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Social Scale and Collective Computation: Does Information Processing Limit Rate of Growth in Scale?

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Abstract: Collective computation is the process by which groups store and share information to arrive at decisions for collective behavior. How societies engage in effective collective computation depends partly on their scale. Social arrangements and technologies that work for small- and mid-scale societies are inadequate for dealing effectively with the much larger communication loads that societies face during the growth in scale that is a hallmark of the Holocene. An important bottleneck for growth may be the development of systems for persistent recording of information (writing), and perhaps also the abstraction of money for generalizing exchange mechanisms. Building on Shin et al., we identify a Scale Threshold to be crossed before societies can develop such systems, and an Information Threshold which, once crossed, allows more or less unlimited growth in scale. We introduce several additional articles in this special issue that elaborate or evaluate this Thresholds Model for particular types of societies or times and places in the world.

Key words: social evolution; thresholds model; information processing; writing; demographic scale; collective computation

RNA and speech retain fundamental roles in their respective systems, but they are overshadowed by the elaborate, cumulative effects of DNA and writing ... It was only the development of writing—and related technologies of measurement and manipulation—that truly pushed human culture across the threshold of complication. Literacy led culture to become civilization.[1]

(Waters, 2021)

Connectivity is very costly and requires system scale and density to pay off.[2]

(Bettencourt, 2014)

1 Introduction

From slime molds through multicellular organisms, ant colonies, and human societies, all living systems transport energy and materials via a set of (typically overlapping) networks. In addition, all such living systems transport information across such a network, and process that information within the nodes on that network. Importantly, there are several different types of information‒not only Shannon's syntactic information[3], but also several types of semantic information[4]. All such types of information are transported and processed within networks in living systems. In particular, flows of information of all these types among the parts of a social group and the

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associated processing of that information to produce action are hallmarks of Homo sapiens, stretching back at least to its emergence hundreds of thousands of years ago.

These flows and processing of information within a social group have been referred to as the group's "collective computation"[5], and occur at multiple levels of granularity. Abstractly, such social collective computation refers to social groups that change "their internal states in ways that can expand their information content …in tandem with changes of connectivity as determined by their relative costs and benefits"[2]. Concretely, this involves both communication among and within families, kin groups, and / or institutions†. Collective computation also encompasses gathering of relevant information from the external physical and social environments, the subsequent process of making a joint decision, and determining how to carry out the decision.

Importantly, collective computation also encompasses decision processes by a society that is top down, bottom up, or (as is often the case) a mix of both. The road constructed by members of a polity following the order of a socially legitimate authority is obviously the product of a complex series of information accumulation, exchange, decisions, and actions. But the footpaths emerging among locations commonly visited by a band of hunter-gatherers also constitute a computation solving an energy-minimization problem for the collective. In this sense, collective computation can be seen as "collective behavior" construed more broadly than do the classic game-theory-derived, bottom-up approaches of collective action theory[8].

We emphasize that collective computation in the sense we mean it is a property of the social group as a whole - information processing within an individual member of a social group is a separate topic, comprising the field of cognitive science. Such individual-level information processing obviously forms the foundation of collective computation, much as atomic physics ultimately forms the foundation of cellular biology. But the focus here is on analyzing the information processing performed by the joint interactions of a collective, rather than the processing performed by the individuals within the collective.

The critical importance of success in group-level information processing for our hominid lineage could not be more clear. We are specialists in solving problems using information. Our brains have tripled in size since the time of the Australopithecines, and are six times larger than would be expected for a placental mammal of our size[9]. These big brains come at great metabolic cost, and some 60% of their growth over evolutionary timescales has been attributed by some researchers to solving the challenges of our daily individual contests with nature to keep them fed, with the next most important driver being success in social-strategic contests between groups[9]. Brain sizes of course increase only on very long time scales. On shorter time scales we seek advantages in these contests through external cognitive assists, changes in group size, and changes in group organization and connectivity. Clearly, innovations that have potential for increasing information content, durability, or accuracy—of an object, or in an exchange—should be highly valued by such a species.

More or less independently, human societies have developed characteristic methods to make the network's means of carrying materials through space more efficient, e.g., through construction of roads, bridges, and canals. Likewise, transmission of information across space and through time was made richer in content and less error-prone first through the development of language in humanity's distant past, and much more recently through the development of systems for representing information on persistent media such as turtle shells, ox bone, bamboo, clay tablets, or knotted cords (henceforth "writing systems"). Writing systems provide external cognitive assistants; Levinson[10] has termed them "technologies of the intellect" or "cognitive artefacts". They may use iconic signs but often eventually converge on more-or-less arbitrary (conventional) systems of symbols[11] to distill and preserve much of the syntactic and semantic relationships (information) encoded by perishable speech. Information transmission along one-to-many channels becomes more efficient and less error prone with such encodings. Exchanges of materials likewise become more efficient through the development of a symbolic system capable of precisely specifying a unit

† We follow Bondarenko[6] in adopting Turner's[7] definition of institutions as complexes of "positions, roles, norms, and values lodged in particular types of social structures and organizing relatively stable patterns of … activity with respect to fundamental problems in producing life-sustaining resources, in reproducing individuals, and in sustaining viable societal structures…".

of value (automatically allowing it to also specify relations of value) and a political authority guaranteeing that value[12]; this symbolic system is instantiated in money.

Now efficiency is always a good thing but really becomes of central interest as societies scale up in size. Little inefficiencies can be tolerated when they are occasional, but inefficiencies in the exchange of messages or other transactions chained together can come to overwhelm the value delivered by the transaction or message itself. When most production is centered on the household or its local group, exchanges are typically direct and face-to-face; the social messages conveyed are as central as the economic load. When they come to dominate the economic activity of a society, they become indirect and may compound one another so much that the individual inefficiencies become less tolerable.‡

The problem we address in the papers collected in this special issue of the *Journal of Social Computing* hangs on the relationship between types of variables that are useful in cross-cultural research. The first is the scale of societies, measured in terms of total population, population of the largest settlement, and size of its territory, and / or ratios of those variables, e.g., population density. The second is the means of collective computation or information-processing of the society.

Scale may be important in its own right, but here we are concerned primarily with how it interacts with a society's other characteristics. For example, theory strongly suggests that the greater the density of people in a given area, the greater the expected density of their interactions[14], and the greater the pace at which they develop new capabilities for collective computation[15]. So the means of collective computation depends on scale, but dependence in the other direction has long been recognized as well; cities and the states in which they thrive depend on writing[16]. More fundamentally then we would like to ask, to what extent do changes in the number of actors (individuals, groups, and institutions) in a social group and / or their density in space contribute to changes in its methods for transmitting information and conducting exchange? Conversely, can gains in the efficiency or accuracy with which societies transmit or accumulate information or conduct exchange provide sufficient conditions for changes in its scale?

‡ The children's game of telephone reveals how information can progressively degrade as the number chained transmission nodes scales. Thus Thucydides describes how an Athenian military commander in Sicily entrusted a critical report to Athens not to a series of messengers relaying his words, but to a written letter, "to ensure that the Athenians should know his own opinion without its being lost in transmission, and be able to decide upon the real facts of the case"[13].

Such are the general questions underlying the papers collected here, which address the historical, structural, and functional relationships between the scale of specific societies and the means by which they transmit, process, and store information and exchange goods or services. These papers were stimulated in part by two recent analyses of an ambitious effort to code many aspects of human history, along with the later portions of prehistory, in a database known as Seshat[17]. We begin by briefly describing this database and summarizing these two analyses. Then we will provide a high-level overview of the relationship between a society's scale and its information-processing capacities. Finally, we introduce each of the papers collected in this issue.

2 Seshat: The Global History Databank

The Seshat project, founded in 2011 and still growing, is designed to systematically collect and make available a large corpus of data (employing over 1500 variables) on societies of the world between the Neolithic and the Industrial Revolutions. These data are organized by polity which range in scale from independent local communities (villages) to empires. When polity scale is very small the concept of a pseudo-polity is substituted; a pseudo-polity is a representative polity within a region with many similar units of similar size. Data are collected by 100-year intervals in times and places that can support such temporal precision; in other cases the highest resolution permitted by the data is used. The data release that is current as we write, Equinox2020[18], traces polities through time in 35 Natural Geographic Areas (NGAs). The two analyses described below, however, used an earlier release (called the World Sample-30) with data coded for 30 NGAs, selected to have worldwide coverage and to evenly sample NGAs that achieved political complexity early within their world region, late in that region, or at an intermediate date. These analyses subsampled 51 of the subjectively coded indices and combined them into 9 "Complexity Characteristics" (CCs) that were analyzed using Principal Components Analysis (PCA) and sometimes other techniques. The variables selected were considered to be relevant to tracking social evolution and whose values, at least in theory, could be inferred from the archaeological record.

Four of these CCs measure aspects of the scale of a polity: its population, size of territory, population of the capital or biggest aggregate, and a "hierarchy" variable composed of estimates of the number of administrative, military, and religious levels, and an estimate of the settlement hierarchy. The other five CCs code aspects of government, money, infrastructure, information (i.e., writing) system, and texts. In the context of Seshat, we use the term "collective computation" to refer to these five CCs, since they all are involved in how societies encode and process information, communicate, and conduct transactions. We note however that there are many other features in addition to—or even instead of—those five CCs that are involved in collective computation by social groups (see in particular the paper by Steven Wernke, this issue). Turchin et al.[19] discuss how missing, uncertain, and patchy data are handled and the techniques used to arrive at the appropriate codes, which generally rely on research assistants working in collaboration with established scholars. Only detailed examination of these proposed codings and exploration of their implications—such as we begin here—will reveal the robustness of their results.

We can gain insight into some historical processes purely from observing changes in aggregate data over time, without decomposing those data into finer-grained units. For example, much about the industrial revolution can be understood by looking at how aggregate values of various goods produced in England changed during the 19th century, without considering changes in the values of those goods in different municipalities. However, a crucial feature of the Seshat dataset is that it provides fine-grained time-series data—time-series of individual NGAs—not just aggregate time-series data. To give a simple example of the benefit of this feature, suppose that Ibn-Ḫaldūn[20] was correct, in that all societies go through a periodic dynamics, e.g., in population size (though without its known secular trend upwards)—but that as one ranges over the surface of the planet, the phases of the societies in their separate periodic dynamics were uniformly distributed. Then a study of the dynamics of the population size of the whole planet would find that it does not change in time. In contrast, a finer-grained study which looks at the change within a single society over time would reveal (on average) the periodic nature of its scale and information-processing dynamics.

2.1 Quantitative historical analysis uncovers a single dimension of complexity that structures global variation in human social organization

In 2018 the Seshat team published a widely read article of this name[19] that for many readers was their introduction to this project. The main finding of this article was that a PCA over the 30 NGAs and the nine CCs identified a first Principal Component (PC1) explaining 77% of the variation in these data—perhaps a surprisingly high degree of commonality given the geographic dispersion and temporal range of the polities in the sample. PC1 had high positive loadings on all 9 CCs, with low scores on this component for small-scale (and generally earlier) societies and high for empires. Turchin et al. concluded that "different characteristics of social complexity are highly predictable across different world regions … key aspects of social organization are functionally related and do indeed coevolve in predictable ways"[19].

2.2 Scale and information-processing thresholds in Holocene social evolution

Two years later, a group including two of the present authors revisited this same dataset with the aim of drawing attention to some patterns it contained that had not been noted in the 2018 publication[21].※ The most important of these was a change in the direction of the relation between PC1 and PC2 over their ranges. Unlike PC1, on which all the CCs had high positive loadings, PC2 exhibited negative loadings on the four scale CCs and positive loadings on the five collective computation CCs[21].

Figure 1 shows that for the small-scale and generally early polities with scores on PC1 $\leqslant \sim -2.5$ (labeled Zone 1), the average scores on PC2 trend downwards as PC1 increases. Since increases in PC1 reflect increases in the values of all CCs approximately equally, whereas

※ Turchin et al.[19] were of course aware of PC2 and its structure but did not pursue its analysis since it explained a relatively small amount (6%) of the variation in their PCA. Shin et al.[21] argued however that this estimate of the importance of PC2 may be misleading because (1) it is based on the static pattern in the data and does not take into account the dynamic development of this pattern through time, which involves moving through a non-linear relationship between PCs 1 and 2; and (2) the scores on PC1 in the Turchin analysis are bimodal, whereas strict interpretation of percentages explained by each component requires unimodality.

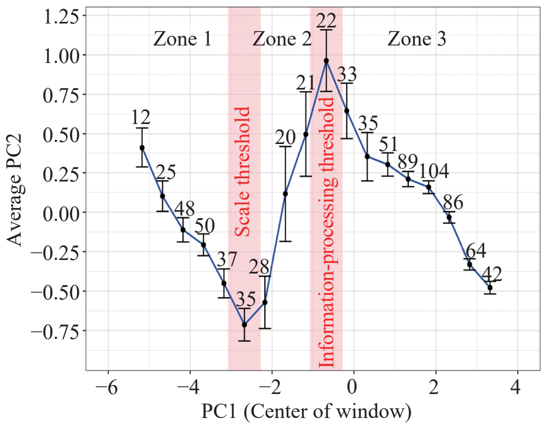

Fig. 1 Average score of observations on PC2 in a sliding window along PC1. The PCA is based on 414 datapoints. Each PC1 sliding window is defined to have width 1.0 (on the scale of PC1) and overlap width of 0.5 with other sliding windows, i.e., the center of the PC1 sliding window occurs at every 0.5 interval. The error bars are defined around the means of the PC2 values within the sliding PC1 windows as +/− the standard error of the PC2 values. Number of samples in each sliding window is listed above each error bar. Based on Shin et al.[21]

decreases in scores for PC2 will happen as the scale CCs increase but collective computation stays more or less constant, polities in this zone are predominately increasing in scale with relatively less increase in collective computational abilities. These are in general societies that use human memory for their primary information storage, supported by external encodings into norms of behavior, craft and artifacts, kinship, mythology, art, ritual, and features of the environment that help organize, simplify, routinize, and recollect this knowledge in appropriate ways (see Hamilton, this issue; and Ref. [22]).

A second zone can be seen in Fig. 1 between scores on PC1 of about −2.5 and −0.5, in which average scores on PC2 are strongly increasing as PC1 scores also increase. In this zone, polities on average are increasing in both their scale and their collective computational capabilities, but with particular emphasis on the latter. Finally, the largest and generally latest polities, with scores on PC1 $\geqslant \sim -0.5$, are once again following a trajectory similar to that of the smallest (often earliest) polities, in which increases in size are once again more prominent than increasing capabilities in processing information and transactions.

Shin et al.[21] suggested that the zone near PC1 scores of −2.5, where the direction of the relationship between PC1 and PC2 changes abruptly, constitutes a "Scale Threshold". To be concrete, example polities in the Seshat database with PC1 values near this threshold include Oaxaca in 900 CE (see Feinman and Carballo, this issue); Iceland in 1000 CE, the moment when the law-speaker Thorgeir Ljosvetningagodi decreed that everyone will become baptised though pagans could continue their practices (the laws would not be written down for more than another century); the Paris Basin at 600 BCE (Late Hallstatt); and Big Island Hawaii at 1700 CE, several decades before the arrival of British naval captain James Cook. These polities have a mean population of a little over 48 000 people (median 22 750) and a mean capital population of about 9400 (median 5400), according to Seshat codings. Shin et al.[21] suggested that polities with scores in this vicinity have on average achieved sufficient size to support, and to gain advantages from, developing more efficient ways of processing information and transactions. Formal systems of representing information persistently are after all expensive, eventually requiring not just specialists such as scribes, but also institutions such as schools, libraries, and archives to support them and deal with the information they produce.

By the same framing, the zone in Fig. 1 with scores on PC1 around −0.5 constitutes an "Information Threshold". Example polities close to this threshold include Latium at 700 BCE (as the Latin League was being formed), Susiana at 3700 BCE (in the "proto-Elamite" period), the Middle Yellow River at 3000 BCE (the Yangshao/Longshan transition, by which time pot-marks possibly denoting ownership or maker[23] have become somewhat common), and the Yemeni Coastal Plain at 1700 CE (the Qasimid state). These polities averaged around 300 000 in population (median 87 000) with capitals or largest cities averaging about 14 000 (median 7000), according to Seshat codings. Shin et al.[21] argued that polities with scores in this vicinity have on average achieved sufficient gains in the means of collective computation to be poised for further increases in scale.

As shorthand we will refer to this bundle of findings and expectations as the "Thresholds Model". This encompasses the two thresholds and three zones identified above, along with an awareness of the possibility that bottlenecks in collective computational capabilities may rate-limit growth in scale in human social evolution.

We emphasize that this model is tentative; it relies on the Seshat dataset, which is the subject of some controversy in the literature. In addition, it relies on one particular and somewhat crude analysis of that dataset. The "sliding windows" algorithm used to make Fig. 1 is quite simplified in the sense that it treats PC1 in a privileged fashion—a sliding window along PC2 would result in a different figure. Also there are two distinct stochastic processes that underlie the Seshat dataset. One is a "birth process" governing when the first datapoint of a given NGA appears in Seshat, and at what PC values. The second is the dynamics process, governing how an NGA that has already been "born" evolves from one timestep of Seshat to another. While the first, birth process, should have little effect on the time-series data in the second and third regions of Fig. 1, it is a major factor determining the data in the first region, to the left of the first threshold. The sliding window algorithm is not refined enough to distinguish these effects. In sum, rather than viewing the Thresholds Model as a firmly established feature of the evolution of human social groups, we view it as a framing device, which generates important questions concerning the interplay between scale and collective computation in the history and evolution of human social groups.

2.3 Evolution of collective computational abilities of (pre)historic societies

In November 2020, the Santa Fe Institute hosted a virtual working group of this name organized by Kohler, Wolpert, and Bird. We had two complementary goals for this workshop which involved two rather different sets of invitees. The first—advanced by archaeologists and historians—was to examine the substantive suggestions made by Shin et al.[21] concerning the presence and importance of these possible thresholds from the perspective of their particular areas of expertise. Some of these authors had been contributors to Seshat and co-authors on Turchin et al.[19], but this forum gave them the space to delve into their cases in detail. Other authors were selected in part because their areas of expertise were not among those not encoded by Seshat. For them an obvious question is whether the arguments made by Shin et al. make sense in their areas. More largely, this working group was concerned with what they saw as the relationship between the development of scale and the means of collective computation in their areas. Articles developed by several of the presenters are collected in this issue.

The second goal of the working group was to identify methods better than PCA for examining multi-dimensional records with a temporal dimension such as those assembled by Seshat. The authors of these papers were drawn from various quantitative and computational specialties that focus on time-series analysis. Their contributions were not specific to Seshat (or indeed to time-series concerning human societies), but illustrated the breadth of techniques that can be brought to bear in analyzing datasets like Seshat. These contributions will be developed and presented elsewhere.

3 Empirical Fluctuation, or Stochastic Law?

How should we think about these proposed thresholds in information processing and scale? One possibility is that they arise because of competitive pressure among polities, a highly contingent process that would always be selecting from the available alternatives at each moment[24, 25]. It is certainly the case that there is abundant evidence for such competitive pressures—see for example Ober[26] on Greece and Turchin et al.[27] on Afroeurasia more generally. Competition coupled with cultural group selection could provide the selective mechanism discouraging wasteful developments (those with no positive returns) and ensuring that enhancements in information processing (or growth in scale) will take place only at the point where such investments will likely reap rewards. Concretely, we suggest that polities might be obliged to achieve sizes typical for polities near the Information Threshold before improvements in the efficiency of processing information and transactions—and the advantages of maintaining the information thus distilled—have a positive payoff.

A second possibility, however, is that these thresholds arise from an interplay between our human cognitive constraints and the physics of information flows as societies increase in scale. This would seem to be the position favored by some 20th-century lines of theorizing in archaeology, for example by Gregory Johnson[28]. In one of the articles presented in this issue, Laura Ellyson revisits Johnson's framework and locates it within a broader context including theories of the firm, examining whether the determinants of hierarchies of various sorts differ in the three zones identified in Fig. 1.

At the extreme under this second possibility, if the earth's surface had always supported but a single society, if that society were to grow in scale we might still see the same changes in means of collective computation arising at the same social scales as we see on the real earth with its churning multitudes of societies in interaction and competition. Whether these common thresholds are enforced by competition or induced by interplays between physical and biological constraints, they can presumably arise without any explicit strategizing on the part of a polity or its leaders, and it may be inappropriate to assume such strategizing for acephalous polities.

In fact we will not dwell on whether competition is required for these thresholds to exist—in the event, there was certainly competition. But fundamental questions about the relationship between scale and information-processing capabilities still remain. The result depicted in Fig. 1 is clearly an empirical generalization based on data developed by the Seshat coders on what happened in 30 geographic areas. But is it more than that? Is it uncovering a general law governing a necessary relation among numbers of parts and efficient communications among them, when those parts are made up of humans and our institutions with our characteristic cognitive limitations? Or is it just showing what happened to occur, largely in Afroeurasia, in essence a statistical fluctuation—implying that under another roll of the divine dice the outcome could have been quite different? Moreover, if it is only an empirical generalization, is it a biased one? We note that only six of the 30 NGAs in the analysis are in the New World.

One way to begin to answer the contingency/necessity question is by considering some cases not included in this sample of 30. If the histories of societies that did not contribute to the model correspond to the expectations of the Thresholds Model of Shin et al.[21], that strengthens the possibility that these thresholds constitute a (stochastic) law of human social group evolution and not just an empirical fluctuation. If on the other hand, they do not fit the model, that destroys the possibility that it is a law. In the article of this issue, Gary Feinman and David Carballo consider some portions of Mesoamerica that were "out of sample" in the context of the Oaxaca NGA, which was in the sample. Johannes Müller discusses the curious out-of-sample case of the Chalcolithic Tripolye "mega-sites" where scale and information processing might appear to be out of balance. And Ian Morris provides a third out-of-sample case in his discussion of Archaic and Classical Greece. A general question of interest for each specific historical sequence is the source of the innovations in processing information and transactions discussed in these papers.

So assessment of more cases provides checks and balances on the Thresholds Model. But here is the critical question: how do we demonstrate fit (or lack of fit) to the model as new cases are brought to bear? This is not straightforward, for two main reasons. First, the model describes the behavior of an ensemble of cases among which there is a fair amount of variability. And second, the model is based on computation of principal components in a nine-dimensional space. Our interpretation of Fig. 1 suggests that once a polity reaches a PC1 value ~2.5, its further growth in scale may be hindered unless it develops its collective computational technologies by invention or by borrowing. But unless we have assessed all the variables for each of our out-of-sample cases in exactly the same way as done by Seshat, we cannot recreate their placement on PC1 or PC2. (Of course, adding more cases will also change those components.) At best we can roughly approximate their placement on PC1 as computed on the existing cases, for example by saying that the Scale Threshold is typically reached with polity populations on the order of 23 000–48 000 and capital (largest aggregate) populations on the order of 5400–9400, but this substitutes just two values for a measure originally determined by nine. The analogous values near the Information Threshold are polity sizes on the order of 87 000–300 000 people with capital cities of some 7000–14 000. These highly variable thresholds actually overlap on capital size.

All these considerations suggest that the best we can hope for, at this point, is to characterize the out-of-sample cases as fitting the model well, poorly, or not at all, rather than striving for some statistical characterization of goodness of fit. And on this basis, we conclude that the four regional case studies (on Greece, the Andes, Mesoamerica, and the Tripolye mega-sites of Moldova and the Ukraine) fit more or less well—though with considerable nuancing provided by each of their authors.

A more powerful index of the utility of the model which we have not yet attempted would gauge whether societies slow their growth in scale as they near the Scale

Threshold if they have not yet developed information-processing technologies, and whether these developments in information processing speed up their growth in scale. Thus speed of growth in scale relative to the timing of improvements in information processing—not considered by Shin et al.[21] either—might eventually help assess or refine the Thresholds Model. This would be a contribution to a field—social kinetics*—that does not quite exist! One object of its study would be whether increases in collective computational abilities were key rate-determining factors in growth of social scale.

If the model can be critically examined through its performance on out-of-sample cases, we can broaden and deepen it by exploring how the shallow coding provided by Seshat corresponds to the detail available to historians and archaeologists on particular cases already in the sample of 30 NGAs. In another article in this issue, Steven Wernke considers the Andes in this vein, noting how Eurocentric concepts of how information is processed lead to the Cuzco case appearing as an outlier given its high scale but low information-processing capabilities as measured by Seshat.

Indeed, the Cuzco case is particularly of interest for another reason. Of the 30 NGAs in the sample considered here, only six were in the New World and writing systems (as we broadly define them) were developed in only two of those, Oaxaca and Cuzco (the khipu). Shin et al.[21] suggested that one reason so few New World polities developed writing may have been that so few grew to the Scale Threshold at which writing would have become advantageous. They further suggested that (with the partial exception of the South American camelids) the absence of large domesticable animals in the Americas contributed to this tendency to remain relatively small in scale. To what extent did these animals facilitate Cuzco's growth in scale, and to what extent did that in turn make a materially based information-storage mechanism such as the khipu a necessity?

In the remainder of this introductory paper we want to acknowledge the very long involvement of anthropology, archaeology, and history in the causes and consequences of improved writing systems, and more generalized and efficient systems for handling transactions. In a short essay it is difficult to even properly introduce the main commentators on these questions. Nevertheless, to set the stage for the papers that follow we briefly sketch some key discussions of these twinned issues. In the interests of space, and because two of the nine CCs deal with it explicitly, we concentrate on growth in information systems and texts, mentioning exchange mechanisms (the focus of one CC) mainly in passing. We refer readers interested in recent discussion of the development of money to Baron and Millhauser[29], Hudson[30], and references therein.

4 Opening the Discussion on Collective Computation: Historical Survey and Introduction to the Case Studies

Although other points of entry would be possible, the anthropologist Jack Goody directed considerable attention to the consequences of literacy in society. This work began in collaboration with Ian Watt in the early 1960s[31] with a much fuller exposition in Goody[32]¤. Like his Cambridge mentor Meyer Fortes, Goody undertook ethnographic work in West Africa (Ghana) early in his career, and his comparative work on literacy consistently contrasted the relatively recent and partial usages of writing he witnessed there with his reading of the history and archaeology of Eurasia, especially Greece and the Near East, and China.

For the Near East, which produced the earliest writing in the world, Goody formulated the now-common story that development of writing effectively served both the intensification of exchange (commerce) and the management of the economic affairs of the temple and the palace[32, 34]; "early writing in Mesopotamia was employed for book-keeping rather than recording myths and rituals"[32]. Even though the forms of language used in book-keeping were largely non-syntactical, these usages fed back into other, syntactical uses; together, in both Egypt and Mesopotamia, "the economy of the temple and the palace entailed a burgeoning of bureaucrats and bureaucracy, of records and record-keepers"[32]. This point appears to be critical, as

* This is likely a discipline that would have appealed to Isaac Asimov's fictive psychohistorian Harry Seldon. Asimov's own dissertation was entitled Kinetics of the Reaction Inactivation of Tyrosinase During Its Catalysis of the Aerobic Oxidation of Catechol.

¤ Goody's work on the relationship between writing and cognitive function (especially on the contribution of writing to the development of logical inquiry) was critiqued by Halverson[33]. Here we emphasize the connections Goody makes between writing and the major institutions of early states, but we also note that Goody's proposal that literacy radically restructures the brain is now receiving abundant support from neurophysiological research[10].

Goody does not claim that writing is essential to the appearance of the state in general, but that it is a requirement for the development of what he calls the "b ureaucratic state"[32]. This would certainly include the entities James C. Scott considers to be early states in the ancient Near East (polities with "walls, tax collection, and officials"[35], as well as the "more collective" polities considered by Richard Blanton[36]). Goody and Scott would seem to agree that the size of the surpluses achieved by irrigation agriculture, and the storability of its grains, catalyzed the joint development of writing and bureaucratic states—in contrast (for example) with the more limited surpluses and lower storability of crops typical of the Indigenous states of Sub-Saharan Africa.

By Goody's analysis, at some (controversial) point, merchants not in the employ of the king or the temple adopted practices such as shareholding and credit which would scarcely have been feasible in the absence of written documentation, which made memory more reliable by storing information over time. Registering title to land (perhaps originally to claim ownership for the temple or palace, but soon extended to individuals) was another prominent early use of written records. Since some lands were subject to taxes, and others not, that too had to be "accounted for" by some bureaucrat, not to mention the documentation of timely transfer of taxes to the state, or rents, or tithes, to the temple. Writing systems also enabled the production of written codes (such as that of Hammurabi, formulated in the 19th century BCE) adjudicated in courts by people filling roles of judges, constables, and lawyers. Writing of codes cemented a distinction between law and custom[32], and facilitated production of more variable and elaborate contracts than would be possible orally. Eventually, documents require the development of filing systems, registers, archives, and libraries. More generally, writing permitted and eventually required a proliferation of institutions just as much as institutions required writing: they have a mutual affinity. Surveying the southern Alluvium of Mesopotamia (with some regard for the situation in China as well), Scott states that "the coincidence of the pristine state and pristine writing tempts one to the crude functionalist conclusion that would-be state makers invented the forms of notation that were essential to statecraft. But it would not be too strong to assert that it is virtually impossible to conceive of even the earliest states without a systematic technology of numerical record keeping"[35].

Given the immense differences in the rise and structure of the state in the Near East, Egypt, and China, the fact that writing developed very early in all instances speaks to its centrality. Consider the contrasting paths for the rise of the state in the Near East and in Egypt. As described by Juan Carlos Moreno Garcia[37], states arose around great cities in Mesopotamia, Syria, the Levant, and Anatolia, with consolidation among them relatively late and often short-lived. By contrast kings from Abydos in Egypt established a unified kingdom some 1000 km in length by around 3100 BCE, controlling a "barely urbanized provincial world … the most conspicuous elements of which (writing, visual codes) were to last for millennia"[37]. But writing was early in all cases.

In Egypt, Mesopotamia, and China the first writing systems were ideograms or logograms. These systems were inherently cumbersome and complex, severely limiting the spread of literacy in the general population, and guaranteeing the literate positions of relative power and privilege. Development of syllabaries for Semitic languages in the late third millennium BCE, and then the consonant-only alphabets in the Near East[38], and not long after, in the early first millennium Greece, the rise of "true alphabetic" script in which consonants and vowels were accorded equal status[39], were each boons for the spread of literacy as they were increasingly easier to learn. (Steven Wernke's paper in this issue critiques the Seshat coding scheme for writing and texts for assuming a lexigraphic foundation in which signs represent speech sounds, which is probably not the case for the Andean khipu.) Goody credits the high rate of literacy in ancient Greece as foundational to both its democracy and its prosperity. Josiah Ober, a leading expert on the practice of democracy in Classical Athens, would perhaps agree (though we are not aware that he engages the problem). Ober attributes the competitive and economic success of Athens in great measure to its highly participatory form of democracy that was able to effectively collect, aggregate, and turn into policy the highly dispersed knowledge of its citizens—knowledge to which literacy must have been relevant[26].

The New World is the only non-controversially independent case for the development of writing, although most also consider China's writing system to have developed independently. Although the development of scripts had a different impetus and trajectory here[40], it is critical to note that scripts were developed, reinforcing the possibility of functional necessity. The earliest script that is currently widely accepted was found incised on a serpentine block at the Olmec site of Cascajal in disturbed context but with an apparent date near the Early Formative–Middle Formative transition[41], or perhaps as early as 1000 BCE. It contained about 28 distinct glyphs laid out in a way suggesting syntactic relationships among them. It has no obvious connections with later scripts; local experimentation did not automatically lead to persistence of particular encodings, and apparently whatever was being recorded did not have to be understood by people beyond a relatively local context. Other Formative notational systems have been identified in the Isthmus of Tehuantepec (Zoquean), the Mayan area of the Pacific Coast of Guatemala and the Petén district of Guatemala, and the Valley of Oaxaca (Zapotec) (see Feinman and Carballo, this issue; and Ref. [42]).

As pointed out by Feinman and Carballo in this issue, the small scale of Mayan polities and their high achievements in information processing seem problematic from the perspective of the Thresholds Model. We are encouraged though by the discussion of Simon Martin, who considers the Classic Maya world to have maintained a "dynamic equilibrium" within a system "best understood not as an array of individual polities but as an interactive whole"[43]. Somewhat the same situation obtained for the dense network of polities in Archaic and Classical Greece discussed in Ian Morris' paper; the size of each individual polity alone is not a good estimate of the size of the interacting population that created and supported the accomplishments of Attica or the much larger commercial and knowledge network of Classical Greece. The difficulty of accurately determining the size of the interacting population that is both supported by, and makes possible, the collective computation in each NGA is a hindrance in evaluating the Shin et al. model.

We may look to another out-of-sample case not dealt with in any of the papers here to see some support for the notion that as polities increase in size they find it desirable (perhaps necessary) to improve aspects of their communications. The largest religious-political entity in the prehispanic northern US Southwest, centered on Chaco Canyon and reaching its maximum extent between 1030 and 1140 CE, never developed a system of writing. Nevertheless, Chaco was not just outstanding for its size (a spatial extent of some 160 000 km^2) but for other features that seem to be attempts to deal with this size by overcoming distance. The Chacoan hierocracy constructed two systems of intraregional connection that were highly unusual within the context of regional culture history. The first was a system of "roads" that provided partly practical, partly metaphorical connections among Chaco's far-flung network of outlier settlements[44, 45]. The second was a network of "shrines", built on high places, that appears to have enabled "meaningful connections for communication and identity" across the Chaco world, using either night-time signal fires or perhaps selenite mirrors by day[46].

For more detailed evaluation of the model for specific regions, we are extremely fortunate to have comments by some of the leading experts for those regions. These are prefaced by an introduction to considerations of scale and collective computation in the operation of forager societies by Marcus Hamilton, and an overview by Laura Ellyson of the intersection of Thresholds Model with the research of Gregory Johnson, introduced above.

4.1 Marcus Hamilton: Collective computation and the emergence of hunter-gatherer small-worlds

Hamilton develops a model for the interaction between information processing and energy flow, and demonstrates how the interaction between them affects the socioecology of hunter-gatherer societies at multiple spatiotemporal scales. How individual optimization of information processing and energy flow constrains social organization at higher scales of social organization is a main focus. He first situates this research within Tinbergen's four questions regarding the role of evolution and ecology as they affect collective computation, then considers scaling relationships in mammalian, primate, and hunter-gatherer groups using data on individual brain size, body size, group size, population density, and home range size for each species or society. These data are used to develop a model for individual information processing power at the group or band level, which he uses to scale up to not only the hunter-gatherer band level, but also to higher levels of social organization. He concludes that the formation of groups, and fission-fusion cycles leading to scaling and turnover between groups, increases the collective computational abilities of humans to better achieve local optimization.

In the context of this collection of papers, Hamilton expands our consideration of collective computation not just to hunter-gatherer groups, which are not included in the Seshat database, but also to mammals in general, demonstrating the centrality of collective computation to group success. He shows how the modular nature of human group organization encourages the production of collective computation technologies and rituals even among groups that are small in (apparent) size most of the time. His model additionally introduces the importance of social networks for collective computation, a topic explored further by Morris. Given that all Seshat polities have deep roots as hunter-gatherer societies it is critical to understand that they emerge into the focus of Seshat from a long prehistory of dealing with constraints imposed by scale and information-processing thresholds underlying all those discussed elsewhere in this collection.

4.2 Laura Ellyson: Applying Gregory Johnson's concepts of scalar stress to scale and Information Thresholds in Holocene social evolution

In a series of papers published in the 1970s and 1980s, Johnson defined a system for estimating the computational load likely carried by individuals in settlements of various sizes, and illustrated how those concepts could be applied in the archaeological record. Johnson argued that communication flows could be read from spatial distributions within and between settlements. Drawing on management science and social psychology, he suggested that these spatial arrangements also carry clues for how these societies prevented communication loads from reaching levels that would degrade decision performance (a condition he called "scalar stress"). Ellyson examines his predictions using multiple linear regression on the same Seshat data examined by Shin et al.[21], which also allows her to evaluate predictions of the Thresholds Model for societies from Zones 1, 2, and 3 (Fig. 1) as three separate groups.

Because Johnson focused on hierarchies of information processing in small-scale and middle-range societies, Ellyson uses Seshat's Hierarchy CC (or its several components) as the dependent variable in her analyses. The Thresholds Model has some modest success under this evaluation. As anticipated from the discussion of this model by Shin et al.[21], two of the three significant predictors of increases in the Hierarchy CC for polities in Zone 1 are scalar variables (larger territories and capital populations), though more developed governments (a collective computational variable) also play a role. For polities in Zone 2, only one of the two significant predictors of higher levels for the Hierarchy CC is scalar (increasing populations) whereas the other (more types of texts) is related to computation. Likewise polities in Zone 3 depart similarly from predictions, since two of the four significant predictors of higher levels for Hierarchy CC are scalar (capital population and political territory) and two relate to organization for computation (government and infrastructure).

Overall, the verdict of this analysis is mixed, with only the first group of cases (from Zone 1) being clearly in line with model expectations. In retrospect the importance of both polity territory and infrastructure in this third group of polities is not surprising, as polities in this zone are (in general) growing rapidly in spatial scale. In general Ellyson's analysis provides more reasons to doubt whether a single PC across the entire range of cases in this Seshat dataset provides an adequate description of social evolution, as argued by Turchin et al.[19], and reminds us that many of Johnson's insights 40 years ago remain relevant to an archaeology interested in collective computation.

4.3 Johannes Müller et al.: Tripolye mega-sites: "Collective computational abilities" of prehistoric proto-urban societies?

The very large Chalcolithic settlements of Tripolye (or the Cucuteni–Trypillia culture) built between 4100 and 3600 BCE may pose a problem for the Thresholds Model since by some indices their sizes approach or exceed that expected of polities near the Scale Threshold yet they exhibit few of the usual indications of increasingly capable collective computation. At their peak, Tripolye sites consist of a mega-site with few if any rural communities, each defining a polity or quasi-polity. Their resident populations of up to ~15 000 individuals places each Tripolye polity below the typical range at the Scale Threshold (~23 000–48 000), though their largest settlements are probably above the central tendencies (5400–9400) for polities at this threshold. The mega-sites are politically distinct and present no apparent inter-polity hierarchy, though intra-polity organization is clear and facilitates information processing at up to five levels of social organization. Hamilton's and Ellyson's discussions of information processing in societies of relatively small scale provide more detail on how this might have worked.

The archaeological site of Maidanetske is especially critical to the argument by Müller et al. as the intra-site settlement planning, public architectural development, and artifactual inventories are well understood. Organizational changes in information-processing do occur here over time, though all these societies remained non-literate and without any form of currency. Among the possible causes for the sudden collapse of Tripolye societies, Müller et al. note a late tendency for an increasing "lack of correlation" among the components of complexity, suggested by Shin et al.[21] as a candidate general explanation for decline and collapse in cases without clear exogenous triggers.

4.4 Steven Wernke: Explosive expansion, sociotechnical diversity, and fragile sovereignty in the domain of the Inka

The Inka state has long been considered an outlier in social-evolutionary studies given its very large scale—achieved only shortly before the Spanish entrada—coupled with its apparent lack of several technological hallmarks (e.g., iron, the wheel, lexigraphic writing system, and currency) of most Old World complex societies. In the Thresholds Model proposed by Shin et al., the Inka Empire is a unique case that crosses the Information Threshold but does so only with a very low score on PC2. Wernke argues that the Inkas fit the model better than it appears, or at least would do so if Seshat accurately considered and coded the distinctive technologies the Inkas used to process information and perform collective computation. Wernke describes Inkan information-processing and transport systems in detail, arguing that these technologies and systems either constituted effective substitutes for analogous Afroeurasian systems or (as in the case of currencies) made them irrelevant. He provides a thoughtful commentary on the general difficulties of formulating unbiased systems of encoding social evolution worldwide as he identifies some specific failures of the Seshat scheme for the unique and compelling case of the Inka.

4.5 Gary Feinman and David Carballo: Communication, computation, and governance: A multiscalar vantage on the prehispanic Mesoamerican World

Feinman and Carballo take a multi-scalar approach to analyse the diachronic relationship between collective computation and scale in prehispanic Mesoamerica. An important element of their analysis is to introduce variability in the nature of governmental organization (an axis between despotic and collective) as being just as important as scale in influencing the presence and repertorial depth of written systems of communication. This argument is developed in detail in a contrast between modes and styles of information exchange in the collective Teotihuacan polity and the more autocratically organized polities of the Classic Maya. On a fine scale (30 pre-modern cases) they find only a weak positive correlation between either polity size, or size of the largest aggregate, and a 10-point index of writing elaboration that they create. This positive correlation is driven primarily by the very large, late highland center of Tenochtitlan at the heart of the Aztec empire, which employed a large variety of computational and exchange technologies that were likely important to its expansion. A critique of both the models proposed by Turchin et al. and Shin et al. —connected to their failure to consider variability in governance logics—is the (inferred) variable importance of oration in public settings to convey information and cement identity. Nevertheless, considering Mesoamerica as a whole over some three thousand years, they suggest that four episodes they identify in which "the scale of settlements and/or polities increased markedly" were each "preceded by (or roughly coincided with) the establishment of new sociospatial contexts or the advent of novel computational technologies that facilitated or expanded the potential for interpersonal communication" roughly as suggested by the Thresholds Model proposed by Shin et al., though that model recognizes only two thresholds.

4.6 Ian Morris: Scale, information-processing, and complementarities in Old-World Axial-Age societies

Morris approaches the Seshat dataset via the out-of-sample case of first millennium BCE (Axial Age) Greece, emphasizing potential issues with using "polities" or "NGAs" as sampling units. He demonstrates this issue by highlighting Greece's supposed falsification of the Thresholds Model proposed by Shin et al., since in this region the polities and locations with the greatest increases in scale were not the same as those with the greatest innovations in science, religion, or philosophy. Further, the size and shape of the "polity" varied rapidly over time. Considering the case of the extremely innovative Athenian polity, Morris quite reasonably argues that this character is not attributable to the polity by itself, which was rather small, but the dense network of polities in which it was embedded and Athens' key position as a major port and cultural and religious hub. He further suggests that the locations at the margins of large polities are frequently centers for intellectual innovation, presumably due in part to less local governmental control. Therefore a strong positive correlation between innovations in computation and in scale of polity might not be found, depending on the sampling frame used.

An issue that Morris raises in passing is the anomalously high population density in classical Attica, arguing that these densities might have been a key factor encouraging the high rate of development of collective computational abilities. This suggestion accords with the findings of West[15] on the superlinear scaling of rate of innovation relative to population density in social groups: perhaps not just cities but even regions can serve as "social reactors"[47]. Since the Seshat dataset includes both polity population and polity size (in logarithmic forms) it captures both the overall, raw scalar size of a polity, as well as the scalar density. This in turn suggests that if classical age Attica had been included in the Seshat dataset analyzed by Shin et al.[21], it might have strengthened the patterning of the hinge points they noted, though this is speculative absent the analysis itself.

5 Conclusion

Archaeologists have been thinking for a long time about the relationship between social scale and how information is represented, accumulated, stored, and processed. Flannery[48] considered a principal trend in the "evolution of bands into tribes, chiefdoms, and states (to be) a gradual increase in capacity for information processing, storage, and analysis". We think Flannery's thesis is now well accepted, and in this special issue we formulate some more focused hypotheses. Have "the Paris Basins of 600 BCE" of the world reached a point in their growth in scale where further growth becomes unmanageable or even impossible absent improvements in their means of collective computation? Have "the Latiums of 700 BCE" acquired those tools of abstract representation, persistent recording, and low-friction exchange permitting a more open-ended growth into spaces occupied by polities that have not yet crossed the Information Threshold? The papers collected here suggest that such questions are not just approachable, but perhaps need to be cautiously answered in the affirmative. On the evidence here we minimally suggest that historical researchers should consider such factors as part of the causal nexus underlying social persistence, expansion, decline, and collapse.

Overall the case studies collected here seem to support the existence of two (or more—see below) thresholds in long-term social evolution, even though they also clearly demonstrate how difficult it is to evaluate such a model cross culturally. It seems plausible that a first Scale Threshold has to be met before the expense (with costs for specialization, other social differentiation, and technological advances) of putting in place abstract and persistent representation of information and transactions, and high-throughput networks of spatial interconnection, becomes worthwhile. As Bettencourt noted in one of our epigraphs, connectivity is costly and it requires some system scale to make it worthwhile. Chaco and Tripolye seem to have been approaching that scale; innovations such as roads, trackways, and signalling stations betray their efforts to minimize problems imposed by growth in distances whereas features such as the hierarchically embedded levels of representation in the Tripolye mega-sites (and in Puebloan sociospatial organization—see Crabtree et al.[24] and Ellyson, this issue) helped minimize computational problems raised by growth in population size. Nevertheless, their relatively small scale did not favor development of abstract conceptual tools such as writing and money. Their relatively short duration may speak to their near-mismatch in scale and information-processing capabilities. It seems clear that Imperial Cuzco crossed the Scale Threshold shortly before the arrival of the Spanish, permitting rapid development of its unique system of recording information even in the absence of currencies and markets, which were unnecessary given its political structure. The case for Mesoamerica is obviously more complicated; an NGA centered on the main Classic Maya polities might show anomalous growth in computation versus scale, but perhaps not, if populations were summed across the tightly interacting network of polities. Based on Feinman and Carballo's discussion, we speculate that an NGA including both Teotihuacan and Tenochtitlan might fit the model proposed by Shin et al. reasonably well.

However, some of the case studies (including at least those for Mesoamerica and the Andes) can be read as suggesting that social evolution is generally characterized by increases in social scale whose rate is (almost continually) limited by existing computational abilities. Thus this would be true throughout a growth sequence in an NGA, rather than just occurring at one juncture as Shin et al.[21] proposed. Feinman and Carballo (this issue) identify four step-like increases in both social scale and information processing in Mesoamerica; Wernke notes that predecessors of the khipu were also used by the expansionist state preceding the Inka, the Wari (600−1000 CE), albeit on a smaller scale (and with less richness of information content). This perspective on scalar growth as in a continual state of near disequilibrium with available information processing is rather close to that recently articulated by Sander van der Leeuw[49], who emphasizes the centrality (and potentially limiting character) of information processing in human evolution as far back as one cares to go.

But can we approach these possibilities more rigorously than was possible in these exploratory papers? As suggested above, one promising avenue lies in the rates of growth and their change through time. The hypothesis that "rates of scalar growth are always limited by constraints arising from the existing means of collective computation" expects a decrease in rate of growth in scale prior to each major computational advance; and an increase in rate of growth immediately after each such advance (for example when crossing the Information Threshold of Shin et al.[21]). Such an analysis has yet to be attempted so far as we are aware.

These closing speculations (and in fact, this entire effort) should not be read as naively functionalist. The claim that societies may be pushed to develop computational assists (from technologies for representing and storing information, to new sociopolitical arrangements for managing and processing it) does not exclude the certainty that people were making choices all along the way, or that these new technologies and sociopolitical arrangements which in our view arose to serve growth, cannot also be manipulated to benefit one group over another[50]). We are certainly aware that our focus on information and computation as abstract categories capable of measurement—rather than on knowledge, meanings, and intentionality, for example—derives from the granular metaphysic more or less required of comparative, cross-cultural work[51]. This is a choice, too. These codicils are clear in the accompanying studies, and if we have not spent much time dwelling on them it is only for clarity of focus.

Also clear from this collection of papers is that the process of incorporating more NGAs needs to be continually coupled with a critique and expansion of Seshat coding conventions to ensure that to the extent possible they encompass the rich variety of encodings and modes of transfer of information, goods and services these papers reveal. The power and potential of studies at the scale of Seshat's are worthy of some compromise, even perhaps for some who would prefer a more Hegelian approach. On this path lies the only possible Archimedean point—one from which the view is global—for weighing the relative strengths of historical contingency and necessity in social evolution.

6 Postscript: the Second Social Media Revolution

Today we live in a world undergoing rapid change in directions that are likely unsustainable, due in no small measure to the huge scale, volatility in social network structure, and capacity for developing and rapidly spreading misinformation afforded by social media[52]. In the midst of this third social media revolution, we find that it is disrupting our affairs every bit as much as pressing issues in public health and in the economy.

The first social media revolution was the development of speech and language, enabling individuals for the first time to share thoughts and plans with those close to them. This created a community of shared information (and surely some disinformation) immeasurably richer than just what could be jointly perceived by co-located individuals. It also created a "spatially and temporally self-projecting awareness that manifested itself as extra theory of mind and mental space-and-time-travel capacities, which increasingly enabled intentional or conscious, top-down executive adjustment of past behaviors for the sake of achieving better ways of doing things in the future"[53]. Unfortunately, the resolution of the relevant archaeological record does not allow us to determine the connections of this development to changes in group size or the specific productive/reproductive activities these facilitated.

Logically, the uniquely group-relevant aspects of speech and language would have greatly facilitated any task benefitting from coordinated activity.

This paper concerns the second social media revolution in which writing was the key innovation. Like the first, it extended the scale of communication: this time to others not physically present, and to lengths of time vastly exceeding the duration of sound waves. If the first revolution created a community of those hearing a message and learning from it, the second extended that community to those who could interact with it in thought, speech or writing at any subsequent time, and from any place. The pace of publication and the reach of writing was hugely extended by the sub-revolution of movable type and the printing press[54]. Western civilization is the broad though shallow community linked polythetically by such nodes as the writings of Aristotle, Martin Luther, Charles Darwin, and Toni Morrison, among countless others. It is undoubtedly true that we do not yet fully understand the dynamics and effects of the third social media revolution. Perhaps we will develop a more informed approach once we have completed the job of accurately characterizing the causes and consequences of the second revolution.

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