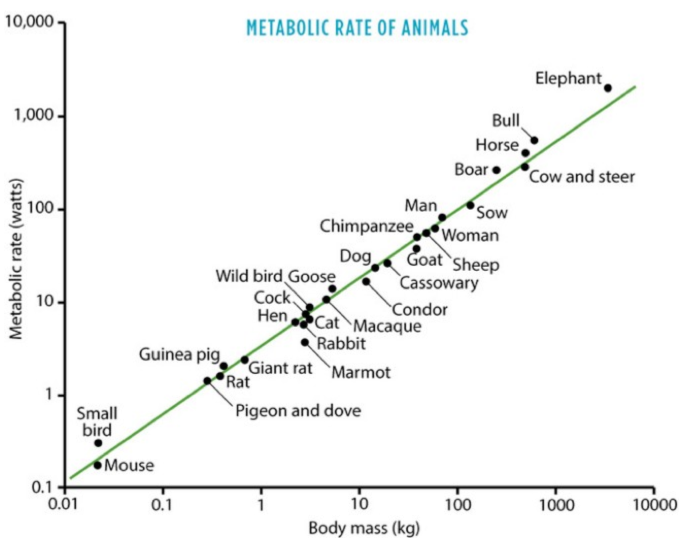
III. Where Do We Come From?

Complex adaptive systems science is useful for understanding the hidden order that governs social and ecological systems. Taking a nod from Gauguin, we can build our understanding up from examining the ways that ecosystems both govern and are constructed by human systems, to the ways that interactions among people help to shape social systems. Gauguin's work suggests a society living in close contact with the natural world, but even industrialized nations seem to be subject to the same organizing principles as smaller-scale societies (Ortman et al. 2014; Lobo et al. 2019).

At the base of this human organization we can look at the human body itself, and then beyond that to our ecosystems and societies. Within our bodies, our circulatory system is governed by networks—our blood vessels—that enable the efficient spread of blood throughout our bodies. These networks are hierarchical, and the routes along which things spread—the blood vessels themselves—get smaller the farther they move from the central hub—the heart (West 2018). These types of hierarchical networks exhibit fractal-like properties, whereby they look similar in both miniscule and magiscule and can be found throughout the human body [although the human circulatory system is not strictly fractal (West 2018 p. 129)]. The ways that nutrients flow from the trunk of a tree to the tips of leaves can be described in a similar way. The self-similarity within these systems seems to follow a ¼ power scaling law. A scaling law "describe[s] the functional relationship between two physical quantities that scale with each other over a significant interval" (Nature Portfolio 2021). The reason for this scaling is the efficiencies they bring upon the flow of blood within the human body. For blood to reach the extremities of our fingers and toes it needs to be pumped hard. By decreasing the size of capillaries this allows for the blood pumped from the heart and the largest blood vessels to reach the farthest extremities. Constricting the blood vessels allows the decreasing volume of blood to be appropriately accelerated to its final destination (West 2018).

Scaling laws also apply to the metabolic rates in aging versus body mass, where larger animals live longer than a simple 1:1 scaling would suggest. Described another way, for an animal that has twice as many cells as another (say, a vole compared to a house sparrow), double the amount of energy is not required to power those cells. Instead, there is an economy of scale that governs the process of doubling in size, where the metabolic rate only increases by, approximately, 75 percent, or a power of ¾. This process is known as Kleiber's Law after Max Kleiber, the scientist who defined this work in the early 1900s (West 2018; Kleiber 1947). In Figure 2 we can see that many common animals, from humans to horses to rats and mice, fit neatly on a graph of metabolic rate versus body mass with a scaling exponent of ¾ when they are log-normally graphed (West 2018).



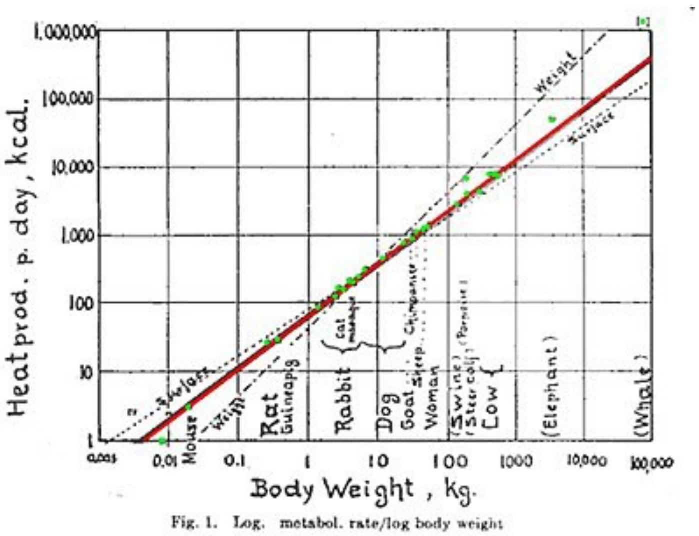


Figure 2. Body mass is said to scale with our basal metabolic rate. When the size of an organism is graphed against its metabolic rate, which is graphed logarithmically, a scaling rate can be seen at a scale of ¾, where for every doubling in mass, an organism's metabolism is ¼ more efficient. In the above panels, panel (a) is recreated from the Wall Street Journal. *Panel (b) is the original drawn by Kleiber (and calculated by hand).*

A challenge in understanding the growth of organisms lies in the juxtaposition of scaling of size to metabolic rate and the ways that blood vessels branch within a mammalian body, creating a constraint in allometric scaling laws. It turns out that capillaries, the smallest of blood vessels, are size invariant across mammals, being of the same size in voles and blue whales (West 2018). Capillaries allow for the exchange of matter between tissue and blood cells, most critically, oxygen. When an organism doubles in size, its capillaries enlarge by approximately ¾; sizes beyond that would be impractical according to allometric scaling laws. An organism larger than a blue whale that would be constrained to allometric scaling laws would suffer tissue death, killing the animal. In answer to Gauguin's question *d'où venons nous* the answer here would imply, metabolically, we come from a scaling relationship somewhere between a sheep and a sow (Figure 2).

Yet our metabolic rate can also tell us much about the process of aging and death. Larger organisms, like blue whales, elephants, and humans, tend to live longer. If again we used a 1:1 ratio for doubling, we would not predict the longevity that is experienced by these larger mammals. Wear and tear on the body seems to predict the *terminus ad quem* of an organism's lifespan, with greater wear and tear proportionally on smaller organisms. This is because with each doubling in the size of an organism, a decrease of roughly 25 percent in the quantity of heart beats per minute is reached. A shrew experiences approximately 1,000 beats per minute; a human roughly 70; a blue whale only four to eight beats per minute. Metabolic processes cause significant stress on the body; this decrease in the number of beats means larger organisms generally enjoy longer lives. Lifespan scales as ¼ power of mass (West describes this as following the ¾ scaling exponent on “terminal units” with the number of cells scaling linearly, forcing lifespan to scale at ¼ power of mass) (West 2018).

Scaling also impacts the ways that social relationships form among individuals and even within societies. Physiological constraints limit the number of individuals we can maintain relationships with; in the early 1990s anthropologist Robin Dunbar proposed that the size of the brain corresponded to the sizes of social groups among non-human primates. Dunbar determined that a limit of approximately 150 would be reached among humans (Dunbar 1992). Since Dunbar first proposed this theoretical limit, appropriately called Dunbar’s Number, others have tested this theory, such as in work by Lewis et al. (Lewis et al. 2011), who discovered that the volume of the prefrontal cortex likely dictates the upper bound of the number of individuals we can recognize and befriend. This hardwired boundary limits the size of the social network we can maintain (Dunbar et al. 2012). Unless brain size can increase, which anthropologists suggest is impossible due to the limits in the size of the birth canal (Dunsworth 2016), the upper limit on our social network is around 150 individuals. Hypothetically, if babies were born premature and continued brain development outside the womb, this social network size could expand, though this likely would require biohacking or something similar on a population scale to enable an expansion of Dunbar’s number in a meaningful way.

A. Scaling and Settlements

If the number of individuals we can form close relationships with is hardwired, then ways to move beyond those constraints include innovations such as scaling our relationships. Often, anthropologists look at modern non-industrialized small-scale societies to see the development of social structures, since these societies provide a useful analogue for pre-industrialized societies.

Among cross-cultural studies, researchers have found that groups typically form with a nested hierarchical structure, with family units of approximately five, and language groups of 1,500 individuals forming the upper bound, with a scaling ratio of approximately 3 for each level (5, 15, 50, 150, 500, and 1,500) (Dunbar et al. 2012). Within these levels include foraging groups of 30 to 50, larger residential units of about 150, and sodalities or other groups of relatedness of about 500 people (Zhou et al. 2005).

A feature that is shared between small-scale hunter-gatherer societies and village societies is the number of individuals with whom the members of those societies can have meaningful relationships. While humans recognize and maintain weak ties with a larger number of people—approximately 1,500 can be named and recognized by face at any given moment (Dunbar et al. 2012)—the number of individuals we maintain strong ties with remains consistent between mobile hunter-gatherers and residents of modern industrialized cities due to the physical constraint of our brains. Even though social media enable us to maintain social ties with a larger number of individuals, recent studies suggest that we frequently interact among the same subset of 150 of our "friends." Even outsourcing a friendship network to a computer does not seem to enable us to move beyond a hardwired Dunbar's number (Dunbar 2016).

Another way to maintain connection to the larger group beyond face-to-face contact can be codified in language, in stories, or rituals. In a study that makes use of ethnographic interviews of a living small-scale society, Fitzhugh finds that people living on the Kuril Islands maintain long-distance social ties specifically to help tribes survive disasters. Via oral tradition, distant groups pass down stories to subsequent generations; usually there will be little contact between the groups after the initial sharing of the story. The impact of these shared stories is critical, though, for the survival of the societies. The Kuril Islands are beset by natural disasters, including earthquakes and tsunamis. When a group is impacted by one of these events, they can then travel to another group hundreds of kilometers away. The telling of a shared story identifies them as part of a distant node in a social network. The long-held stories identify a connection in the social hierarchy (Fitzhugh, Phillips, and Gjesfjeld 2011).

This type of hierarchical communication, based on maintaining social ties without direct face-to-face contact, can be seen in other distantly spaced small-scale societies. To examine how and where a hidden source of order maintained a social hierarchy and distant social networks, we can look to work examining the formation of hierarchical groups (Kohler et al. 2018; Crabtree et al. 2017) across long distances and before modern communication. In this work, the researchers examine the Ancestral Pueblo of the American Southwest to understand how small households could be part of larger, nested polities.

To understand why they modeled the growth and decline of polities, a brief account of the archaeological history of the region is needed. Around A.D. 600, migrants came into the central part of the Mesa Verde region (Figure 3), bringing the farming package of corn, beans, and squash with them. They settled into widely spaced farmsteads. Aggregated villages began to form in the 700s and 800s, yet they were relatively small. By the 10th century, a settlement in Chaco Canyon (New Mexico) was formed, but it wasn't for a few more decades, until the growth of the Chacoan Regional System, when settlements far from Chaco Canyon were built with similar architectural styles, and roads radiated from Chaco Canyon to outlying regions, and similar iconography can be found. Toward the end of the 1100s, surrounding droughts and political unrest, Chaco Canyon collapsed, with several other regional systems developing. During the 1200s the iconic cliff dwellings in Mesa Verde were built, while the entire region was abandoned between A.D. 1280 and A.D. 1300 (Kohler et al. 2012).

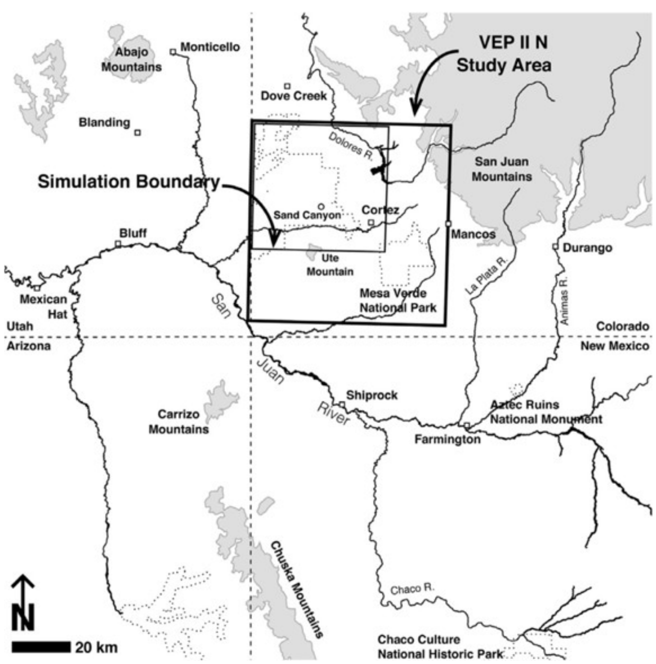


Figure 3. The Four Corners region involved in the study by Kohler et al. (2019) and Crabtree et al. (2017). This region provides a case study of how hierarchy could grow.

Among the archaeological community, the question of whether the Ancestral Pueblo people were hierarchical or egalitarian has been hotly debated, becoming particularly fraught in the 1980s (Crabtree et al. 2017). For some archaeologists, because descendent communities like the Hopi are egalitarian and eschew hierarchy, this suggested that the antecedent communities must have been as well; what community would become acephalous if they came from a hierarchical system? Yet, for those archaeologists who worked at Chaco Canyon, where prestige goods like turquoise, silver, macaw feathers, and cacao were unearthed, the Ancestral Pueblo must have been part of a large polity. Further, burials at Aztec, New Mexico, which fluoresced after the decline of Chaco Canyon, suggest there were powerful individuals. Finally, recent evidence suggests that the burials deep in Chaco Canyon itself, where much of the prestige goods were unearthed, come from a single matriline (Kennett et al. 2017), suggesting matrilineal inheritance over time. Yet areas far from Chaco Canyon do not exhibit prestigious burials, nor do they exhibit households with greater wealth than others. Rather, within settlements it seems that everyone was egalitarian.

To reconcile these opposing viewpoints, Crabtree et al. hypothesized that *if* hierarchy were to develop, it would develop as most things in the U.S. Southwest seemed to develop—as a means to control productive yields of maize and arable land. To examine whether hierarchy could emerge from egalitarian antecedents, the researchers built an agent-based model. The model compares mechanisms for hierarchy against the empirical archaeological record, to examine the ways that groups could connect into larger entities (Kohler et al. 2018). Within the model, households form (mother, father, children) as the economic unit that farms maize; hunts for deer, rabbits, and hares; and domesticates turkey for protein. Maize yields correspond to a paleoproductivity model based on realistic hindcasting of precipitation coupled with the likely soil productivity, calculated cell-by-cell (cells 200 by 200 meters). Children track their matrilineage back to the original 200 founding families when the simulation is begun in A.D. 600. Groups are formed based on relatedness, expanding over time, with a minimum-bounding polygon circumnavigating the members of the group. Households respond to local productivity and will move to more productive lands. When this happens, the group's polygon expands. If a household wants to move to a location that causes the two group's polygons to overlap, the groups decide whether to engage in a fight.

Following logic based on Lanchester's Laws (Lanchester 1956), a set of coupled differential equations developed during WWI to help predict casualties during battle, the number of fighters for each group is subject to a stochastic multiplier to determine who would win the battle. The winner, then, can offer a merger with the losing group, which becomes subordinate and must pay a tax to the winner. Groups can choose to fission from their dominant group based on similar logic to the initial battles.

Via this process, large polities with chains of dominant and subordinate groups can form. The researchers (Crabtree et al. 2017; Kohler et al. 2018) found that when productivity in the simulation was good—high rainfall creating high yields of maize—larger polities tended to form. Yet when productivity decreased, polities tended to disintegrate in favor of more regional structures.

To determine if these mechanisms could be detected in the archaeological record, Crabtree et al. measured the sizes of ceremonial buildings, called kivas, as well as the sizes of settlements over time. They then measured the bounding polygons that encompassed groups in the simulation, subjecting each of these datasets to a scaling analysis, examining whether the distribution of sizes of sites, kivas, and simulated polygons were more log-normal or were more closely related to a Pareto distribution, a type of skewed distribution with a characteristic heavy-tail. They reasoned that Pareto distributions would exhibit a rich-get-richer dynamic, where the larger the site, the disproportionate amount of power it would wield. Yet, if the distributions conformed to a log-normal distribution, that would suggest a more equal distribution of power within those sites/kivas.

They found that during the early years in the simulation and in the empirical data, distributions conformed to a log-normal distribution, suggesting that things were fairly egalitarian. Yet during the time that the Chacoan regional system occurred, there were few very large sites and very large kivas, which would not be predicted based on an egalitarian distribution. In the simulations, this is when the largest settlements occur. During the final decades of population in the region, the signal gets much weaker, with local power consolidating but leaving a distribution at the regional scale (Figure 4).

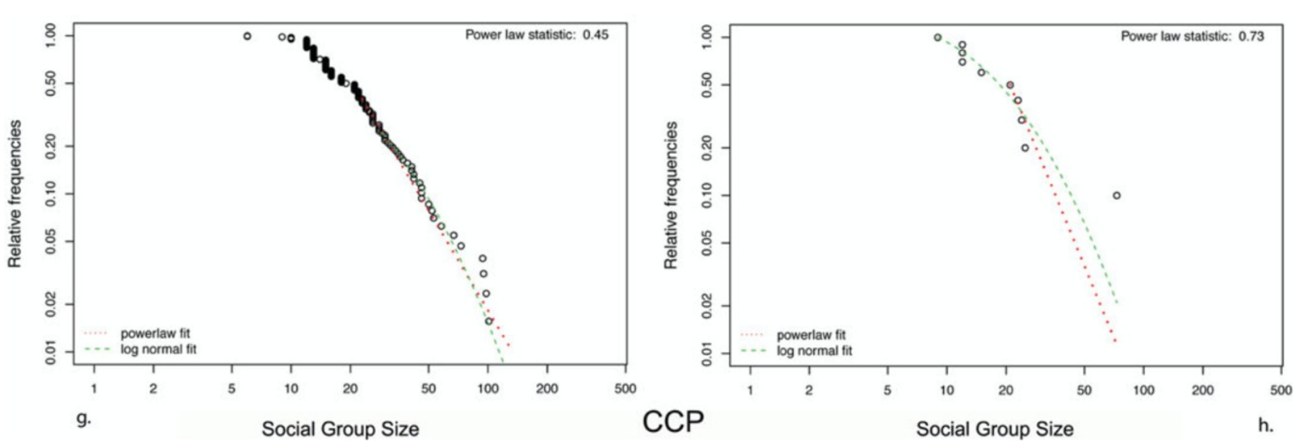


Figure 4. From Crabtree et al. (2017), examining whether the size of social groups follows a heavy-tailed distribution, suggesting consolidation of power, or a log-normal distribution, suggesting regular growth. Crabtree et al. suggest that archaeological data favor the consolidation of power in the Chaco region.

While the sample sizes are small, their analyses suggest that, especially during the height of the Chacoan Regional System, there is a consolidation of power at Chaco Canyon. Further, they calculate the number of individuals who could have been involved in decision-making at Chaco by examining the number of individuals who could be housed in the largest ceremonial kiva there, Casa Rinconada. With 130 individuals who could be accommodated at Casa Rinconada, they suggest that following nestedness logic from Hamilton (Hamilton et al. 2007), decisions made in a Great Kiva like Rinconada could reach approximately 2,900 individuals. (130/2 = 65. Most small kivas accommodate 45 individuals, so decisions made in a Rinconada would be translated at approximately 65 kivas to 45 individuals, or 2,925 individuals.) Thus, these ritual centers could be used in a nested hierarchy to reach thousands of individuals. Their work, of creating a simulation to examine how hierarchy could form, and comparing the simulated data to the archaeological record, demonstrated that Ancestral Pueblo people were hierarchical but also non-hierarchical; it just depends on when you look.

At the end of the continuum of hierarchy is the concept of the "State," a core concept in anthropological and archaeological research for the past 100+ years. In the edited volume, *The Emergence of Premodern States* (Sabloff and Sabloff 2018), the contributing authors explore, through many case studies, the ways that complex adaptive systems science can further our understanding of how states emerged. Fortunado, in her chapter "Systemic Comparative Approaches to the Archaeological Record" (2018), suggests that even though early anthropology was built on the concept of developmental continuum from "savagery" to "civilization," making modern anthropologists wary of comparison, comparative work can be useful for understanding regularities over space and time. For example, Sabloff and Cragg (2018) find that by looking at the different roles that people in prehistory held, and the statuses that were afforded to these different roles (e.g., serf versus king) they can examine such questions as whether or not statuses were similarly distributed across premodern states that had different developmental processes.

Ortman et al. (2018) in *The Emergence of Premodern States* suggest that anthropologyand archaeology face challenges due to the ways that societies can be studied and described in such detail that it is difficult to generalize. They note that physics and biology coarse-grain to avoid issues of too much detail at the individual level. In this way, complex systems can be useful for studying societies, providing a coarse-graining lens to view "human societies as dynamic networks of people, energy, and information that exhibit emergent properties related to their structure and functioning" (p. 188). By looking at specific variables across multiple societies, Ortman et al. demonstrate that there are regularities in archaeological societies. For example, they look to the population of the largest settlement in a society compared against the length of the archaeological tradition, finding a negative trend. The application of comparative approaches, as suggested by Fortunato and by Wright (2018), enables these examinations.

In the same volume, Hooper et al. (2018) suggest that underlying ecology can be seen as a"push" factor in the development of hierarchy. In the above model by Crabtree et al. (2017), we see that the fight over resources can lead to the development of hierarchy in the specific Pueblo case. Yet Hooper et al. (2018) found that a patchy distribution of resources would lead to hierarchy. In their general model, they find that when resources are predictable and evenly distributed, agents would not choose to live in hierarchical situations. Yet, when resources are unevenly distributed, hierarchies seem to develop. They find that territoriality over patches with resources leads to strong hierarchies. Looking at both the Pueblo case, where we know hierarchies developed and where the simulation suggests territoriality over resources, and Hooper's general model, we can suggest that in environments with unpredictable and patchy resources, hierarchies can encircle populations and become the *de facto* situation for citizens. Yet, as above, we show that hierarchies can enable more efficient communication, and due to the ubiquity of them, we can infer that they provide other positive effects as well. As Wright states, "everyone who reads this chapter is under the control of a state" (p. 15). Their ubiquity bespeaks their utility, which can be detected in prehistory.

B. A Modern and Ancient Source of Order

The work by Crabtree et al. showed efficiencies in communication in the Ancestral Pueblo world, yet there are other ways to examine efficiencies with ancient data and determine a concordance between ancient systems and modern systems. It turns out that the way our cities are organized may have an influence from ancient systems. Cities, after all, are not a new invention, but have been in existence for millennia. Yet cities were not the norms in ancient times. Rather, most individuals lived in rural contexts, with cities being core locations that non-residents would visit for business.

Recently, and for the first time in human history, populations shifted from being primarily agricultural to moving to urban centers. In 2000, 70 percent of the population of developed countries lived in cities, with 40 percent of developing countries living in cities (Crane and Kinzig 2005; UN 2018). In 2016, there were 512 cities globally with a population of one million or more. Yet the United Nations projects that by 2030 there will be 662 cities with at least one million residents (UN 2018).

A unified definition of a city is required before going further. Bettencourt (2013) suggests that human settlements are the physical manifestation of social networks, embedded across space. Geographers have long established cities as permanent settlements where people live in high densities (Kostof 1991; Wirth 1938) and where strangers are likely to come into contact with one another (Sennett 1977). Combining these definitions, cities are densely inhabited settlements where individuals can frequently interact with strangers, with the built environment representing the manifestation of social networks. With this definition, cities have been around for millennia, the first cities corresponding to the first permanent settlements during the Mesolithic, such as at Çatalhöyük (Hodder 2012). These settlements were founded before we were dependent on domesticates, suggesting that we wanted the benefits of aggregation before we realized the costs associated with sedentism (namely, abandoning our roots in hunting and gathering). Of course, today's cities are often denser, have higher proportions of strangers interacting, and often have the physical manifestation of social networks—roads and buildings—extending farther from the center thanks to efficiencies in modern transportation.

Movement is costly. As noted by Lobo et al. (2019) "social interactions in space have, throughout history, involved travel, which carries monetary, energy and time costs." Moving to a dense urban environment can reduce those costs, especially when the costs of movement are incurred directly by humans (walking, running, paddling) or by their beasts of burden. As they note, humans can only travel a certain distance within a day, limiting what can make an urban boundary (Lobo et al. 2019; Marchetti 1994). Cities, both historic and modern, can be defined as a space a person can get to within about a day, though the distance traveled can, of course, change as new types of movement are introduced. So, a final definition includes not only the physical representation of a social network, the property that people are highly aggregated and frequently interact with strangers, but also the property that a city's boundaries should only extend to where an individual can move within a day.

Taking this definition to the extreme, the UN defines settlements known as megacities, which comprise 10 million people or more, to differentiate them from regular cities (UN 2018). As of 2016 there were 31 megacities, with 24 of these in the less developed global south. The UN projects that an additional 10 cities will join the ranks of megacities based on demographic projections, all within developing countries (Table 1). Due to the constraints of the prefrontal cortex, it would be physiologically impossible for a person to recognize more than approximately 0.015 percent of the inhabitants of a megacity, allowing for the definition of frequent interaction with strangers to be clear in the definition of a megacity. The physical boundaries of megacities, such as Tokyo or São Paolo, may also stretch the limits of a daily commute and are only possible with modern infrastructure.

Rank	City, Country	Population in 2016 (thousands)	City, Country	Population in 2030 (thousands)
1	Tokyo, Japan	38 140	Tokyo, Japan	37 190
2	Delhi, India	26 454	Delhi, India	36 060
3	Shanghai, China	24 484	Shanghai, China	30 751
4	Mumbai (Bombay), India	21 357	Mumbai (Bombay), India	27 797
5	São Paulo, Brazil	21 297	Beijing, China	27 706
6	Beijing, China	21 240	Dhaka, Bangladesh	27 374
7	Ciudad de México (Mexico City), Mexico	21 157	Karachi, Pakistan	24 838
8	Kinki M.M.A. (Osaka), Japan	20 337	Al-Qahirah (Cairo), Egypt	24 502
9	Al-Qahirah (Cairo), Egypt	19 128	Lagos, Nigeria	24 239
10	New York-Newark, USA	18 604	Ciudad de México (Mexico City), Mexico	23 865
11	Dhaka, Bangladesh	18 237	São Paulo, Brazil	23 444
12	Karachi, Pakistan	17 121	Kinshasa, Democratic Republic of the Congo	19 996
13	Buenos Aires, Argentina	15 334	Kinki M.M.A. (Osaka), Japan	19 976
14	Kolkata (Calcutta), India	14 980	New York-Newark, USA	19 885
15	Istanbul, Turkey	14 365	Kolkata (Calcutta), India	19 092
16	Chongqing, China	13 744	Guangzhou, Guangdong, China	17 574
17	Lagos, Nigeria	13 661	Chongqing, China	17 380
18	Manila, Philippines	13 131	Buenos Aires, Argentina	16 956
19	Guangzhou, Guangdong, China	13 070	Manila, Philippines	16 756
20	Rio de Janeiro, Brazil	12 981	Istanbul, Turkey	16 694
21	Los Angeles-Long Beach-Santa Ana, USA	12 317	Bangalore, India	14 762
22	Moskva (Moscow), Russian Federation	12 260	Tianjin, China	14 655
23	Kinshasa, Democratic Republic of the Congo	12 071	Rio de Janeiro, Brazil	14 174
24	Tianjin, China	11 558	Chennai (Madras), India	13 921
25	Paris, France	10 925	Jakarta, Indonesia	13 812
26	Shenzhen, China	10 828	Los Angeles-Long Beach-Santa Ana, USA	13 257
27	Jakarta, Indonesia	10 483	Lahore, Pakistan	13 033
28	Bangalore, India	10 456	Hyderabad, India	12 774
29	London, United Kingdom	10 434	Shenzhen, China	12 673
30	Chennai (Madras), India	10 163	Lima, Peru	12 221
31	Lima, Peru	10 072	Moskva (Moscow), Russian Federation	12 200
32			Bogotá, Colombia	11 966
33			Paris, France	11 803
34			Johannesburg, South Africa	11 573
35			Krung Thep (Bangkok), Thailand	11 528
36			London, United Kingdom	11 467
37			Dar es Salaam, United Republic of Tanzania	10 760
38			Ahmadabad, India	10 527
39			Luanda, Angola	10 429
40			Thành Pho Ho Chí Minh (Ho Chi Minh City), Viet Nam	10 200
41			Chengdu, China	10 104

Table 1. The UN Projection of megacities predicts that between 2016 and 2030 the number of megacities will increase from 31 to 41. A megacity is any city with greater than 10 million inhabitants. Several of the new megacities will be in the developing world, suggesting challenges and requiring novel solutions.

This shift to city dwelling is strongly tied to economic development (Bettencourt 2013). More opportunities for cash paying jobs entice people to urban centers, leaving behind traditional land-based jobs. Though concentrating people into dense urban areas can also leave them prone to economic losses related to disasters (UN 2018). These losses can be sudden and catastrophic, such as with the earthquake in Haiti in 2010, which forced approximately 1.5 million people into makeshift internally displaced rescue camps (World Vision 2021). Urbanization can also create challenges for the adaptation of the human body; urban heat island effects (Kalnay and Cai 2003) can be proximal causes of mortality, as seen in the summer 2003 European heatwave that killed up to 70,000 people (Robine et al. 2008). These impacts may become more frequent, as more people move into cities and as climate change strains the environment and creates greater challenges to an ever-increasing number of people.

These potential losses, however, may be offset by the benefits from living in cities. Education, medical care, governance, cash-paying jobs, and social services like the number of restaurants or the possibility of attending operas or ballets are more easily reached in the city (Bettencourt 2013; Bettencourt et al. 2007). Cities are "social reactors" providing engines for economic growth and innovation, allowing citizens a disproportionate access to these services in comparison to their rural counterparts.

While cities have their own unique character, certain properties link them and seem to be invariant whether in a smaller settlement or a megacity. From Spokane, Washington to the megalopolis of Tokyo, each city is subject to scaling laws. First is the suggestion that social innovation scales with cities. We may predict that as population doubles, the number of patents double, since the number of individuals increased the same. This would suggest a log-linear relationship as described above. GDP, as well, should increase in a similar way. Yet, when subjected to a scaling analysis, these are seen to increase super-linearly. With more people come a disproportionate quantity of patents as well as wages. Within cities, a "rich get richer" dynamic emerges, as it seems that people benefit from close living quarters, deriving substantial gains from social contact. This scaling property can be seen in Figure 5 (Bettencourt et al. 2007).

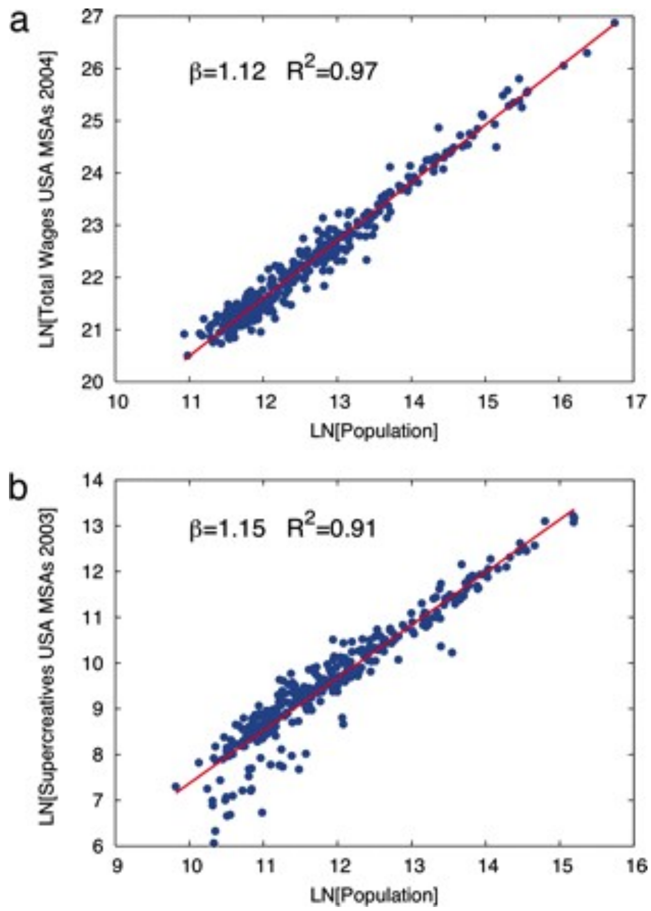


Figure 5. From Bettencourt et al. 2007's Figure 1. Examples of scaling relationships. (a) Total wages per MSA in 2004 for the U.S. (blue points) vs. metropolitan population. (b) Supercreative employment per MSA in 2003, for the U.S. (blue points) vs. metropolitan population.

However, there is a dark side to this rich get richer dynamic. Along with increasing numbers of patents, GDP, and other social gains indicative of an increase in creativity comes a disproportionate increase in crime, infectious disease, and the negative aspects of urban living. When cities grow quickly, slums develop quickly to provide housing for the urban poor, often with poor sanitation, no utilities, and little oversight to how individuals should heat their homes. In one example, the Ger district in Ulaanbaatar is a dense transposition of the typical nomadic Mongolian yurt (known as a *ger*). These homes are usually spaced apart, moved seasonally, and are heated with a central coal stove. When they are packed in together and are not transhumant, human waste becomes problematic, as does pollution from the stoves. Aggregation comes at a cost. Along with rich get richer it seems there may be a "sick get sicker" dynamic in cities, as can be seen in Figure 6. (Bettencourt 2013).

Figure 6. Much of the drivers of the population explosion are from informal slums that develop within and surrounding city boundaries. These informal slums generally have poor sanitation and develop in unplanned ways. One such example is Ulaanbaatar, Mongolia, where the Ger Districts have exploded in the past decade surrounding several climatic downturns in the country, causing strain on the municipalities, leading to greater air pollution from unregulated coal stoves and poor sanitation. Photo from Miroslav Hodecek in Lens Culture of Ger District Slum in Mongolia

Yet the benefits for a city may, indeed, outweigh the costs at the individual level (often felt by the urban poor). For the costs of creating infrastructure decrease in aggregated cities. As a city increases in size, the space-saving metrics of building new main roads and adding sewer pipes, powerlines, or telecommunications lines makes cities more efficient. Often, these can just be "tacked on" to the original infrastructure, allowing for cost saving at the urban level. (Bettencourt et al. 2007).

Taking a closer look at the scaling relationships in Figure 5, we can examine how these things scale together. In work led by Bettencourt, we can see that both the benefits of urban living are seen as being subject to an increasing economy of scale of about 1.15. So, as a city doubles in size, its number of patents, GDP, and wages increase by not double, but with an exponent of $n + .15$. Unfortunately, crime and infectious disease also increase at the same rate. With a fair amount of accuracy, given the population of one city versus another you could estimate the GDP, the number of patents, and the number of violent crimes with a fair amountof accuracy (West 2018).

On the other side, the scaling exponent of $n - .15$ seems to explain the growth of infrastructure. On this side it seems an increasing economy of scale is felt as a city increases in size. Proportionally less investment in infrastructure is required to build a city as it grows than one may expect. This property seems similar between ancient and modern cities. This suggests that the principle that as a city grows, it does not have to invest heavy amounts in its infrastructure is potentially time invariant; roads that radiate from a city, gas stations, temples, and other services can be created without the 1:1 ratio. This holds true in antiquity as much as it does today.

Yet we know cities are millennia old, and so the origins of scaling in cities may also have deep roots. Work led by Ortman examines the origins of settlement scaling in the Basin of Mexico (Ortman et al. 2014). Analyzing approximately 1,400 settlements in varying timescales (230 sites in the earliest period, and 546 settlements in the latest period), they show that despite changes in political centralization and differences in urbanism, as urban boundaries and population increase, these ancient cities conform to a scaling relationship with an exponent of between 2/3 and 5/6. Even though transportation has changed dramatically since these ancient cities were built and we now can harness fossil fuels for our movement, we still see similar scaling powers.

C. You Are What You Speak

Another avenue of the question, *where do we come from,* is to examine similarities and differences in human speech. While studies have examined the diversity of the semantic similarity of concepts, until recently those focused on examining similarity of concepts from Western, educated, industrial, rich, democratic societies [known as WEIRD in the literature (Henrich 2020)]. All humans evolved from a common ancestral group, somewhere in East Africa approximately 300,000 years ago. Thus, any divergence in complexity of language should be related to the cultural constraints and environmental opportunities that came as humans spread out of Africa.

To examine the ways that languages change and can relate to cultural complexity, Youn et al. (2016) examined how 81 different languages from geographically and phylogenetically diverse spaces relate concepts of material and natural entities (e.g., sun, moon, stone). Focusing on these external and physical (and universal) entities enables an understanding of how different objects relate to concepts. The words they choose are polysemous—there can be many meanings for a word. By beginning with multiple universal words and examining other meanings for the words, the researchers can examine universality of language concepts.

In Figure 7 the relation of concepts to one another is shown in a lexical network. Edges link nodes when polysemous words cover both concepts. The words the researchers began with are capitalized, while synonyms for the starting words (identified in the language groups) are in lower case. The width of connecting edges reflect the frequency those concepts were linked. The thick linking between sky and heaven, for example, demonstrates that these concepts were frequently linked among the 81 languages (Youn et al. 2016).

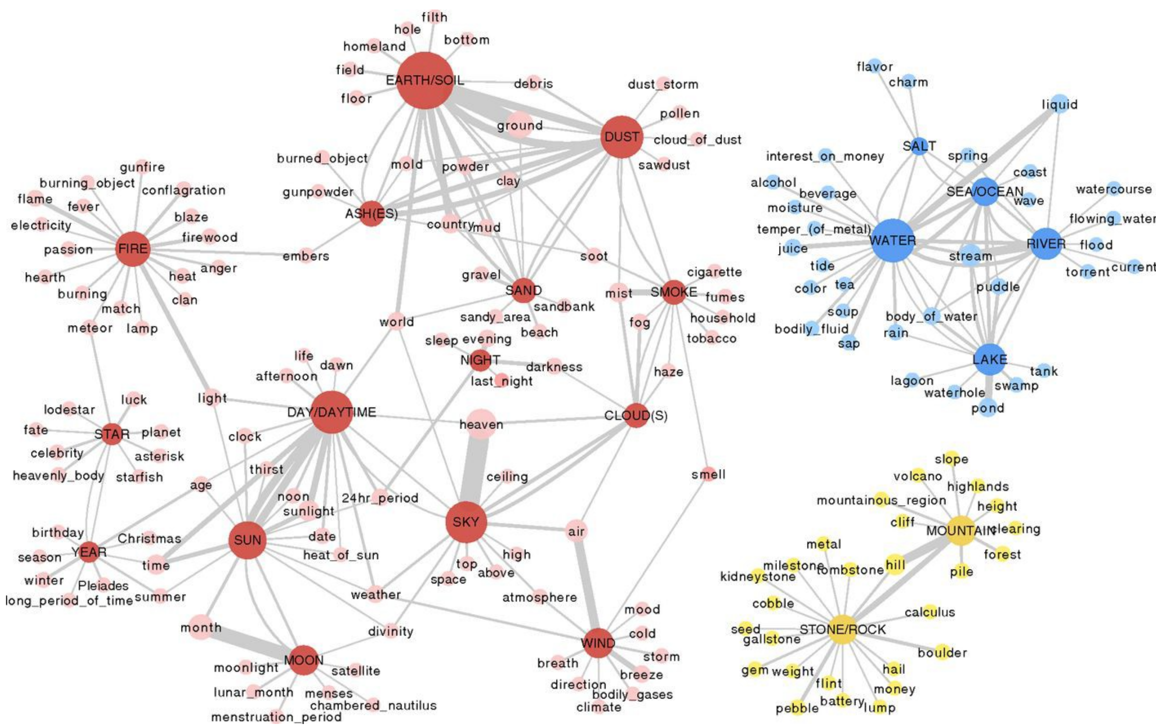


Figure 7. Youn et al. 2016 examined how 81 different concepts linked together, choosing universal entities (e.g., "moon") to examine how communication can be universal.

The work by Youn et al. suggests a universality in the meaning of words relating to physical and observable phenomena (e.g., earth and floor), but also the linking of a physical phenomenon (sky) to a non-observable concept (sky to heaven; fire to passion). Their work may point to common concepts that link all 6,000 plus languages worldwide.

Examining the relatedness of concepts can also be useful in looking to migration events. Ortman

(Ortman 2012) demonstrates that the use of terms for antiquated technology among Tewa speakers links them to ancestral populations in the Mesa Verde region. Specifically, Tewa speakers call the ceiling of a building a "sky basket." As basket-making technology disappeared with the advent of pottery among Pueblo groups, Ortman suggests this links Tewa speakers directly to Ancestral Pueblo people. These works suggest that language can show us where we come from.

The origins of scaling in cities combined with our understanding of the prefrontal cortex and the limits it creates on our social relationships seems to answer the question of *d'où venons nous* posed by Gaugin. We come from a species that is trying to understand the world, maximizing our social relationships by living in highly aggregated contexts. We benefit from these relationships by being more creative, by increasing wages, increasing access to health and social services. We come from a collectedness of languages, with root concepts joining individuals from a diverse set of communication styles. We come from a species that with highly dense networks suffers from infectious disease and crime as a biproduct of our aggregation. Yet, we continue to aggregate, for the benefits may outweigh the costs. The roots of these settlements run deep, from before we truly became dependent on domesticates. As our cities grow, we will have to face more challenges of sustainability, challenges that were met by our early ancestors as they realized they needed more reliable food sources in their settled villages. To understand where we have come from, we need to understand what we are.

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IV. What Are We?

At the most basic level, we can understand what we are by examining our place in a taxonomic tree. Humans are of the genus *Homo*. Currently we represent the only species from that genus, which is a lonely club to belong to, shared with the likes of the porcupine, the only extant species from the genus *Erethizon* (Banks, McDiarmid, and Gardner 1987). Yet there were other species in the genus *Homo* as recently as 60,000 years ago. *Homo neanderthalensis* (sometimes referred to as *Homo sapiens neanderthalensis*) was our cousin and with whom many people of European and Asian descent today share DNA. While paleoanthropology is muddy, other extinct species from the *Homo* genus include *Homo erectus*, *Homo ergaster*, *Homo naledi*, *Homo heidelbergensis*, and *Homo habilis.* This genus is defined by a greater brain capacity than prior *Australopithecines* and the habit of always walking upright. Many species in this genus could make tools and construct their own niches, and it is the versatility of *Homo sapiens* that enabled our species to adapt to every ecosystem around the world (Wood and Collard 1999; Patterson et al. 2019).

Above we mention that cities are the physical representation of social networks, but a definition of social networks is required before going forward. Social networks are the ways that individuals, be they individual people, cells, groups of species, or people, connect with one another via physical links like roads, or non-corporeal links like friendship or even predation. In network parlance the individuals are known as *nodes* and the connections are known as *edges* or *links*. Networks enable examination of how the interactions between two nodes can influence the structure of the entire network, or how a network constrains the opportunities for a given node.

We can further understand what humans are by understanding our place in the web (or network) of life. Just as understanding that our cities today are built on antecedents of cities from history and prehistory, we can understand where humanity is today by understanding where humanity came from and examining the structure of ecosystems worldwide.

Examining the place of humans in food webs provides a way to understand *que sommes nous*. The first paper that examined the human place in ecological networks focused on the Sanak Archipelago on the coast of Alaska among the hunter-fisher peoples who inhabited the region for the past 7,000 years (Reedy-Maschner and Maschner 2013; Maschner et al. 2009).

Archaeological research on Sanak compiled detailed zooarchaeological and archaeobotanical data that enabled an understanding of the human place in the Sanak ecosystem. To add to these data a full ecological survey was undertaken, compiling data on intertidal and near-shore ecosystems. This was the first highly detailed food web to include humans (Dunne et al. 2016).

In their work, Dunne et al. (2016) examined both the near-shore food web and the intertidal food web to understand how humans inserted themselves into the ecosystem of the islands that separate Alaska from the Kamchatka Peninsula. Via creating a full food web of the Sanak ecosystems (Figure 8), they were able to assess the roles that humans played within the overall trophic web of the region. They found that humans fed on 30 percent of the organisms in the intertidal food web and 24 percent of the organisms in the near-shore food web. This suggested that humans fed on a greater variety of organisms than any other taxon except Pacific Cod. Moreover, the Aleut fed at all levels on the trophic web, from basal organisms like algae to top predators like sea lions, and everything in between (Dunne et al. 2016).

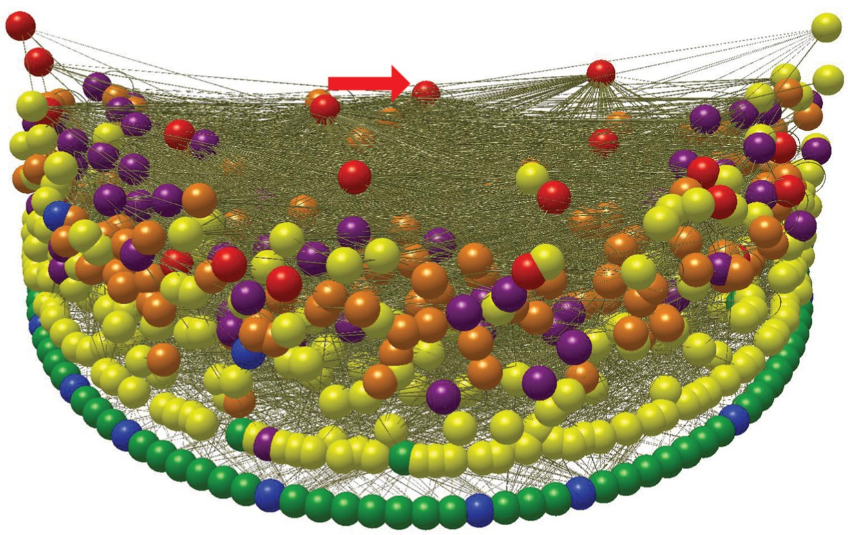

Figure 8. The creation of a food web that includes humans. Here, Dunne et al. (2016) examined those taxa that humans consume, as well as all the other taxa that could be identified in the near shore. They organize these according to their trophic level, or the level on the food web of each organism. Those at the bottom are primary producers, such as plants. As we move up the graph we move up in trophic level, to herbivores, omnivores, and true carnivores toward the top. Sphere color indicates the type of taxon: green = algae; blue = miscellaneous (e.g. detritus, protozoa, bacteria, biofilm, lichen, seagrass); yellow = invertebrates; orange = fish; red = mammals; purple = birds; red arrow indicates humans.

The place of humans in food webs was examined in another study, this time terrestrial, that built a full human food web in the Ancestral Pueblo southwest (Crabtree, Vaughn, and Crabtree 2017). In this study the Pueblo farmers lived in the region from A.D. 600 to A.D. 1300, farming but also still foraging and hunting within the region, in contrast to the 7,000 years that humans lived and hunted in Sanak. The researchers created three food webs corresponding to three different archaeological periods to understand the changing human place in food webs.

As with Dunne et al., they found that humans were highly omnivorous, yet their reliance on cultivated foods seemed to increase during a period of high socio-political integration. Yet, as with Dunne et al.'s study, they found that humans also fed at all levels of the food web. Unsurprisingly, both these studies place humans not at the "top of the food chain" as one may be led to believe. Humans can eat at all trophic levels, identifying them firmly as omnivorous (Crabtree, Dunne, and Wood 2021).

As food webs are a type of network, they can be analyzed with similar network statistics to demonstrate the network's connectedness or the ways that one node impacts the full network. Mean path length is one of the statistics that demonstrates the ways a node can have the largest impact within a network. In the Sanak food web, humans had one of the shortest mean path lengths, suggesting they could have depressed prey throughout the full food web but did not. Likely this was due to the adaptation of prey switching, where the Aleut would switch to a new type of prey when one type of prey became less abundant. In contrast, Pueblo also had a low path length, but their impacts *did* depress large game within the food web (Crabtree, Dunne, and Wood 2021).

The central position of Sanak Aleut people within the food web indicates that they could have depressed prey abundance, reorganized ecological community structure and function, and contributed to short- and long-term local extinctions; yet, they did not. To explore why, Dunne et al. (2016) used computer simulations to examine how an organism similar to the Aleut could invade the ecosystem. Using a non-linear dynamic food-web-modeling framework, the study explored the probability of secondary extinctions as a result of introducing a highly omnivorous species. The introduced species practiced "prey-switching" behavior and made use of simulated hunting technology, allowing them to feed on organisms larger than themselves. These organisms could have unraveled the food web but did not, showing perhaps the intentional conservation by these hunter-gatherers.

These works demonstrated the historical position of humans in the web of life. We are highly omnivorous and due to our central position in food webs we are poised to have strong impacts on them. Yet in some cases the impacts seem minor (Sanak) while in others they can be much larger (Pueblo). In another archaeological case study, Verhagen et al. (2021) find that there is a highly interconnected relationship among plants, animals, and people in the transition from hunting and gathering to agriculture in the Dutch wetlands. Their work further shows how humans embed themselves in ecosystems even as they experiment with domestication.

Yet these papers examine archaeological case studies, which show how people had embedded themselves. Modern food webs may look different. To examine the concordance between historic/prehistoric food webs and today we can look to three other papers that place humans in food webs.

The first paper examines modern small-scale foragers in Australia's Western Desert, creating human centered food webs for pre-1964, when people lived fully nomadic lifestyles, and today (Crabtree, Bird, and Bird 2019). Between 1964 and the late 1980s the Martu Aboriginal people were removed from the Western Desert to missions and cattle stations on the periphery and stopped their traditional hunting practices. In the late 1980s they were allowed to return, engaging in both the market economy and in traditional hunting practices.

In many ways, the food web for the Martu is similar to other archaeological food webs, in that it reflects a subsistence-based small-scale society's provisioning decisions. In the pre-1964 food web, the researchers demonstrate that humans are the most highly connected node—they have the lowest path length—and like the Aleut they do not cause unravelling in the food web. Rather, due to their prey switching behavior they are able to embed themselves in the food web without deleterious effects. In the modern food web, even though Martu do engage in the market economy, they still are a highly connected node. Yet the researchers suggest that the removal of Martu for the approximately 20 years between the 1960s and the 1980s is what precipitated changes in the food web. They show that several small mammals went extinct in the interim, and it was the Martu hunting that helped the food web. Without Martu, the food web reorganized. In this way, we can see that humans can be critical for the functioning of ecosystems. A similar conclusion can be made for the Tagus Estuary food web (Vinagre et al. 2019), where humans are seen as key to the function of the estuary. As climate change may impact the composition of fish species in the estuary, especially with the introduction of a highly omnivorous shark, understanding how humans interact within these places is key. The food webs in both the Western Desert and the Portuguese estuary depend on humans for critical functions.

Each of these studies found humans to be highly omnivorous, findings echoed in a recent paper by Bird et al. (2021), who analyzed 13,000 isotopes from modern, historic, and prehistoric contexts. Their study showed a narrowing of diet among modern industrialized humans, concordant with the findings by Dunne et al. and others. Humans are, it seems, highly generalist feeders, and only through modern industrialized processes are we losing some of this generality.

To answer the question of *que sommes nous,* we are a species of individuals who use hierarchy to enable efficient communication. We eat voraciously and omnivorously, from the bottom of the food chain to the top. Our versatility has enabled us to expand to every ecosystem on earth.

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V. Where Are We Going?

The final question posed by Gauguin, where are we going, is perhaps a founding question that has driven scientific inquiry. Many of the studies discussed above have direct implications for where we are headed as a species, acting as calibration datasets for predictions of our trajectory.

To begin with, the UN projection on global human population provides a statistic on where we are going. Beginning with current population and demographic statistics, we can see in Figure 9 that between 1950 and 2020 the population grew from three billion to almost eight billion.

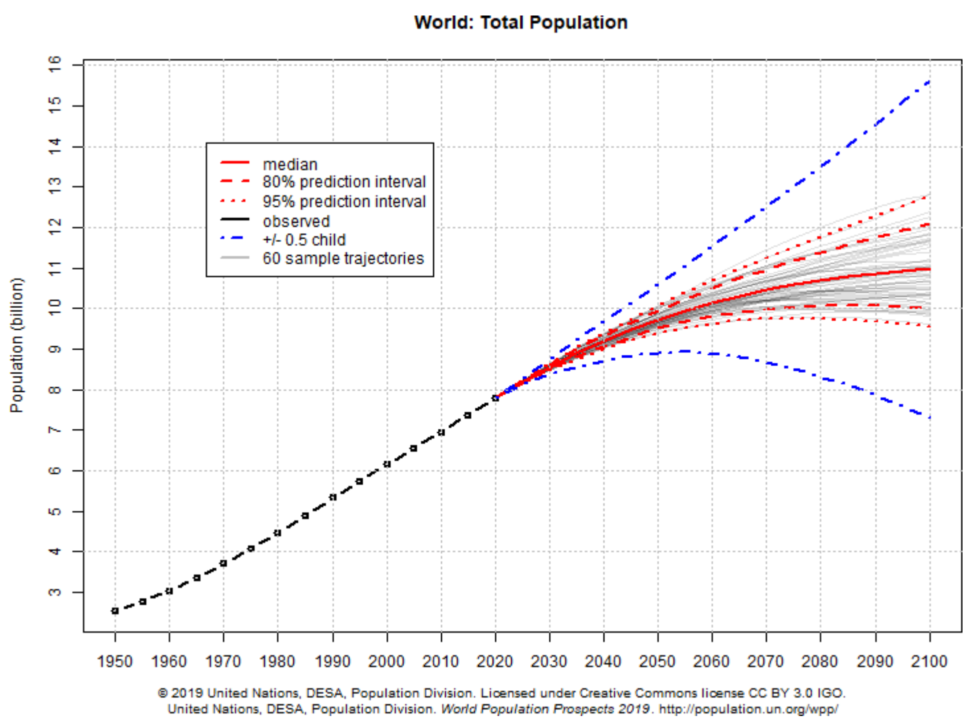

Figure 9. According to the UN Medium population projections, we are projected to reach over 10 billion humans by 2060. If global reproduction can be decreased by 0.5 children, population can decline, but otherwise an upward trajectory is likely.

The UN population predictions show a leveling off of population growth, slowing the acceleration that has been seen since the 1950s. These projections assume that people globally will pass through a demographic transition whereby mortality and fertility decline concomitantly with economic growth. This phenomenon sees high population growth *during* the transition, but as the transition is reached, population growth declines. This leveling off implies a stable population, one where there is replacement but not sustained growth, suggestive of graphs of a reached carrying capacity.

However, while sustained growth is unstable, DeLong et al. (2013) point out that even the UN's Medium Growth population projections are not a stable equilibrium. They suggest that "demographic covariates" such as resource constraints may make this projection unrealistic, and also unsustainable as a planning goal. In their models they find that this leveling at approximately 10 billion individuals is an unstable equilibrium and that actual global populations have been diverging from the projection for decades. To address the issue of a growing population, we have to look at the energy constraints that these people put on the system. Via a model of per-capita energy use, DeLong et al. estimate that the population will stop increasing once every individual has access to high amounts of energy: 13,000 watts per person.

West suggests that humans increased their basic metabolic rate from approximately 90 watts/person toabout 3,000 watts/person with the advent of domestication and early urban life (West 2018). The estimates by DeLong et al. suggest an even higher need: away from our biological needs of 90 watts, and toward a highly inefficient need that has our metabolic rate approaching that of megafauna. Yet as suggested by Nekola et al., “it is logically, physically, and biologically impossible for exponential growth to continue indefinitely within a finite world” (Nekola et al. 2013, 127).

These incredibly divergent metabolic numbers—90 to 13,000—suggest a need to innovate to prevent catastrophic collapse. Thomas Malthus in 1798 suggested that the “increase of population is necessarily limited by the means of subsistence” giving rise to the concept of Malthusian Limits (Malthus et al. 2018). In this concept, populations are capped from continued growth, and face decline, due to environmental limits.

Yet historically our species has been able to move beyond Malthusian limits via innovation. In Figure 10, Nekola et al. juxtapose technological innovations against global population growth. This simple graph shows how human innovation has enabled rapid population growth fueled by birthrates as well as decreasing death from infectious disease. Human innovation, they argue, “provide an effectively infinite capacity to increase resource supply” (Nekola et al. 2013, 127).

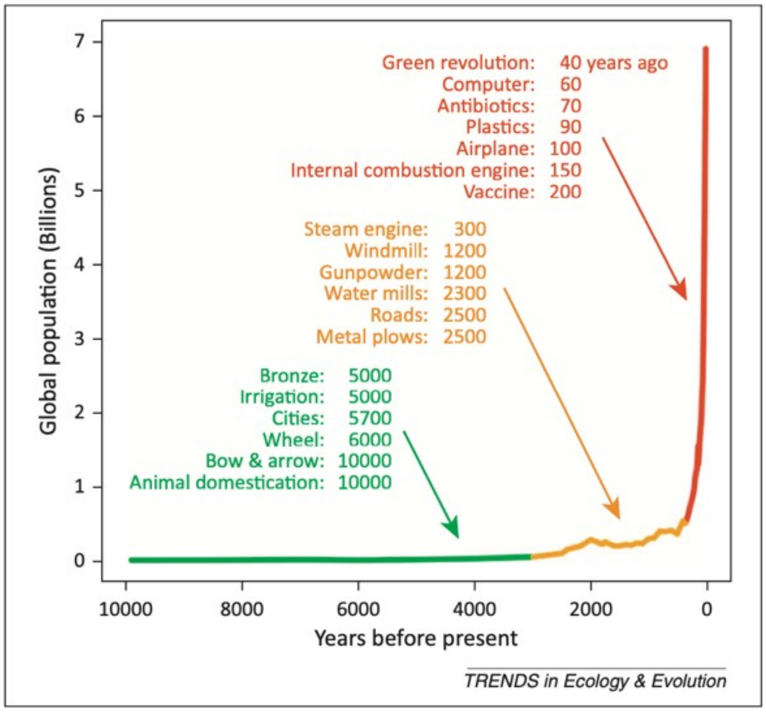

Figure 10. Global population juxtaposed against technological innovation, from Nekola et al. (2013). Here we see major technological innovations, such as metallurgy and irrigation when populations were quite low during the Neolithic, to thegrowth of population during the Industrial Revolution, and the explosion of populations and computational technologies.

Yet just because human ingenuity has enabled us to avoid Malthusian limits thus far does not mean that it will continue to do so. Also, while many innovations can benefit the group (vaccines, antibiotics), as humans are inherently selfish, some innovations can benefit the individual at the expense of the group. To address challenges from population increase, they make three suggestions for creating a more sustainable future: Negative population growth for many generations, to enable populations to underperform on the UN population predictions. A global economy that does not rely on growth, but is instead steady-state based on renewable resources. Social norms that favor global well-being over individual interests (Nekola et al. 2013).

In a recent review, Lehman et al. (2021) suggest that population growth is no longer the main concern, as we are in a "deceleration phase" indicative of having passed through the demographic transition identified by DeLong et al. Yet it is the accumulation of the effects of growth over the past generations that are of primary concern. Lehman et al. suggest following a "possibilist agenda" whereby humanity examines what is impossible (e.g., sending eight billion people back to a hunter-gatherer lifestyle), eliminating that, and addressing what is tentatively possible—such as capping emissions and reducing the increase of global temperature.

Even with Malthusian events, such as the COVID-19 pandemic, which decreased life expectancy in the United States by the largest amount since WWII (Woolf, Masters, and Aron 2021), and caused a temporary migration of urban dwellers to rural centers (Frey 2021), we still are on track for record growth in cities, with increases in megacities globally. To confront the challenges that may come from intense urban aggregation, lessons from complexity science can aid in developing sustainable cities.

As our cities grow, can we expect that they will continue to have increasing returns on beneficial products like wages, patents, services, or will they reach a limit imposed by something akin to thermodynamics, where matter cannot be created from nothing? What are the human limits to creativity? As cities grow, and consumption increases, will crime and disease also increase at such rates that they limit city growth?

The sustainable cities movement desires to make cities safe, affordable, carbon neutral, and environmentally beneficial. As moving to highly aggregated areas can enable arable land to be left vacant for crops or endemic plants, cities can be a way to reduce humanity's footprint. Instead of focusing on the city as a whole, Bettencourt suggests that urban planning should focus on individuals and neighborhoods, providing a bottom-up approach to sustainability. Much as complex systems are the sum of individual strategies creating something greater than the sum of its parts, by acting locally instead of globally, urban planners can flexibly work with the needs of individuals. Then, by aggregating data gained at the local level, planners can "learn globally" to "act locally" (Smith 2020). Bringing people together in this manner can then create action for sustainability of cities. This, then, tracks with the ideas put forth by DeLong, that acting for the benefit of the collective, even when individual strategies may increase wealth and fitness for certain defectors, can help to confront the large challenges that are facing us today.

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VI. Conclusions

Ultimately, a complex adaptive systems approach, beginning from the bottom up, to understand how individuals can act and interact together to make something greater than the sum of its parts, can help us to understand our place in the web of life, the ways that we modify environments to our own needs, and how our cities, our relationships, and even our bodies scale according to universal principles.

Natural philosophers have wondered at the meaning of our existence for centuries. The central ideas of the oeuvre of Gauguin ask where we come from, what we are, and where we are going. Within his painting he suggests, perhaps, that we come from the natural world, from a place where we can engage in omnivory, from picking fruits to eating domesticated animals. What we are is defined as culture-creating bipedal hominids who maintain social relationships with our families and our friends. We create structures of religious and civic symbolism that help define us, offering opportunities and constraints along our life paths. We are going toward an ultimate end of existence as we are subject to allometric scaling laws, getting older and eventually dying. And each of these is subject to principles underlying the order of nature and culture itself.

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