Information, complexity, and the evolution of *Homo sapiens* in an uncertain world

John F. Hoffecker*
Institute of Arctic and Alpine Research
University of Colorado
Boulder, Colorado 80309-0450 USA

Abstract. In addition to specific anatomical characters, *Homo sapiens* may be defined on the basis of a rare cognitive faculty for manipulating a finite set of neuronal information units into a potentially infinite variety of hierarchically-organized arrangements ("discrete infinity"). In the context of language, discrete infinity is achieved by generating higher-order information units in the form of real or imagined vocalizations that function as material aids to computation ("cognitive scaffolding"). This faculty, which entailed changes in brain organization, likely evolved ~150 ka in the unstable evolutionary setting of *Homo* social networks of sub-Saharan Africa, when further increases in brain volume were constrained by mean annual temperature. Although language sounds presumably derive from earlier vocalizations (i.e., a pre-existing communication system), discrete infinity conceivably is related to a pre-existing and analogous faculty for making complex artifacts that evolved no later than 0.5 mya. By evolving an integrated "super-brain" with computational functions, modern human societies represent a new level of organizational complexity that exhibits emergent properties.

There is consensus among paleoanthropologists on a definition of *Homo sapiens* based on features of skeletal anatomy that may be recognized in the fossil record. A sufficient number of these features (primarily cranial) are represented in recovered fossil remains to establish the presence of *H. sapiens* in sub-Saharan Africa by ~150 ka (1, 2). There is a lack of consensus, however, on features in the fossil or archaeological record that would indicate cognitive faculties and behavioral features comparable to those of living people (often termed "modern behavior"). Because many researchers perceive a temporal gap between the appearance of modern human anatomy and the earliest evidence for "modern behavior," it has become an issue in the study of human evolution.

Most paleoanthropologists seem to agree that syntactic language is a central component of "modern behavior." To date, however, they have been unable to find a reliable indicator of syntactic language before the advent of written records in fossil anatomical data, genetics, or archaeology. Noting that a significant feature of language is that it is based on symbols, many archaeologists have cited other manifestations of symbolic expression (sometimes characterized as "material storage of symbols") as a proxy for language (3). These typically include visual art, personal ornamentation, and artifact style. Alternatively, some archaeologists have identified modern behavior in the archaeological record on the basis of a variety of features, both symbolic and non-symbolic (4).

In a recent review, Shea critiqued the concept of "modern behavior" itself as "qualitative, essentialist, and a historical artifact of the European origins of Paleolithic research." He proposed an alternative concept, "behavioral variability," which he defined simply as doing "everything . . . in more than one recognizably different way" (5).

Applying a quantitative measure of variability to the most visible category of archaeological data (i.e., stone artifacts), Shea concluded that the degree of variability evident in artifacts associated with the earliest *H. sapiens* fossils in Africa, as well as those associated with most of their contemporaries in Eurasia, was roughly comparable to that of living humans.

While the behavior of *H. sapiens* may be defined broadly in terms of variability, a more specific definition with reference to cognitive function is available. The concept of *discrete infinity*, defined by Chomsky and colleagues (6) in the context of language as "the capacity to generate an infinite range of expressions from a finite set of elements," may be applied broadly to the unique cognitive faculties of *H. sapiens*. Discrete infinity is known in only one other metazoan—the male humpback whale, which generates a potentially infinite range of "song" compositions by recombining a finite set of sounds in the form of the neuronal information units from which they are generated (7, 8).

In *H. sapiens*, the concept may be expanded to a general cognitive faculty for creating potentially infinite variations of hierarchically-organized arrangements of information units. The units are ultimately based on synaptic connections in the neuronal networks of the brain (i.e., neuronal information). Because neurons store and transmit information in discontinuous (or discrete) and continuous (or analog) form, the concept also may be broadened in this respect. The wider faculty is sometimes labeled *recursion* (9) and, because it pertains to the manipulation of information units, it may be considered a form of *computation* (10).

Although more difficult to document in the archaeological (or fossil anatomical) record than "behavioral variability," a capacity for recursively generating potentially

infinite varieties of arrangements or structures based on translated neuronal information units can be recognized in many archaeologically visible expressions of human cognition. The expressions include symbolic forms such as visual art, and also non-symbolic forms such as patterned arrangements that lack meaningful content (e.g., decorative designs) and complex artifacts that possess a function but also lack symbolic content (11).

Information and Evolution

A theoretical context for discrete infinity may be found in evolutionary biology, specifically the idea that "major transitions" in evolution may be characterized by fundamental changes in the role of *information* in living systems. Less than two decades ago, Maynard Smith and Szathmáry proposed that modern humans represented a major transition in evolution on the basis of fundamental changes in the storage, transmission, and translation of neuronal information, as demonstrated by syntactic language (12, 13). Manipulation of information, i.e., *computation*, may be added to the list.

A formal concept (and mathematical definition) of "information" emerged from the communications industry in the years following the Second World War (14). It also is tied to development of the programmable digital computer during the same period (15). In both cases, the intellectual roots lie in wartime applications of mathematics to cryptography and target prediction. Deeper roots lie in the rise of thermodynamics during the late 19th century and Leo Szilard's solution to the dilemma posed by Maxwell's "demon" (16). Despite the "decoding" of DNA during the 1950s, however, information theory had limited impact on evolutionary biology until the final decades of the 20th century and development of techniques for the rapid sequencing of DNA (17).

The concept of *information* never has been fully defined or explained in evolutionary biology and, in this context it may be best understood in terms of how it functions. First, organisms receive or collect information about their environment to reduce its unpredictability (or "entropy'). Genetic information about the environment is accumulated indirectly through the effect of selection on randomly generated variation (10, 17), while neuronal information is collected directly through genetically-based sensory organs among the metazoa. Second, information is the means by which organisms replicate themselves as complex systems (i.e., "instructions"). The inevitable "errors" during transmission of large quantities of genetic information introduce the variation necessary for evolutionary responses in unpredictable environments.

Maynard Smith and Szathmáry identified eight "major transitions" in evolution with respect to changes in the storage, transmission, and translation of information: 1) replicating molecules to populations of molecules in proto-cells; 2) independent replicators to chromosomes; 3) RNA as gene and enzyme to DNA genes and protein enzymes; 4) bacterial cells (prokaryotes) to cells with nuclei and organelles (eukaryotes); 5) asexual clones to sexual populations; 6) single-celled organisms to animals, plants and fungi; 7) solitary individuals to colonies with non-reproductive castes (eusocial animals); and 8) primate societies to human societies and language (12, 13).

Maynard Smith and Szathmáry observed that each transition is completed when the components of the newly evolved entity can no longer replicate themselves independently. They concluded that evolution was characterized by a general trend towards increased complexity (12, 13). Each transition yields a new level of organizational complexity that exhibits emergent properties (18).

Humans not only represent a "major transition" in evolution, but the first such transition based on changes in neuronal rather than genetic information. Neuronal information exhibits different properties from that of genetic information. These properties reflect the origin of the former, which evolved >500 mya as a *temporary* form of information—to be acquired and discarded by the organism as necessary to adapt to environments comprising many unpredictable elements. Although lacking in sponges, neuronal information is collected by all other known metazoans, primarily to cope with other metazoans (19).

Neuronal information may be manipulated more freely than genetic information and therefore offers wider possibilities for computation (10). More complex systems are less predictable, and may require enhanced computational abilities to reduce unpredictability (or entropy). Moreover, while genetic information is constrained with respect to the materials into which it may be translated (i.e., amino acid chains and their products), neuronal information may be translated into any conceivable material or form (e.g., chipped stone, vacuum tubes) though human hand function or its technological extensions.

Language as Information Technology

The starting point for a discussion of how the cognitive faculty of "discrete infinity" might have evolved in humans is a focus on language as computation rather than communication.

Chomsky and colleagues stress a fundamental distinction between language "as a communicative system" (i.e., transmitting information from one brain to others) and "the

computation underlying this system" (i.e., the manipulation of information units). Discrete infinity is a property of the latter, and Chomsky has suggested that "the use of language for communication might turn out to be a kind of epiphenomenon" (20). Indeed, it is easier to explain how language evolved as computation than it is to explain how it evolved as communication.

How does language function as a computational system? Words generated in spoken form (or in imagined form as "virtual sounds" in the head) provide "cognitive scaffolding" in the same way that abacus beads help the brain keep track of numerical computations (21). Phonemes and morphemes are higher-order information units, created by the firing of many synapses (i.e., the fundamental information units of the brain). Even in the form of virtual sounds, they represent perceptible "objects" (i.e., discrete units) that may be manipulated as if they were material objects outside the brain. Modern humans evolved a faculty for recombining a finite set of these spoken or imagined objects into a potentially infinite variety of hierarchically-organized arrangements (i.e., discrete infinity). Language is therefore the original information "technology."

Bickerton suggested that the language of modern humans was preceded by a simpler, non-syntactic form (or "proto-language") comparable to that of a two-to-four-year-old child or a pidgin (22). If so, the sounds of proto-language would have been a logical source for the "objects" that are manipulated as higher-order information units by modern humans, although some argue that manual gestures are likely to have played an important role in early human communication (23, 24). Brain-imaging studies reveal significant overlap between areas activated for speech and sign-language in living

humans (25). In any case, early human communication may have been a pre-adaptation for the enhanced computational faculty of modern humans.

An emphasis on the computational functions and "technological" character of syntactic language may explain the most significant neuro-anatomical change in humans since the appearance of *Homo sapiens*. This is the size increase (absolute and relative to the neocortex) of the cerebellum, accompanied by an overall decrease in brain volume, that occurred after the dispersal of modern humans (26, 27).

Syntactic languages exhibit a significant amount of redundancy. Modern English, for example, is estimated to be roughly 50% redundant (16). The redundancy of natural language reflects its communicative role, and the fact that when messages are transmitted from source to destination, they often are exposed to "background noise" that may cause information loss. The same principle applies to messages transmitted through electric or electronic communications technology, which also must incorporate a significant amount of redundancy to ensure successful transmission (14). Why didn't humans evolve a more efficient system of computation? The answer presumably is that having different systems for computation and communication is even less efficient.

A focus on the computational aspects of language also helps explain how it evolved. This is because it is difficult to account for the transmission of information from one individual to another, unrelated individual in terms of Darwinian selection (i.e., how does transmitting the information benefit the transmitter?). In the case of alarm calls among some birds, it appears that the caller benefits at least as much as the recipients of the alarm, while the sometimes complex information transmission found in many social insects has evolved among siblings (i.e., through inclusive fitness) (28).

Humans routinely transmit substantial amounts of information to non-siblings, and their use of language in this context is hard to explain, either in terms of net benefits to the transmitter or in terms of inclusive fitness. Sometimes individuals *exchange* information with others, and this could be accounted for the development of reciprocal relationships among non-relatives (discussed below) (29). However, the evolution of syntactic language is more simply explained as Darwinian selection for superior computational powers in individuals. This is especially true because it is apparent from the fossil record that the faculty of discrete infinity did not require any measurable increase in the number of neurons (i.e., did not incur added energy costs). Moreover, following Dunbar and others, selection for enhanced computational skills is more plausibly attributed to competition within human social groups for mates and friends (i.e., the ability to predict and manipulate the behavior of others) than it is to environmental factors (also discussed below) (30).

Complex Artifacts and Discrete Infinity

In addition to the sounds and signs of a hypothesized "proto-language" in early humans, a logical source of syntactic language, when viewed in its capacity as a computational system, is the cognitive faculty—and associated motor skills—for generating *complex artifacts* in the form of composite tools and weapons. It exhibits parallels with the cognitive faculty of discrete infinity, especially when language is cast as a form of information technology (31). The archaeological record reveals that a large-brained form of *Homo* was making complex, hierarchically-organized, artifacts no later than 0.5 mya

(32), and they precede both the appearance of the modern human anatomical pattern and evidence for discrete infinity by several hundred thousand years.

Although intact examples of complex artifacts are unknown before 15 ka, their presence is reliably inferred from microscopic traces of hafting wear and adhesives (e.g., pine resin) on the stone blanks. Stone-tipped spears and hafted scraping/cutting tools—more effective and energy-efficient than wooden spears or stone scrapers—were composed of three or four components, each representing a different type of material and each requiring a different sequence of production steps. The sub-components were assembled into a hierarchically-structured composite tool or weapon (33, 34). The stone blanks were themselves manufactured to a pre-conceived size and shape with a hierarchically-organized prepared-core procedure (reconstructed through core-reduction sequences) (35).

Before the appearance of complex artifacts, human technology was *reductive* (although it may have included *combination* of elements). Flakes or fragments were removed from larger pieces of stone and—presumably—wood and other plant materials were modified. The reductive character of technology before 0.5 mya also applies to the large bifaces or handaxes, which were being made by 1.7 mya (36). Although initially crude, large bifaces eventually were produced through a three-stage process that rendered a preconceived ovate form in three dimensions (37).

Large bifaces are a likely precursor to prepared cores, and they also represent a logical step towards composite tools. They reflect the development of neural pathways and associated motor functions for translating neuronal information to complex patterns in the form of shaped stone objects. There is a parallel in the evolution of neural

pathways and connected motor functions for the elaborate (hierarchically constructed) courtship songs of birds and other animals (38), and the cognitive architecture that evolved to produce bifaces conceivably was a preadaptation for the translation of neuronal information to complex structures with functional properties (i.e., composite tools and weapons) and other forms of information (i.e., language).

Although they often were used as tools, it is unclear if the ovate shape of the bifaces contributed to their function. An alternative interpretation is that they were patterned arrangements—material/object *displays* based on a pattern that lacked information content, as well as any functional properties, and analogous to a courtship song (39). If so, they could represent an artifactual analog to Darwin's hypothesis for the origin of language. Darwin suggested that language (and music) was ultimately derived from elaborate courtship songs of early humans (40).

In any case, the emergence of complex artifacts is one of most significant developments in human evolution, and may represent what Maynard Smith and Szathmáry termed a "major transition" (12, 13). In contrast to earlier human technology, as well as all nonhuman technology, complex artifacts reflect the translation of a large body of hierarchically-organized neuronal information to structure. They are analogous to the translation of genetic information to structure in the form of protein enzymes and higher-order biological structures, including organisms (transitions #3 and #4 in Maynard Smith and Szathmáry's list). The design templates for composite tools and weapons were shared among social groups and transmitted from one generation to the next (i.e., were replicated at the composite artifact level).

Homo Socioecology and Evolutionary Change

Most, if not all, of the changes in how *Homo* stored, transmitted, translated, and computed information are plausibly attributed to the selection pressures of a competitive social environment. The linkage between competition for mates and friends on the one hand, and the collection and manipulation of neuronal information on the other, is important to explaining the evolution of the cognitive faculties that are unique to modern humans.

To begin with, humans are among the small percent of mammals (~3%) that form long-term pair bonds between males and females (41, 42). Pair-bonding selects for special skills related to establishing and/or maintaining a cooperative bond between non-sibling males and females over a period of many years. The skills include various forms of cheating, as well as the ability to detect and limit cheating by the opposite sex. Pair-bonding probably has driven both the expansion of information storage and computational faculties in males and females (43).

Other mammals, including a close relative (i.e., gibbons), have evolved pair-bonding without also evolving syntactic language and other unique cognitive faculties, however. A more important feature of human sociality is the formation of cooperative networks among non-relatives (42, 44). Noting a significant correlation between neocortex volume and social group size in primates, Dunbar suggested that selection for social networking skills drove the substantial increase in human brain size after 2 million years ago ("social brain hypothesis"). He argued that enhanced computational abilities, as well as expanded memory storage capacity, were the result (30).

The development of cooperative networks within large groups with a relatively low mean coefficient of genetic relationship—which is found in all human societies, including recent hunter-gatherers—apparently created an unstable evolutionary strategy or phenotype (as opposed to an *evolutionarily stable strategy* or ESS) (45). The phenotype was cranial volume, which underwent continuous or nearly continuous expansion after 2 mya. The evolutionary instability was created by the networks, which could sustain themselves only the maintenance of long-term reciprocal ties among their members (outside sibling and parent-offspring relationships). Reciprocity should select for individuals who manipulate the relationships to their advantage (i.e., for "Machiavellian intelligence"), which apparently was reflected in cranial volume (30, 46).

How and why did the networks of non-relatives evolve in the first place? The most plausible answer is that early humans established both pair-bonding and reciprocal exogamous mating networks as part of a social foraging adaptation to habitats containing scarce and unpredictable resources. In such habitats, females cannot forage both for themselves and their offspring, and require a long-term investment in the latter from their mates. Foraging "search time" is too high for the pair in isolation, however, and only pairs that establish reciprocal bonds to pool information about resource locations can reduce search time to a viable level (47).

The honeybee evolved an information-sharing foraging adaptation to the temperate zone, where resources were scarcer and less predictable, but did so as a super-organism (i.e., without the need to maintain reciprocal relationships) (48). The shift to pair-bonding and reciprocal mating networks in humans probably coincided with their colonization of the temperate zone after 2 mya. Reduced sexual dimorphism is a reliable

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indicator of pair-bonding, and began to decline in *Homo* at this time (49). It is more difficult to establish the presence or absence of reciprocal networks in early humans, but there is indirect evidence for transmitting information at this time (i.e., expanded Broca's area in the 1470 endocranium) (50).

The Evolution and Dispersal of Modern Humans

Modern humans are derived from a large-brained species of *Homo* that was present in Africa before 500 ka and dispersed to Eurasia, where it evolved into at least two regional forms, including the Neanderthals (51). Often referred to as *H. heidelbergensis*, this species shares many features with *H. sapiens* that distinguish both from earlier forms of *Homo*. Although lacking the diagnostic cranial features that define modern humans, brain volume was comparable to that of living humans in sub-Saharan Africa (~1250 cc). *H. heidelbergensis* translated neuronal information to complex artifacts (i.e., composite tools and weapons). Analysis of ancient DNA from the remains of a group of Neanderthals recovered from one site in Europe indicates the likely presence of exogamous mating networks similar to those of living humans (52), which, in turn suggests an origin in their last common ancestor (if not earlier).

Both anatomically and behaviorally, however, *H. heidelbergensis* was not a modern human, and the primary difference is the absence of evidence for discrete infinity or recursion in the former. The difference is magnified in the archaeological record of *H. sapiens* because discrete infinity was and is applied to the: (1) probably pre-existing capacity for translating neuronal information to patterned designs that lack both information content and functional properties (i.e., sexual and social displays); (2) pre-

existing capacity for translating neuronal information to structure with functional properties (i.e., complex artifacts); and (3) probably pre-existing capacity for translating neuronal information to another form of information (i.e., non-syntactic language or "proto-language"). The latter is supported by the presence of the same FOXP2 allele in Neanderthals and living humans, again suggesting an origin in the last common ancestor, if not earlier (53).

Ultimately, the consequences were explosive, yielding a rapidly expanding body of material in the archaeological record comprising: (1) personal ornaments and decorated objects (i.e., patterned arrangements that probably lack both information content and functional properties) (54, 55); (2) visual art (analog information translated from digital neuronal information) and notation (digital information analogous to language units, translated from neuronal information) (56, 57); and (3) complex technology (based on the translation of neuronal information to analog structure) (58). In each category, the property of discrete infinity is expressed by novel recombination of information units, often on multiple hierarchically-organized levels, and the potential for infinite variations of recombination is evident.

Discrete infinity evolved because it conferred a significant increase in computational power on individuals in a competitive social setting. Individuals with this faculty were better able to manipulate the complexities of marriage and friendship to their long-term reproductive advantage (i.e., they reduced the unpredictability of these relationships). The other consequences of discrete infinity, however significant, as applied to the translation of neuronal information to patterned arrangements, other forms of information, and structure were—to borrow Chomsky's term—"epiphenomenal" (20).

Both the time and place in which modern humans evolved, i.e., after 500 ka in sub-Saharan Africa, reflect the likely role of brain volume in the process. By 500 ka, brain volume in *Homo* had reached what appears to be an optimum level for the equatorial zone. Subsequent increases in cranial volume in the African population probably exceeded this level (as indicated by later reductions in cranial volume) with respect to thermo-regulation and possibly other constraints on size. Although the same constraints were present in the north Eurasian population, the threshold for thermo-regulation was significantly higher, given low mean annual temperatures (49, 59, 60). A capacity for discrete infinity—which apparently entailed neuro-anatomical changes in organization rather than further increases in brain volume—evolved in a population that had reached, and even exceeded, the limits of cranial expansion.

The neuro-anatomical changes that underlie the upgrade in computational function seem to have little or no visibility in the fossil record. They may eventually be teased out of comparative analyses of the autosomal DNA of *H. sapiens* and Neanderthals/Denisovans. In theory, the latter should lack one or more critical substitutions (perhaps in Human Accelerated Region 1) that code for brain development related to information processing (61). The locus of any important changes in cognitive function in modern humans seems likely to be the prefrontal cortex, which functions as a center of integration and is implicated in novel task performance (62).

Arriving at a more precise estimate of the timing of the changes remains difficult because their visibility in the archaeological record also is somewhat limited, especially before 50 ka. A capacity for recursion clearly antedates the movement out of Africa (which is estimated at ~55 ka on the basis of mtDNA) and also must precede the dispersal

throughout Africa (estimated at ~135 ka on the basis of mtDNA). The latter is close to the more conservative age estimates on anatomically modern human fossils in Africa (~150 ka) (1, 2).

A striking consequence of the application of discrete infinity to making artifacts was the dispersal of the innovators throughout Africa and subsequent spread into Eurasia and Australia. While composite artifacts may have played a role in the earlier expansion of *H. heidelbergensis* out of Africa, the ability of *H. sapiens* to design its own traits with translated neuronal information (e.g., tailored clothing, small-mammal traps, throwing darts) ensured a rapid global dispersal (11, 58).

Homo sapiens: A New Level of Organizational Complexity

Homo sapiens represents a level of organizational complexity above that of the organism. This level of complexity does not correspond to the super-organism, but emerges from the collective activity of multiple human brains (or *super-brain* [47]).

A super-brain is a neuronal information system above the level of the individual brain. It may be compared with a sexually reproducing population, which represents a genetic information system above the level of the individual organism. While the latter is weakly integrated (i.e., the flow of information within the system is constrained), a super-brain can evolve a relatively high level of integration, reflecting the properties of neuronal information.

"Emergent properties" often are attributed to the individual human brain (and may be attributed to any metazoan brain), but its organization is at the level of the organism, or more specifically, the organ within the individual organism (63). The human super-

brain is based on the flow of information among multiple brains within social groups (and now weakly integrated on a global or species-wide level). In individual brains, information is stored and manipulated in the neuronal networks (i.e., neuronal information), but it is translated to other forms for transmission to other brains.

A super-brain also evolved in the honeybee. Neuronal information in individual brains concerning resource locations or potential nest site characteristics is translated to body movements ("dance") for transmission to other brains, and computations among a swarm regarding potential nest sites are performed collectively (64, 65). The honeybee colony and swarm is a super-organism, however, and its super-brain functions as a component at this organizational level (12, 13).

If early humans evolved a proto-language (e.g., to transmit information regarding resource locations after 2 mya), they would have evolved a super-brain above the level of the individual, including the individual super-organism (47). If early human groups made collective decisions with shared information (like honeybees and modern hunter-gatherers), their hypothesized super-brain would have possessed computational functions.

The modern human super-brain is a relatively well-integrated neuronal information system. Large amounts of hierarchically-organized information flow from one brain to others by being translated to spoken language or other forms of information. The modern human super-brain transcends the individual brain in time, as well as space, because information flows through generations and across thousands of years. And because multiple individuals manipulate the same information sets (e.g., the data and concepts discussed in this paper), it exhibits collective computation. The super-brain cannot replicate itself at the level of the individual brain.

Homo sapiens and the Evolution of Information

Another feature that distinguishes modern humans from most other organisms is the generation of new forms of information. And *H. sapiens* has created new ways of storing, transmitting, and translating various forms of information, as well as new ways of manipulating information (i.e., computation). For the most part, the new forms of information have played the same role in the lives of modern humans that genetic and neuronal information have played in the evolution of living systems: the reduction of uncertainty in the environment, including the social environment (10, 17).

H. sapiens also has employed its computational powers to create a new category of information that probably has no precedent in evolutionary biology. While the genetic and neuronal information accumulated by other living systems invariably pertains directly or indirectly to their environment, modern humans recombine neuronal information units into arrangements that have little relationship to any environment (e.g., imagined people and places in novels or paintings). This faculty reflects the power of discrete infinity for constructing a potentially infinite variety of alternative possibilities in a complex and unpredictable world.

Neuronal information evolved in the early metazoa, apparently a response to the increasing complexity and unpredictability of environments (due primarily to other metazoans) (19). Although other new forms of information may have evolved among now extinct metazoa that lack visibility in the fossil record, the only known examples that antedate *Homo* are found among the honeybee, which translates neuronal information to body movements for transmission to the brains of other bees, and among vervet monkeys,

which translate neuronal information concerning specific types of predators, to vocalizations (64, 66).

Early *Homo* is widely believed to have evolved one or more new forms of information, but they have no visibility in the fossil record and remain hypothetical. The new forms of information would have been the vocalizations and/or gestures (i.e., body movements) of a non-syntactic language (or proto-language). The strongest evidence for proto-language is the 1470 endocranium (*H. habilis*) from East Africa (50, 67), but it also may be necessary to explain how early *Homo* groups were able to forage in less productive environments after 2 mya (47).

Assuming the presence of a proto-language, the evolution of a capacity for discrete infinity—which underlies syntactic language—yielded a new process of computation but probably not a new form of information. The latter does not materialize in the archaeological record until after 50 ka with the appearance of two- and three-dimensional representational art (analog) and notation in the form of marks engraved on bone and other materials (digital) (56, 57). Earlier evidence of discrete infinity is confined to patterned arrangements that probably lack information content (e.g., abstract design, ornamentation) or complex artifacts (55, 68).

The new forms of information were the first created with human tool-making skills and the first produced by manipulation of neuronal rather than genetic information. Notation presumably was used as a computation aid, as it is today. Unlike neuronal information, notation offers a non-volatile form of storage, but while units can be added and deleted ("scratched out"), they cannot be manipulated like counters or beads. Later examples (dating to less than 20 ka) may indicate more than one category of mark was

used and sequences of marks were organized hierarchically (56, 69). Representational art was an entirely novel form of analog information used to transmit messages, as it is today. Unlike notation, it became an important part of human social life.

Novel forms of information also were created with the emergence of very large societies, beginning ~5 ka in North Africa and western Eurasia. The new forms of information exhibited properties similar to those of notation, but—like spoken syntactic language—also possessed the power of discrete infinity. They seem to have arisen in response to the greatly increased needs for information storage and transmission, as well as demands for higher-order computation, among complex societies. Written language and mathematics were used as information storage and computational aids (initially by a small class of specialists), but the former also was used to transmit messages and became a digital form of representational art. In Mesopotamia, writing was preceded by moveable mnemonic objects (similar to the earliest gaming tokens, which also appear about 5 ka), and both here and elsewhere (e.g., China), the first mechanical information technology was developed as a numerical computation aid (i.e., abacus) (70, 71).

The invention of moveable type and printing in Europe (1455) represented less a new form of information and more a novel means of transmitting written language and mathematical symbols. An equally significant development was the mechanical clock (1092 in China and ~1250 in Europe), which was the first self-acting piece of mechanical information technology and a general model for the machines of the industrial revolution. The latter included the first calculating machines (1600s) and the first software, which took the form of punch cards used to program the Jacquard loom (1801) (72, 73).

The first attempt at a mechanical computer was undertaken during the early 19th century (i.e., the Analytical Engine of Charles Babbage), but the advent of information in the form of transmitted electromagnetic pulses (i.e., the telegraph), which has been described as "proto-digital," had much greater impact. Electric and electronic technology was employed in early and mid-20th century to create new forms of information for analog and digital computers. The vacuum tube, which mimics the neuron as a volatile information storage device, but may be used to manipulate both analog and digital information, was adapted for early prototype computers in the 1950s. It was soon replaced with the transistor, installed on a silicon chip, which offered more reliable and non-volatile storage of information in electronic form (73, 74). Operating independently, and later networked together like the super-brain, electronic digital computers have significantly expanded information storage capacity and computational power outside the brain. The most recent form of newly created information is the carbon nanotube (75). The property of discrete infinity has not yet been replicated technologically (76).

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