5 Social Complexity I: Origins and Measurement

5.1 Introduction and Motivation

What is social complexity? How did it originate in human societies thousands of years ago? How is social complexity measured? How is the emergence of complexity detected in a previously simple society? What do we know about the long-term evolution of social complexity? What does current knowledge about social complexity tell us about the likely features or plausible trajectory of future trends? This chapter covers both the "Cosmology" or "Big Historical Picture" of social complexity, as well as underlying foundations in CSS. It introduces facts, methods and theories about social emergence and subsequent dynamics, starting with the simplest social systems that originated in early antiquity and their long-term evolution. The chapter leverages materials from previous chapters, showing how ideas learned in previous chapters are essential for a deeper understanding of how social systems operate and can be modeled computationally.

There are concepts, measurement methods, and theoretical models of social complexity in early, contemporary, and future societies. Accordingly, this generates something like a 3×3 matrix of topics. These are presented from a scientific perspective (i.e., the main sections of this chapter) rather than by historical epochs. The chapter ends with an overview of measurement, which leads to more formal approaches to description (laws) and explanation (theory) in the next chapters.

5.2 History and First Pioneers

The first extant systematic study of social complexity was arguably the one by Greek philosopher Aristotle, who conducted the first comparative research on what we would now call "critical phase transitions" between different regimes of government (which he called *stable* and *degenerative* forms) in three types of political

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systems:

$$Monarchy \rightsquigarrow Tyranny \tag{5.1}$$
$$Aristocracy \rightsquigarrow Oligarchy \tag{5.2}$$
$$Democracy \rightsquigarrow Ochlocracy, \tag{5.3}$$

where the symbol "$\rightsquigarrow$" denotes decay.

The modern roots of the scientific study of social complexity date to the time of the French Enlightenment, as do so many other areas of systematic social science research. In this case the history and pioneers of social complexity origins and measurement are intertwined through developments across political science, anthropology, and computational science. Moreover, many milestones are relatively recent, since the core concept of social complexity became a focus of scientific investigation in large part during the past half-century. The following pertain to origins and measurement of social complexity. (Laws and theories are discussed in the next two chapters.)

18th century Archaeologists begin uncovering material evidence of early social complexity through excavations in Asia and elsewhere.

1944 Anthropologist Bronislaw Malinowski publishes his classic, *A Scientific Theory of Culture and Other Essays*, where he conceptualizes human institutions as instrumental in achieving basic human needs.

1952–1958 Archaeologist Kathleen Kenyon excavates the ancient neolithic and walled settlement of Jericho, Palestine, dating it to ca. 7000 B.C.; it is still among the earliest known sites of primary social complexity.

1962 Social scientist Elman R. Service publishes his influential monograph on *Primitive Social Organization* with the ordinal-level scale of rank values of tribe-band-chiefdom-state that is still in common use today.

1968 Anthropologist Lewis L. Binford publishes his influential paper on "Post-pleistocene Adaptations."

1972 Anthropological archaeologist Kent V. Flannery of the University of Michigan publishes his influential paper on the cultural evolution of civilizations.

1973 Political scientist Giovanni Sartori of the University of Florence publishes his paper on "What Is 'Politics'" in the inaugural issue of the journal *Political Theory*.

1989 Anthropological archaeologist Timothy Earle of Northwestern University publishes his paper on the evolution of chiefdoms in *Current Anthropology*, followed by other influential work on the theory of chiefdoms during the 1990s (1991, 1997).

1994 Archaeologist Henry Wright of the University of Michigan publishes his influential paper on pre-state political formations.

1995 Douglas T. Price and Anne Birgitte Gebauer publish *Last Hunters—First Farmers*, a highly influential collection of papers on the emergence of agriculture and social complexity, including the important paper by Patty Jo Watson.

1995 The same year Smithsonian scholar Bruce D. Smith publishes his classic monograph on *The Emergence of Agriculture*.

1996 Political scientists Yale H. Ferguson and Richard Mansbach propose the concepts of vertical and horizontal polities in *Polities: Authority, Identities, and Change*, a conceptual innovation for understanding complex societies and political systems.

1997 Archaeologist Joe W. Saunders and collaborators publish their paper on initial social complexity at the site of Watson Break, Louisiana, the oldest mound complex in North America, dated to the 4th millennium B.C., in the journal *Science*.

1998 Archaeologists Gary Feinman and Joyce Marcus publish their influential edited volume on *Archaic States*, including the first comparative, cross-cultural analysis of Marcus' "Dynamic Cycles Model" of chiefdoms, and other important papers on early social complexity.

2001 Oxford historian Felipe Fernández-Armesto publishes his comprehensive monograph on *Civilizations*, a descriptive world history in remarkable harmony with Simon's computational theory of social complexity through adaptation to challenging environments in ecosystems.

2001 The earliest origins of primary social complexity in South America are dated to the late 3rd millennium B.C. at Aspero and Caral, in the Supe River Valley, a short distance north of Lima in present-day Peru.

2005 Computational social scientists and other scholars hold the first international conference on sociogenesis in St. Petersburg, Russia, inviting mathematicians, computer scientists, historians, and social scientists from the various disciplines.

This braided history of social complexity science demonstrates how diverse disciplinary strands have finally begun to interact in more systematic fashion only in recent years. The main result of this process is that today there exists a critical mass of facts and measurement methodologies for conducting research on social complexity, including specific scientific knowledge about origins thousands of years ago in a few and quite special regions of the world. Modeling and theoretical milestones are highlighted in the next two chapters.

5.3 Origins and Evolution of Social Complexity

The primary purpose of this section is to provide an empirical, factual base to learn about the precise geographic locations and specific historical epochs—i.e., the space-time coordinates—of social complexity origins within the broader context of global history. This brief long-range survey has intrinsic value in addition to providing foundations for better appreciating the significance of concepts, measurements, models, and theories presented later in this chapter. A long-range perspective is also needed for understanding the substantive, interdisciplinary, and methodological demands on CSS theories and research on social complexity.

When, where, and how did social complexity originate in the global history of human societies? For now, by **social complexity** we mean simply the extent to which a society is governed through non-kin-based relations of authority. In simple, precomplex societies (e.g., in hunter-gatherer groups before the invention of agriculture) individuals are governed by kin-based authority, such as the older member of a household. At the other extreme of social complexity, a modern democracy is governed by elected officials who exercise authority through the executive power of large state bureaucracies comprised of government agencies and specialized government workers. This initial definition of social complexity, based on **relations of authority**, is sufficient for now. Later we will use a more precise definition.

As we shall see later in this chapter, the **chiefdom** represents the simplest form of complex society, one that is governed by rulers who derive their authority from a source that is different from family ties (although the latter never quite disappear entirely from the scene).[1] Hence, the previous, general, and more abstract questions concerning social complexity origins now translate into the more specific, and hence more scientifically tractable, quest for the origins of the earliest chiefdoms.

The **Service scale** is named after American anthropologist Elman R. Service, who was the first to propose the following ordinal-level scale of social complexity:

$$\textit{band} \prec \textit{tribe} \prec \textit{chiefdom} \prec \textit{state} \prec \textit{empire}, \tag{5.4}$$

where the symbol $\prec$ denotes an ordinal relation on ranked values of social complexity.[2] The Service scale of social complexity in expression (5.4) is extended to empires, which are polities that display significantly greater social complexity than states. We shall examine this scale and others more closely later in this chapter.

Specifically, we are most interested in those chiefdoms that eventually developed into states. By **state**, for now, we mean a polity more developed than a chiefdom, in the sense that (1) authority relations are sanctioned by institutions and (2) government operates through a system of public administration that carries out specialized functions. (Later we will also examine the concept of **empire** as a polity that is significantly more complex than a mere state).

5.3.1 Sociogenesis: The "Big Four" Primary Polity Networks

The earliest developmental stage of social complexity—what is often called " primary" social complexity—consists of the formation of the earliest polities or "chiefdoms," a major social milestone that occurred after the great Ice Age in their most simple form approximately 10,000 years ago (the early Holocene Period) in both northern and southern hemispheres. These early polities were not yet "states," but rather societies that departed from egalitarian norms in public activities (e.g., in communal worship, warfare, and major monumental works, among others) through non-kin relations of authority. As a consequence, a chiefdom polity is also *centralized* in the person of a *paramount* leader, chief, or strongman (an individual who is

[1] A more formal definition of "chiefdom" and "state" is provided later in Sect. 5.4.

[2] This is the same notation used to denote preferences, since they too are usually expressed on an ordinal-level scale. In LaTeX, these are written as backslash-prec for $\prec$ and backslash-succ for $\succ$. Symbols such as greater than or less than should be avoided for ordinal relations, because they imply interval- and ratio-levels of measurement.

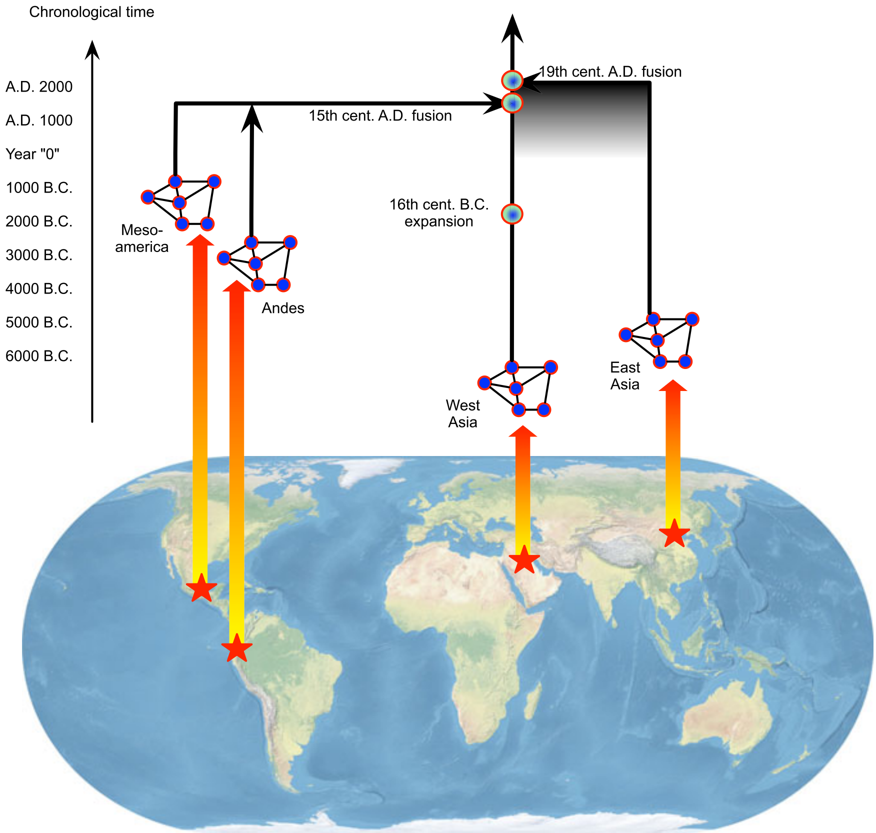

Fig. 5.1 Global geo-chronology of origins of social complexity in the four "cradles of civilization." *Source*: Adapted from Cioffi-Revilla (2006)

primus inter pares, or first among equals, relative to other local leaders); governance is *hierarchically* organized (the leader commanding local sub-leaders or confederates); and it has a *ranked* social order (the family of a leader, whether paramount and confederate, being more important and richer than a commoner family). A chiefdom is an intermediary society between an egalitarian simple society and a state. Therefore, the formation of a chiefdom in a region previously populated by a set of simple egalitarian societies marks a distinctive **phase transition** on the Service scale, and understanding the origins of social complexity—that is to say, when, where, and how the simplest chiefdoms emerged for the first time in human history—is fundamental for understanding not just the origin but also the evolution of complex societies.

Complex societies originated in four separate regions of the world thousands of years ago, during the early Neolithic Period, as summarized in Fig. 5.1. In each regional case a set of local polities generated the first regional interaction network for that part of the world. The description of each region of original social complexity—

based on the evidence currently available for each case (which will certainly increase due to current and future archaeological research!)—is described in terms of first-generation chiefdoms, which were the earliest polities to appear, followed by first-generation states, in chronological order by region. Numerous other states and empires later followed in these regions during subsequent epochs.

How do we know all this? Or, more specifically, how were these determinations of space and time in the initial social complexity of each region, and globally, arrived at in the first place? We will answer questions like these in the next section when we examine the measurement of social complexity from a methodological perspective.

5.3.1.1 West Asia

The earliest chiefdoms in human history formed in the ancient near East (Mesopotamia and the Levant), in the region presently occupied by the countries of Iraq, Israel, Palestinian Territories, Jordan, Iran, Lebanon, Syria, and Turkey—the region known as the Levantine Fertile Crescent. This occurred about 8,000 years ago (8 kya),[3] or by the middle of the sixth millennium B.C.. Early polities centered at Jericho, Çatal Hüyük, and other Neolithic sites in this region are among the oldest extant manifestations of social complexity or individual chiefdom-level polities. Although the Pre-pottery Neolithic-B (PPNB) polity of Jericho (7500 B.C.) once stood in relatively temporal isolation from the earliest West Asian chiefdoms of the 'Ubaid period (5500–4000 B.C.), archaeological investigations have uncovered other pre-'Ubaid polities chronologically situated between PPNB-Jericho and 'Ubaid. Umm Dabaghiya (Iraq) and Ain Ghazal (Jordan) are two examples. Therefore, it is quite possible that the antiquity of the West Asian system of regional polities may some day be pushed back to ca. 7000 B.C., or almost two thousand years earlier than the current dating.

The earliest West Asian system of polities formed between ca. 5800 and 4000 B.C., or during the 'Ubaid period, and consisted exclusively of chiefdoms involved in trade, warfare, and other regional interaction relations. Eridu, Ur, Uruk, Kish, Umma, and Haggi Muhammad were among the most important chiefdoms in Lower Mesopotamia, with Susa [Sush in Persian], Boneh Fazili, Choga Mish, and Farukhabad to the East, and Brak, Gawra, Hacilar, Gian Hasan, and Mersin to the north and northwest.

The first true inter-state system formed in Lower Mesopotamia by ca. 3700 B.C. (Middle Uruk period). Although the exact complete composition of this pristine inter-state system is still unknown, some of the most important states were Uruk and its neighbors in Lower Mesopotamia (Rothman 2001; Algaze 2008); Mish, Susa, and Fanduweh in the eastern regions (present-day Iran); and a number of Anatolian states to the northwest (present-day Turkey).

5.3.1.2 East Asia

The second original polity system emerged in East Asia after ca. 7000 kya, approximately 1,000 years after the formation of the West Asian polity system in the Fertile Crescent. This system emerged pristine, not by any known direct process of diffu-

[3]The acronym "kya" has the standard meaning of "thousands of years ago."

sion from West Asia (*ex nihilo*). This hypothesis might change, as investigations uncover previously unknown links between West and East Asia, but for now we continue to assume socially disjoint separation between the two Asian polity networks. Whereas the traditional Chinese paradigm (Han ideology)—based largely on Confucian culture—has been to view the origins of social complexity in East Asia as centered solely in the Yellow River basin, this belief has now been proven to be a misconception. Today, archaeological investigations are documenting the origins of the East Asian polity system in a multitude of regions across China, not just in the traditional Han homeland. Future investigation will no doubt further clarify the social complexity landscape and show a multi-cultural spectrum of societies at the dawn of East Asian history, perhaps a more diverse social landscape than the spectrum of societies that generated the earlier West Asian system a thousand years earlier.

The first East Asian polity system probably formed over a large area during the Early Banpo to Yangshao and Dawenkow periods (ca. 5000–3000 B.C.), among chiefdoms such as Banpo, Chengzi, Jiangzhai, Dawenkou, Daxi, Hutougou and other Hongshan chiefdoms (4500–3000 B.C.). During the subsequent Longshan period (3000–2000 B.C.) the East Asian polity system already consisted of numerous chiefdoms scattered across a vast area in virtually all regions of present-day China—not just the north.

The Erlitou period (ca. 2000–1500 B.C.) and early Shang period (1900–1700 B.C.) witnessed the emergence of the first interstate system in East Asia, with a core area comprising the polities of Xia (capital at Erlitou) and Shang (capital at Xiaqiyuan), as well as other states that emerged soon after nearby. Traditionally, this is when the Xia dynasty is supposed to have ruled, but today the evidence for these polities is established by anthropological and dirt archaeology, not by epigraphy alone, as we shall examine in the next section. In addition to the state of Shang and the state of Xia, other states also formed, probably at Panlongcheng (Hubei) and Suixian (Wuhan), although the complete system composition is still unknown.

5.3.1.3 South America

The third oldest polity system emerged in South America after 5 kya, or Late Preceramic period, ca. 2500–1800 B.C., and was centered in present-day Peru. A well-known characteristic of this network system is that it functioned for over three-thousand years without a written language, which remains a puzzle from a political science perspective. Another remarkable feature of the South American social complexity is the highly constrained natural environment in which it emerged and evolved for thousands of years, specifically its north-south linear form, in contrast to the more diversified natural environments of the other three original polity regions.

The first phase of South American social complexity took place with the emergence of interacting chiefly polities located up and down the Peruvian coastal regions irrigated by numerous mountain valleys and river basins draining from the Andes: Aspero (Supe river drainage, 2700 B.C.), El Paraíso (near Lima 2000 B.C.), La Galgada (Santa river basin, 2400–1900 B.C.), Río Seco, Salinas de Chao, and other polities.

According to most Andean specialists the first state in the South American region—Moché or Mochica—emerged in the first centuries B.C. from this landscape of warring chiefdoms. However, the material and cultural influence of the much earlier Chavín de Huántar polity (900–300 B.C.) could support an alternative hypothesis that Chavín—earlier than Moché—may have been the first state of the Andean region, given additional evidence besides its own monumentality, as we shall examine later.

The first true interstate system in South America probably emerged after the fall of the Moché state (ca. A.D. 600, after the Middle Horizon period), when two powerful contemporary states emerged—Wari in the north (centered in the Peruvian highlands) and Tiwanaku in the south (centered in northern Bolivia)—and competed for primacy. This was also the first bipolar system of the Western Hemisphere. Both Wari and Tiwanaku were extensive territorial states governed from large capitals and powerful provincial administrative centers.

5.3.1.4 Mesoamerica

Last but not least, Mesoamerican social complexity occurred most recently, having emerged only approximately three thousand years ago, perhaps 3.5 kya. Similar to the oldest polity system in the Old World—the West Asian world system—Mesoamerican social complexity also had a highly diversified set of cultural origins: Olmec, Zapotec, Maya, and other major early Amerindian cultures that shared some common attributes but also differed in significant respects. Another commonality with both Old World primary systems—West Asia and East Asia—lies in the variety of ecotopes (natural environments) in which the Mesoamerican polity system originated and subsequently evolved.

The earliest Mesoamerican polity network that formed was arguably among Olmec chiefdoms, such as those centered at La Venta, San Lorenzo, and others nearby, but regional clusters of chiefdoms developed early in the Zapotec and Maya areas as well. In fact, prior to the emergence of a true interstate system, Mesoamerica was politically organized into chiefdom clusters or subgraphs of chiefdoms with weak links among clusters. Calakmul and El Mirador provide examples in the Maya area; San José Mogote and other Zapotec chiefdoms are examples in the Oaxaca Valley.

The earliest Mesoamerican state probably formed in the Valley of Oaxaca—the Zapotec state, ca. A.D. 400—and had its capital at Monte Albán. On a much larger regional scale, the first interstate system of Mesoamerica was formed by no later than the Late Formative period, and consisted of the Zapotec state, the state of Teotihuacan to the northwest, and the cluster of powerful Maya states to the southeast. After ca. A.D. 500, the composition of this system included Tula in the Mexican central highlands, El Tajín in the Gulf of Mexico, and the post-Classic Maya states in the Yucatán Peninsula. The polity of Teotihuacán may have been an empire during the period A.D. 200–600, with colonial outposts as far south as Kaminaljuyú in present-day Guatemala City (reminiscent of Uruk's Tell Brak in Mesopotamia) and possibly others.

5.3.2 Social Complexity Elsewhere: Secondary Polity Networks

In other regions of the ancient world besides the four original ones we have just discussed—in Africa, Europe, North America, and Oceania—systems or networks of polities also developed. However, such systems were not pristine and persistent in terms of having produced original social complexity extending to large-scale imperial complexity. For example, the Indus Valley region gave rise to the polities of Harappa, Mohenjo-daro, and others in the same region, but most likely these polities were inspired by or at least influenced by the much earlier and powerful polities of West Asia, in Mesopotamia, and in the Levant. Similarly, the network of Egyptian polities in the Nile Valley was also influenced by earlier and more complex developments in Mesopotamia and the Levant. Both cases—the Indus Valley polities and the Nile Valley polities—were linked by trade networks (and possibly migration as well) to the pre-existing West Asian polity network.

In Africa (excluding Egypt) the emergence of social complexity came much later, perhaps as late as the 11th century A.D. during the late Iron Age. In Europe, chiefdoms formed earlier, but they formed states much later than in the near East, as in Greece and Italy and elsewhere, or they were conquered by nearby Asian polities.

Social complexity also originated in North America, but only after A.D. 600. The most complex polities before the European invasion and conquest were centered at Chaco Canyon (New Mexico) and Cahokia (Illinois). The scientific consensus today is that both were chiefdoms, not states. A **complex chiefdom** is a term that would best describe them, because they may have been at the threshold of the phase transition to statehood. The history of the two largest and most complex North American polities overlapped chronologically, but there's no evidence of contact between them. Both had declined by the time of the arrival of the Europeans in their former territories. We shall return to these later, after some further ideas that are necessary to appreciate their great significance from a CSS perspective.

5.3.3 Contemporary Social Complexity: Globalization

How do we arrive at the state of contemporary social complexity in the global system from the four original regional networks that we have just examined? In terms of social complexity, most of the history between those early origins and the present consists of second-generation polities, both chiefdoms and states, as well as empires, which we shall examine later.

Globalization, defined as a significant and relatively rapid increase in the size (network diameter) and connectivity of a world system of polities, is an ancient social complexity phenomenon that began thousands of years ago, not a recent or unprecedented occurrence that is unique to modern history. In a certain sense, globalization began in conjunction with the very origins of social complexity, because each of the four primary polity systems began to globalize almost as soon as it originated.

Two quantitatively and qualitatively distinct classes of globalization events are observable in world history. **Endogenous globalization** occurs as a process of growth or expansion that takes place within a given polity region (e.g., the expansion of the Uruk polity in Mesopotamia, Rome in the Mediterranean basin, or Chaco in the American Southwest), while **exogenous globalization** occurs between geographically distant polity network systems that had been previously disjoint as isolated subgraphs (e.g., the 16th century A.D. merging of Eurasian, South American, and Mesoamerican world systems during the European expansion to the Western Hemisphere).

As shown by the evolutionary model in Fig. 5.1, four disjoint and distinct politico-military polity network systems were evolving in parallel—i.e., each of these systems was oblivious of the other since the time that each had originated—around the end of the third century B.C. By this time, several episodes of endogenous globalization had occurred in world history, as we have just seen. By contrast, there have been only two events of exogenous globalization in world history.

The first true episode of exogenous globalization began with the emergence of the Silk Road, which for the first time linked the already vast Euro-Afro-West Asian world system with the equally vast East Asian system by 200 B.C. This new large-scale network of interacting polities was unprecedented, creating an Afro- Eurasian world system in the Eastern Hemisphere and unleashing a set of social and environmental transformations with aftershocks that are still reverberating in today's world system. The formation of the Silk Road and its subsequent development was by no means a linear or uniform process, because it experienced several phases of growth and decline, but its significance cannot be overstated in terms of having caused the first truly massive collapse of world systems—in this case the merging of the Euro-Afro-West Asian world system and the East Asian world system into a single Eastern Hemisphere world system. Thus, only three of the original four truly autonomous world systems remained after the rise of the Silk Road.

The second and last exogenous globalization event occurred when the Euro-Afro-Asian (or eastern hemispheric) world system became linked by politico-military conquest and commercial expansion with the two separate world systems of the Western Hemisphere, around 500 years ago. This time the fusion or catalytic event was the European conquest of the Americas, an event in important ways systemically analogous to the emergence of the Silk Road more than a thousand years earlier. This time the fusion was even greater than it had been with the emergence of the Euro-Afro-Asian world system (which collapsed two systems into one), since this time a single and truly global world system emerged from the previous three that had existed in isolation.

After A.D. 1600 the global world system has greatly increased its connectedness and further reduced its connectivity diameter—down to the "small world" compact structure observable today; no further exogenous globalization is possible. The contemporary world in which we live today consists of a vast, relatively compact or dense network of socially complex units, which range in scale from tiny countries to huge superpowers linked by governmental and non-governmental international and transnational organizations. The recent emergence of networks of international organizations is especially significant from a social complexity perspective, because it indicates that global society has begun to produce structures of governance that exercise some degree of authority and policymaking activity beyond the state level—especially since their dismantling is increasingly unthinkable. Viewed from this long-range perspective, the contemporary global system could either (1) endure in its present level of social complexity (with a hybrid ecology of states and international and transnational organizations, as it has during the past 200 years); (2) continue to grow towards the emergence of world government at some future point (which would mark another major phase transition); or (3) recede toward a prior situation of autonomous nation states linked by relatively weak international organizations that are purely technical and lack any authority—such as, for example, the international system prior to World War I, or before 1914.

5.3.4 Future Social Complexity

The inventor and social philosopher Charles Franklin Kettering [1876–1958] once said that he was interested in the future because he was going to spend the rest of his life there. (He also said that "the whole fun of living is trying to make something better,"[4] which is consistent with the drive to improve quality of life, which generates increasing social complexity.) Future social complexity is uncertain in its details, of course, but its general features are not difficult to sketch out. The best scientific way to predict future social complexity is to understand its causes, based on proven principles informed by data. Based on this approach, the current state of social complexity indicates that human societies will continue to develop artificial systems, both engineered and institutional, to address threatening challenges, exploit opportunities, or enhance our quality of life.

A highly significant feature of contemporary human civilization—from a social complexity perspective—has been the development of the space program, which has been in progress for many decades. The space program is an excellent example of how humans have generated a remarkable array of complex systems and processes within the same logic of strategic adaptation to meet the challenges of space exploration, travel, and eventually colonization away from the earth. The space program that exists today can be considered an embryonic form of **spacefaring civilization**, both in the form of (1) vehicles and their engineered physical facilities that constitute a complex network of infrastructure systems, as well as (2) in the human organizations and institutions that have been decided, planned, and implemented to support space missions. In August, 2012, NASA confirmed that the spacecraft Voyager 1 became the first man-made artifact to reach interstellar space.

A future spacefaring civilization is entirely compatible with the history of human social complexity, as we will see in greater detail following the examination of some additional concepts and theories that are necessary in order to assess its plausibility.

[4] As quoted in *Dynamic Work Simplification* (1971: 12), by W. Clements Zinck.

However, the incipient spacefaring civilization that we already have today displays a large number of features related to social complexity.

1. Computation and information-processing not only play a major role in the current space program but also provide critical infrastructure for maintaining and enhancing performance.
2. Highly complex artifacts, such as space vehicles (capsules, shuttles, and stations), have enabled the performance of human activities of unprecedented complexity in environments with extreme by hostile physical conditions for humans. Such conditions include the vacuum of space, exposure to intense solar radiation, and small and large asteroids while in orbit, in addition to re-entry and landing failures, among the most common lethal hazards.
3. Societal dependence on an increasingly complex and vast array of space-based systems (both orbiting and geostationary systems of systems), ranging from GPS to highly sophisticated remote-sensing satellites, among others, is arguably irreversible. All critical infrastructure systems in the majority of countries in the world now rely on essential links to space assets.
4. A space-based economic sector is already in its formative stage, with examples such as commercial weather satellites, private navigational systems that support surface and airline travel, soon to be followed by other economic activities already making the headlines.
5. Numerous and unprecedented challenges in design, implementation, management, and integration of complex human organizations and technical systems (i.e., coupled socio-techno systems) have been overcome, and there is no indication— at least not judging from all relevant evidence from university training programs, the manufacture of vehicles and systems, professional conferences and associations—that such a trend will end anytime soon.

The dependence of contemporary civilization on spaced-based systems today may be quite unobtrusive—and it is admittedly so for most members of society, concerned as they are with issues in everyday life—*but from a scientific point of view that does not make it less real.* Solar flares and electromagnetic storms are also real, and space weather has major effects on our planet. These and other indicators do not seem easily reversible patterns, barring some extreme, catastrophic event. Even the threat of major hazards posed by such catastrophic events, such as near-Earth objects and asteroids, provide, further impetus toward a spacefaring civilization by generating new programs, economic growth, and international collaboration, under at least some imaginable set of reasonable conditions. Understanding future social complexity, with or without a spacefaring civilization, requires further development in our conceptual, methodological, and theoretical foundations.

5.4 Conceptual Foundations

In this section we take a closer look at key concepts in the study of social complexity in ways that are more specific than discussed so far. Several of these have already been introduced, but require more powerful definition, while others are new and introduced here for the first time.

5.4.1 What Is Social Complexity?

Earlier we introduced the concept of **social complexity** in the context of Simon's theory, which applies universally to societies both ancient and contemporary, and more recently discussed it in our survey of how the first sociopolitical systems formed in early human history (sociogenesis), based on the Service scale—specifically as *the extent to which a society is governed through non-kin-based relations of authority*.

These ideas already suggest basic features of social complexity that merit highlighting:

Goal-seeking behavior: Humans are goal-seeking actors, not purely passive agents.

Basic goals sought: Basic goals sought by humans, and society as a whole, include **survival** and **improvement**. The former includes meeting existential challenges while the latter refers to the human desire to improve one's quality of life, if not for oneself then for one's kin, friends, or descendants. Both goals are universal cross-cultural drives.

Adaptation: Goal-seeking behavior generally requires adaptation, because individual and collective environments in which humans are situated can be challenging or shifting. Quite commonly the goals being sought are pursued in difficult environments or adverse circumstances.

Artifacts: Implementing adaptive behavior requires the activities of planning and constructing artifacts which, as we have already discussed, can be tangible or intangible, generally corresponding to engineered and organizational systems, respectively.

Polity: The complexity of a society is expressed by its polity and economy, which represent the way it is governed and sustained.

Ordinal scale of social complexity C: Let $a(C) \prec b(C)$ denote an ordinal relation defined with respect to social complexity C, such that the complexity of b is greater than the complexity of a. A society's level of complexity is expressed by the ordinal level of its polity (band/tribe $\prec$ chiefdom $\prec$ state $\prec$ empire $\prec$ world system) and economy (barter $\prec$ monetary), which represent the way it is governed and sustained, respectively. Other ordinal features of social complexity include the authority of leaders (decentralized $\prec$ centralized), territorial control (putative $\prec$ effective), tax extraction ability (null $\prec$ effective), among others.

5.4.2 Defining Features of Social Complexity

We use these basic ingredients of social complexity to understand other facets of this concept. Among these are the fundamental notions of bounded rationality, emergence, near-decomposability, modularity, and hierarchy.

5.4.2.1 Bounded Rationality

Goal-seeking behavior by humans situated in real-world conditions or normal circumstances —i.e., the context where social complexity occurs—is never completely based on rational choices, often not even remotely. Humans make decisions and behave according to what is known as **bounded rationality**. This is best understood by briefly examining the **model of perfect rationality** in terms of its main assumptions when compared to assumptions of human bounded rationality. The basic ingredients of the rational choice model consists of goals, alternatives, outcomes, utilities, and probabilities.

Assumption 1—Goals: *Decision-making goals are clear/precise*. By contrast, humans often have an imprecise understanding of the goals they seek, particularly when deciding under stress.

Assumption 2—Alternatives: *The complete set of available alternatives is known*. Similarly, humans usually have an incomplete understanding of available alternatives. This problem is compounded by numerous circumstances, including the presence of stress, incomplete information, and similar factors.

Assumption 3—Outcomes: *Each alternative entails a set of known outcomes*. The estimation of outcomes that can follow from alternatives is difficult, to say the least, since it involves prediction. This is further compounded by human biases, such as wishful thinking, group-think, and many other well-documented biases.

Assumption 4—Probabilities: *Each outcome occurs with known probability*. Probabilities derive from a mathematical theory, whereas we humans normally employ intuition, which is well-known as a poor guide for estimating true probabilities.

Assumption 5—Expected utilities: *Expected utilities can be computed for each outcome and integrated for each alternative*. Human reasoning is incapable of conducting expected utility computations except in the simplest circumstances or through extraordinary efforts.

Assumption 6—Utility maximization: *The alternative with the highest expected utility is chosen*. By contrast, humans often decide to act by what they feel obligated to do, which may not be in their best interest, or by what their friends appear to be doing, or they choose a course of action through some other principle that may not bring the highest expected utility.

Since the rational choice model is critically dependent on these six stringent assumptions—both individually and as a set, since they are formulated as jointly necessary conditions—perhaps it is not so difficult to understand why the model fails to meet even a mildly realistic test, especially because each assumption is difficult if not impossible to obtain.

Behavioral social science is founded on the bounded rationality model.[5] It is interesting to note that violations of the perfect rationality model occur because humans have **imperfect information** or they experience **faulty information-**

[5]Herbert A. Simon, Daniel Kahnemann, and other social, behavioral, and economic scientists have been recognized for their pioneering work in this area by receiving the Nobel Prize.

processing even when the quality of the information itself may be excellent. Human processing of information— analysis and reasoning—is not fault-free, because it, too, is affected by biases and other cognitive effects. This is another instance in which information-processing is highlighted in CSS, this time specifically in the context of social complexity.

The estimation of outcomes and probabilities, by individual humans and groups, constitutes a large area of research in behavioral science. *Experimental work* in this area has now documented literally scores if not possibly hundreds of **human biases** caused by our incapacity, under common circumstances, to correctly estimate true outcomes and probabilities. Besides wishful thinking and group-think, other biases include referencing and other distortions.

The bounded rationality that is natural in humans also has significant institutional consequences: *humans often create institutions* (i.e., organizational artifacts) *precisely for the purpose of managing or attempting to overcome their faulty rationality*. For example, the purpose of deliberative bodies and agencies in contemporary polities (such as legislative or executive branches of government) is to discuss, discern, and agree on goals, explore alternative options, and conduct assessments of outcomes and probabilities in order to improve cost-benefit analyses that support policymaking—from legislation to implementation. Hence, *increased social complexity through creation of institutions and procedures, often in the form of large bureaucracies, is explained by social complexity theory as simply an adaptation strategy for coping with our innate lack of perfect rationality.* In other words, social institutions are causally explained by bounded rationality. Institutional growth and development is also a major occurrence of "emergent" phenomena.

5.4.2.2 Emergence

The term emergence denotes the processes whereby aggregate, macroscopic phenomena result from individual, microscopic behaviors. The study of social complexity comprises many forms of emergence. Social complexity itself is an emergent phenomenon, because it results from goal-seeking decisions under bounded rationality conditions and adaptive behaviors on the part of many individuals or groups. *All artifacts, whether engineered or institutional, are emergent phenomena.* Networks, polities, economies, and culture itself, among many other macroscopic phenomena in the social universe, represent instances of emergence.

An emergent phenomenon is particularly interesting and well-defined when the *aggregation association* among micro-level components is *strong*, in the sense of *composition*, rather than mere aggregation, in an object-oriented sense. (Recall the earlier discussion of the aggregation association in Sect. 2.8.2.1.) This is because in the case of association by composition the component objects or entities are strictly defined in terms of the aggregate, macro-level entity. Instances of this include polities, networks, organizations, social movements, public moods, all forms of collective behavior including the significant class of collective action phenomena, and numerous other significant entities in the study of social complexity. By contrast, simple aggregation is not considered a form of emergence in the strict scientific sense of the term (e.g., a meeting of persons without a collective action outcome is an instance of simple aggregation but not an emergent phenomenon; collective action would turn the meeting into an instance of an emergent phenomenon).

5.4.2.3 Near-Decomposability

The structural organization of social systems and processes is highly significant, because not all structural forms are characteristic of social complexity. For example, a fully connected network may be considered complicated—such as when in a given group everyone is speaking with everyone else—but it is not complex. At the other extreme, a network composed exclusively of singletons is also not complex. Social complexity lies at a specially structured location in between these two extremes, specifically when the organizational structure in question is said to be "near-decomposable." Near-decomposability refers to a system having subsystem components interacting among themselves as in clusters or subgraphs, and interactions among subsystems being relatively weaker or fewer but not negligible. A classic example of a near-decomposable structure is a hierarchical organization that is divided into divisions and department units.

High-level descriptions of social systems and processes often conceal near-decomposability in their social complexity. For example the near-decomposability of a polity system is not revealed by its first-order composition in terms of a societal component (Society) and a governance subsystem component (Government) interacting for managing Public Issues through Policies. Society and Government are subsystems that compose a polity system, such that Polity is a **system-of-systems**. However, each major component of a polity is, in turn, composed of strongly connected components. Society is composed of individuals, households, and groups that interact among themselves in terms of numerous social relations. Similarly, Government is composed of numerous agencies and entities (e.g., legislative, executive, judicial) that are linked by numerous tightly coupled interactions. Hence, while the first order composition of a Polity does not appear to be decomposable, its second- and higher-order structures, especially those of the operational level, are decomposable.

The property of near-decomposability applies equally to the complexity of social systems *and* processes, not just the former. Accordingly, a process is nearly decomposable when each of its subsequent stages is, in turn, composed of multiple activities. An example of this is the *legislative process* within a given polity, whereby the enactment of law consists of several major stages (such as caucusing, drafting, bargaining, initial voting, reconciliation, final voting), each of which entails numerous other intermediate interactions. *Policy implementation* is another classic example of near- decomposability in social processes, as a policy cascades down from the central administration to local agencies to the point where policy consequences reach individuals and groups that are part of society.

A nearly-decomposable structure is also said to be **modular** or modularized. Therefore, **modularity** or modularization is a defining feature of social complexity. A related feature of modular organizational structure is the presence of **hierarchy** as a characteristic of social complexity. This explains why so many forms of social organization are also hierarchical: chiefdoms, states, and empires, as well as the structure of social relations and bureaucratic institutions that support them vary according to scale, but they are all hierarchical and modular in their organization.

5.5 Measurement of Social Complexity

Social complexity is a **latent variable**, which means that it is a property (i.e., a variable or attribute) that is *measurable* but not directly observable. Although we may not be able to measure social complexity directly, we are certainly able to measure it, assuming we are clever enough to use appropriate **proxy indicators** or empirical, operational measures for recording it. For example, the size of artificial systems that support a given society, such as the size of the bureaucracy (measured, say, by the number of public employees), among other dimensions, is a proxy measure of social complexity. This is also true for the size and sophistication of infrastructure systems, which are highly indicative of social complexity. Latent variables are common throughout the social sciences, not just in CSS and the study of social complexity: social status, literacy, wealth and poverty, inequality, unemployment, socioeconomic development, the size of wars, or something even as seemingly observable and countable as voter turnout, all refer to latent variables that rely upon proxy indicators for purposes of measurement. All theoretical concepts are latent, by definition, since they rely on operational variables or empirical indicators for assessing their values. The Service scale (expression (5.4)) is defined in terms of latent values, because data-based proxies are needed to determine the ordinal-level polity value of a given society on the basis of all available empirical evidence.

Social complexity is measured by means of proxy indicators defined at various Stevens-levels,[6] which can be qualitative (nominal or categorical) and quantitative (ordinal, interval, ratio). In this section we present both types, and later in this chapter others will be added.

5.5.1 Qualitative Indicators: Lines of Evidence

Six important and relatively independent **lines of evidence** are used for detecting and measuring social complexity, especially for detecting original formation in the earliest societies (sociogenesis), although these are also applicable to contemporary society.

Structural: The built environment constitutes structural evidence of social complexity, especially structures intended for collective or public use as opposed to private. Temples, plazas, fortifications (walls, gates, towers, barracks, and other types of military engineering), storehouses, cisterns, irrigation canals and networks, monumental tombs, and palaces are examples used to establish emergence of complexity in the earliest societies. Today, airports, public

[6] The Stevens level of measurement of a given variable refers to whether it is a nominal-, ordinal-, interval-, or ratio-scale variable.

buildings, metropolitan transportation systems, and the coupled network of critical infrastructure systems, are common examples of structural evidence of 21st-century social complexity. Structural evidence is among the strongest signals of social complexity, because it is often large, sometimes massive, and long-lasting.[7]

Pictorial: Imagery depicting leaders, ceremonies, or places of government, and similar visual representations indicative of social complexity, constitute another line of evidence. Court scenes, formal processions, depictions of conquerors and vanquished, portraits of leaders, including those on coins, and heraldry, among others, are diagnostic of initial social complexity. Leaders of ancient polities often used extravagant imagery and exotic pictorial representations of themselves or their allies or territories for propaganda purposes. This is another universal, cross-cultural pattern, not unlike that observed in many modern leaders today. In more modern times, similar evidence persists, in addition to imagery associated with social complexity in a large variety of information media.

Artifactual: Artifacts made by humans are diagnostic of social complexity when their production or technological process requires organization beyond the private, household, or strictly kin-based level. Handmade household pottery for daily utilitarian purposes is not indicative of social complexity; however, an elaborate jade artifact or, even more so, a bronze vessel, are both diagnostic of social complexity. This is because both jade and bronze artifacts require considerable social organization and proven technology in their respective production processes, including specialized knowledge of production, sourcing the appropriate raw materials (minimally copper, tin, and lead in the case of bronze, often from different sources found only at remote locations), specialized workers and facilities (high temperature ovens), warehousing, and a system of accounting. Today, some typical examples of artifacts indicative of contemporary social complexity include computers, cell phones, airplanes, satellites, and other artifacts that, in turn, require hugely complex organizations and supply chains in order to produce them. The global world economy is based on organizational and technological systems with unprecedented complexity.

Epigraphic: Written evidence in the form of many types of documents or inscriptions can provide direct evidence of social complexity. In ancient societies some of the earliest forms of epigraphic evidence was provided by clay tablets written in the cuneiform system of writing for purposes of accounting, teaching, correspondence, and maintaining court records. The Mesopotamian government produced a large quantity of historical chronicles and other epigraphic records. Epigraphic evidence is also abundant in the form of inscriptions on artifacts and buildings, providing **compound evidence** of social complexity. In modern times, history books and a panoply of media, both in print

[7] A classic example of this is the Great Wall of China, but there are also numerous other examples of similar long-lasting structures, such as irrigation canals in ancient Mesopotamia, road networks in Mesoamerica, among others that are only visible through modern satellite imagery and remote sensing.

and electronic form, provide clear examples of epigraphic evidence of social complexity.

Forensic: The condition of human skeletal remains provides another line of evidence for measuring social complexity. In ancient times such practices as cranial deformations, encrustations (such as onyx decoration of the front teeth among the Maya aristocrats of early Mesoamerica), and features of bone tissue indicative of particular diets available only to elites, provide evidence of initial social complexity. In modern times, human remains are relatively less susceptible to forensic analysis that is specifically diagnostic of social complexity.

Locational: Finally, the geographic location of human settlements can be another line of evidence for measuring social complexity. Defensible locations, as on high ground or places with difficult access, are often indicative of widespread warfare, which in turn can imply complex social organization. Numerous chiefdoms and early states were established on such locations, often requiring organizations and infrastructure to render them sustainable. Even in modern times, cities located in inhospitable environments, such as deserts or high mountain regions, require extraordinary complexity in terms of urban support systems.

The level of confidence in the measurement of social complexity is proportional to the number of lines of evidence that provide positive support—the more the better, because the probability of a false positive decreases exponentially with the number of lines that provide evidence of social complexity. A single line of evidence is generally viewed as insufficient, although it may be useful because it suggests that additional lines of evidence may be found. This is because social complexity exhibits numerous manifestations which should be measurable by all available data from multiple lines of evidence, rather than confined to a single source of information.

It should be stressed that lines of evidence for measuring social complexity are relevant not only for establishing initial, formative stages—such as identifying the phase transition from egalitarian to ranked societies in chiefdoms (and later states and empires)—but are also necessary for measuring the complexity of modern societies, such as different levels of social, economic, and political development. There is much more than a simple, nominal difference between advanced and developing societies; the difference can also be quantified in terms of numerous indicators such as critical infrastructure systems, especially when viewed as coupled sociotechnological systems.

5.5.2 Quantitative Indicators

We have already been using Service's ordinal-level scale of social complexity, which measures and ranks polities using the ordered values of **chiefdom** (base level) and **state**, to which one can add subsequent ordinal values of **empire** and **global system**. Other quantitative indicators of social complexity include, for instance, the size and structural features of infrastructure present in a given society, since infrastructure is a proxy diagnostic measure of social complexity. The percentage of the population that is not involved in basic subsistence activities (such as individuals involved in education, government, national defense, and a host of others that rely upon that portion of the population not engaged in the production of food and similar basic needs) is increasingly large in advanced, contemporary societies. It too can be considered a proxy measure of social complexity.

Quantitative measures of social complexity can be divided into two broad categories, based on the nature of operational independent variables used to define each measure: formal measures and substantive measures. These should be viewed as heuristic, complementary categories, not necessarily mutually exclusive. They should also be used for comparative purposes.

5.5.2.1 Formal Measures of Social Complexity

Formal measures of social complexity are based on mathematical approaches, such as network-based or graph-based metrics, or information-theoretic measures, among others, all of which use formally defined independent variables. These measures assume that a network matrix is available for computing appropriate indices.

Near-decomposability, a defining feature of social complexity (Sect. 5.4.1), is a latent variable that can be measured by a clustering coefficient proxy. In general, a clustering coefficient measures the number of nodes that are linked by triangles forming subgraphs of various size. Several clustering coefficients have been defined in the context of various near-decomposable structures. The standard **undirected network clustering coefficient** is the average of the clustering coefficient of nodes in an undirected network (such as in an organizational diagram), where the **node clustering coefficient** C_i of node i is defined as

$$C_i = \frac{2\lambda_i}{\delta_i(\delta_i - 1)}, \tag{5.5}$$

where λ_i is the number of connected pairs between all neighbors of node i and δ_i is the degree of i (number of neighbors, defined in Sect. 4.6.1). Therefore, the network clustering coefficient $C_{\mathscr{N}}$ of network $\mathscr{N}$ is given by

$$C_{\mathscr{N}} = \bar{C}_i \tag{5.6}$$

$$= \frac{1}{g}\sum_{i=1}^{g} \frac{2\lambda_i}{\delta_i(\delta_i - 1)}, \tag{5.7}$$

where $g = card(\mathbb{N}) = |\mathbb{N}|$ is the total number of nodes in network $\mathscr{N}$, or the size S of $\mathscr{N}$.

The **Barrat-Weigt clustering coefficient** is defined as

$$C_{BW} = \frac{3(g-1)}{2(2g-1)}(1-p)^3, \tag{5.8}$$

where g is the number of linked neighbors (degree) and p is the probability of rewiring (Barrat and Weigt 2000: 552).

Another quantitative proxy measure of social complexity is **Shannon's entropy** H, which can be measured over the degree of nodes. In this case,

$$H(\delta) = -\sum_{i=1}^{g} P(\delta_i) \log_2\bigl[P(\delta_i)\bigr], \tag{5.9}$$

where $P(\delta_i)$ is the probability that node n_i has degree δ. A structure consisting mostly of singletons will have high entropy, and hence not be near-decomposable. At the other extreme, a fully connected graph will have maximum entropy, because the degree distribution will have a single peak given by $\delta = g - 1$. A near-decomposable complex system indicative of clustering and hierarchy will have an intermediate value of entropy somewhere in between.

The *comparative statics* of each of these formal measures of social complexity are interesting, because they are mostly nonlinear functions.

5.5.2.2 Substantive Measures of Social Complexity

By contrast, **substantive measures of social complexity** are based on specific social, economic, political, or other cultural variables. Traditional social science methods can be used to construct proxy measures of social complexity. For example, **multi-dimensional scaling (MDS)** is one such method widely used for comparing scores on multiple indicators that measure dimensions of latent social phenomena. Both classical and nonparametric versions are available in the R programming language. Classical MDS uses Euclidean distances across objects aimed at plotting low dimensional graphs.

The **Peregrine-Ember-Ember ordinal Guttman scale of social complexity** is used for measuring the earliest phase transitions into chiefdoms and states.[8] It contains the following items ranked from minimum to maximum values:

1. Ceramic production
2. Presence of domesticates
3. Sedentarism
4. Inegalitarian (status or wealth) differences
5. Population density > 1 person/mi^2
6. Reliance on food production
7. Villages > 100 persons
8. Metal production
9. Social classes present
10. Towns > 400 persons

[8]The Peregrine-Ember-Ember (2004) scale of social complexity is one of the current Guttman scales developed by anthropologists. It is based on the most comprehensive sample of early human cultures, based on the worldwide *Outline of Archaeological Traditions* from the Human Relations Area Files (HRAF), based at Yale University, and builds on earlier scales of social complexity developed by R.L. Carneiro, L. Freeman, G.P. Murdock, and C. Provost, among others.

11. State (3+ levels of hierarchy)
12. Population density > 25 person/mi^2
13. Wheeled transport
14. Writing of any kind
15. Money of any kind

Chiefdoms form between levels 3 and 7, whereas states form between levels 8 and 11. A defining feature of a Guttman scale is that each ordinal value includes all previous value–traits. For example, villages consisting of 100 or more persons (level 7) also rely on food production (level 6), have population density of more than one person per square mile (level 5), experience marked inequality (level 4), and so forth down to level 1 (ceramic production). Similarly, states consist of towns with more than 400 persons, have social classes and metal production, in addition to traits associated with lower scale values.

For modern polities, the United Nation's **Human Development Index** D_H is a specific example of a proxy measure of social complexity at the country or polity level, designed to assess aggregate socioeconomic conditions (Table 5.1).

The Human Development Index is a composite indicator consisting of three other indices: life expectancy L^*, education level E^*, and national income per capita I^*. These three components are strongly associated with significant levels of social complexity, individually but especially in combination. Simple or primitive societies generally score very low across all three indices. Life expectancy is high in all countries where social complexity is also highest, such as in the advanced industrialized economies. High levels of education are attainable only in societies that can sustain the most expensive universities. High income indicators are similarly observed only in complex societies, where cost of living is also highest. Simple societies measure the lowest scores in lifetime expectancy, level of education, and income-related indices. Formally, D_H is defined as the geometric mean of the three component indicators

$$D_H = \left(L^* \cdot E^* \cdot I^*\right)^{1/3} \tag{5.10}$$

$$= \sqrt[3]{\frac{L-\alpha_1}{\alpha_2} \cdot \frac{\sqrt{S \cdot \langle S \rangle}}{\beta} \cdot \frac{\ln(I/P)-\gamma_1}{\gamma_2-\gamma_1}}, \tag{5.11}$$

Table 5.1 Social complexity according to the polity-level Human Development Index D_H (2012) in the top fifteen countries. *Source*: United Nations Development Programme, *2013 Human Development Report*

Rank	Country	D_H	Rank	Country	D_H	Rank	Country	D_H
1	Norway	0.955	6	New Zealand	0.919	11	Canada	0.911
2	Australia	0.938	7	Ireland	0.916	12	South Korea	0.909
3	United States	0.937	8	Sweden	0.916	13	Hong Kong	0.906
4	Netherlands	0.921	9	Switzerland	0.913	14	Iceland	0.906
5	Germany	0.920	10	Japan	0.912	15	Denmark	0.901

where independent variables and constants are operationally defined as follows:[9]

$L =$ life expectancy at birth
$S =$ mean years of schooling multiplied by a factor of 1/13.2, or "mean years of schooling index"
$\langle S \rangle =$ expected years of schooling by a factor of 1/20.6, or "expected years of schooling index"
$I =$ gross national income
$P =$ populations
$\alpha_1 =$ 20 years
$\alpha_2 =$ 62.3 years
$\beta =$ 0.951 years^{-1}
$\gamma_1 =$ 100 dollars/inhabitants
$\gamma_2 =$ 107,721 dollars/inhabitants

Several aspects of the human development index are noteworthy as a quantitative measure of social complexity. The geometric mean in Eq. (5.11) defines a *cubic function* for D_H with respect to its three component indices. It also defines D_H as a function of five independent variables and parameters, in terms of *multiple nonlinear dependencies*. Therefore, the comparative statics are interesting also in this case of measuring social complexity. Empirically, all countries in Table 5.1 are also well-known for operating advanced infrastructure systems, which are necessary for adaptation and achieving high quality of life in complex environments.

Numerous measures of complexity have been proposed for generic systems. For example, the minimal description necessary to describe the features of a system (such as an algorithm) can be viewed as a measure of the system's complexity. In the context of a social system's complexity, we can define a **lexical measure of social complexity** based on the length of the minimal description of its functional structure. Rigorous definitions of chiefdoms, states, and contemporary polities, written with minimally necessary and systematic vocabulary, based on comparative social science terminology, provide viable examples. Another operational approach of the same lexical measurement procedure could be based on formal graphic notation, such as UML class, sequence, and state diagrams for describing specific social systems, such as a chiefdom, a state, or a contemporary polity.

Let S denote a social system with complexity $C(\mathsf{S})$. A lexical measure of C can be defined as the minimal number of characters κ, including spaces, that is minimally necessary to describe S. For example, later in Chap. 7 we will examine the formal, theoretically based definitions of a chiefdom and a state. Definition 7.9 (chiefdom) yields $C(\text{chiefdom}) = 289$ characters, whereas Definition 7.10 (state) yields $C(\text{state}) = 339$ characters, consistent with the fact that a state is more complex than a chiefdom.

Different definitions of the same social system S can be expressed in somewhat different number of characters $(\kappa_1, \kappa_2, \kappa_3, \ldots, \kappa_N)$. However, since they are all describing the same system S, only in different words, and all descriptions are assumed

[9]Notation here is different from the original UN annual report, which uses abbreviations and acronyms rather than proper mathematical symbols.

to be minimally necessary, the number of characters can be assumed to be normally distributed. Therefore, the simple arithmetic mean taken over the set of κ_i values provides a composite lexical indicator of social complexity:

$$C(\mathsf{S}) = \sum_{i=1}^{N} \kappa_i. \tag{5.12}$$

Alternatively, if S is defined in terms of graphic models—such as when using a set of associated UML class, sequence, and state diagrams of S—then the set of features contained in the graphics can be used as information to define $C(\mathsf{S})$. For example, suppose the UML class diagram of social system S consists of a number of objects and a number of associations among objects, denoted by discrete variables O and A, respectively, where $O = 1, 2, 3, \ldots, o$ and $A = 1, 2, 3, \ldots, a$. Similarly, the UML sequence diagram of S consists of O objects and S sequential interactions among objects in separate "lanes," where $S = 1, 2, 3, \ldots, s$. Finally, suppose the UML state diagram of S has X states and Φ transitions among states, where $X = 1, 2, 3, \ldots, x$ and $\Phi = 1, 2, 3, \ldots, \phi$. Then, social complexity based on the three graphic models can be defined by functions of these metrics. For instance, the graphic complexity measure

$$C(\mathsf{S}) = (O + A) + (O + S) + (X + \Phi) \tag{5.13}$$

$$= O(A + S) + X + \Phi \tag{5.14}$$

provides a simple but viable aggregate indicator, as do other similar functions defined in terms of graphic features that specify the complexity of social system S. For example, the norm of a vector $\mathbf{C}(\mathsf{S})$ consisting of graphic values in the UML diagrams,

$$|\mathbf{C}(\mathsf{S})| = \sqrt{o^2 + a^2 + s^2 + x^2 + \phi^2}, \tag{5.15}$$

is another viable graphic-based measure of social complexity.

Social complexity is also measurable on a temporal scale, where **long-range correlations** are diagnostic of complexity in social processes. The **Hurst parameter** is a temporal indicator for measuring the complexity of a time series of social data in terms of its **long-range dependence** (LRD). Let $X_1, X_2, X_3, \ldots$ denote a time series of values at times $t_1, t_2, t_3, \ldots$ with mean μ and variance σ^2. The Hurst parameter is defined by the **autocorrelation function** $\rho(k)$ of a time series as

$$\rho(k) = \frac{E(X_t - \mu) \cdot E(X_{t+k} - \mu)}{\sigma^2} \tag{5.16}$$

$$\sim C_\rho |k|^{-2(1-H)}, \tag{5.17}$$

where $|k|$ denotes time lags or leads of length $0, 1, 2, 3, \ldots$ in either direction, the symbol $\sim$ denotes asymptotic equality as $k \to \infty$, and $C_\rho > 0$ is a scale parameter. Note that $\rho(k)$ decays algebraically as a **power law**, so the autocorrelations are

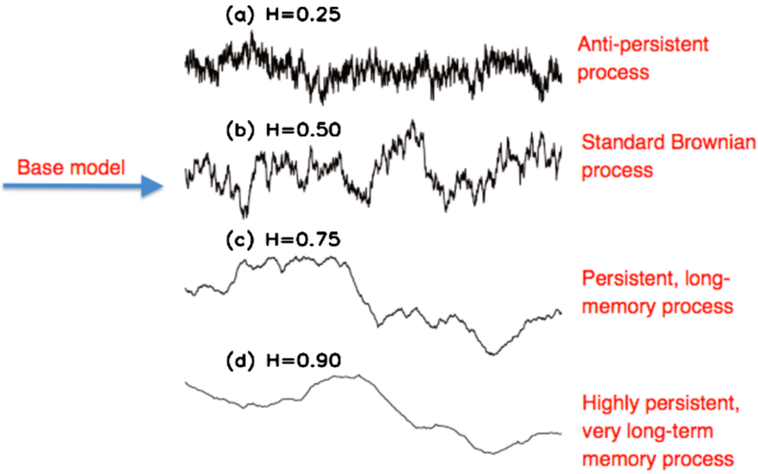

Fig. 5.2 Long-range dependence (LRD) or memory structure in time series measured by the Hurst parameter H. *Source*: Adapted from Gao et al. (2013: 16)

scale-free and, therefore, the process is said to be **self-similar**, that is, **fractal**. We shall examine these properties more closely later, when we focus on power laws of social complexity. **Spatial autocorrelation** is similarly characteristic of social complexity.

The value of the Hurst parameter estimated from empirical data is indicative of process complexity as determined by the following ranges:[10]

Case 1: When $0.5 < H < 1$ the process has long-term memory, or LRD, so the process is also called **persistent**.

Case 2: When $H = 0.5$ the process is standard **Brownian motion** with normal or Gaussian distribution, mean $\mu = 0$, variance $E[(B_H(t))^2] = t^{2H}$, and power spectral density $1/f^{2H+1}$. This is *not* a case indicative of complexity, but rather one of **equilibrium dynamics**.

Case 3: When $0 < H < 0.5$ the process is **anti-persistent**, meaning that it is significantly more jagged than the Gaussian process.

Cases 1 and 3 are driven by **non-equilibrium dynamics** typical of complex systems and processes, as shown in Fig. 5.2. Standard Brownian motion is a base process or **phase transition boundary** (**critical bifurcation value**, $H = 0.5$) for the temporal complexity of a social process. Above the critical value the process has persistent memory ($H > 0.5$), indicative of the status quo or dynamic stability, the process looks increasingly smooth as the autocorrelation length increases, and the distribution of X is heavy-tailed (extreme events have a significant likelihood)). By contrast, below the critical value the process has anti-persistent memory ($H < 0.5$) indicative of high volatility or dynamic instability, and the process looks

[10]Many estimators of the Hurst parameter are available, as reviewed by Gao et al. (2007).

more jagged. The "jaggedness" of a time series is inversely related to the Hurst exponent.

If policy is based on assumptions other than those warranted by a time series analysis of the Hurst exponent for temporal complexity, then the provision of public goods will be misguided. The causes of LRD are often difficult to determine. Sometimes it is related to the cumulative effect of prior processes responsible for generating a time series.

Spatio-temporal autocorrelation is diagnostic of social complexity. By contrast, it is noteworthy that traditional data analysis in social science research generally dislikes spatio-temporal autocorrelation, because it violates standard assumptions of correlational analysis of data. The use of various transformations (logarithmic, inverse, square, among others) to obtain "normal" Gaussian-distributed data destroys information necessary for measuring social complexity and should therefore be avoided in social complexity analysis. The same is true for skewed distributions, as we shall see in the next chapter.

Recommended Readings

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