# Chapter 3
# The Long-Term Evolution of Social Organization

**Sander van der Leeuw, David Lane and Dwight Read**

## 3.1 Introduction: Linking the Dynamics of Innovation With Urban Dynamics

In the first chapter of this book, David Lane et al. point out that the Darwinian approach to biological evolution is insufficient for the description and explanation of the cultural and social transmission of many, if not most, of society's characteristics. Instead, the chapter proposes that we shift from 'population thinking' to 'organization thinking' to understand socio-cultural phenomena. In essence, such thinking focuses on the role of information in shaping institutions and societies. In the second chapter, Dwight Read et al. outline a crucial stage in the evolution of human societies, which they call 'The Innovation Innovation'. It concerns the beginnings of information processing by (small-scale) societies about societies. They outline, in a few steps, how human beings may have developed a conceptual apparatus to describe and to manage their own bio–social (kinship) relations. The main innovation in this story is the capacity to abstract from substantive observations of such relationships to concepts that encapsulate the underlying structure of these relationships.

The current chapter continues the story, outlining how the innovation innovation transformed the world of our distant ancestors into that in which we live today. It focuses on the relationship between people and the material world, as it is the material world that has been most drastically, and measurably, transformed over the last several tens of thousands of years. In view of what we know about such distant periods, and in view of the space allotted to us here, it will not surprise the reader that we do so in the form of a narrative that is only partly underpinned by substantive data.[1] We emphasize this because we do not want to hide from the reader

S.E. van der Leeuw (✉)
School of Human Evolution and Social Change, Arizona State University, P.O. Box 872402, Tempe, AZ 85287-2402, USA
e-mail: vanderle@asu.edu

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[1] Nevertheless, we have referred the reader to other literature where that seemed appropriate.

D. Lane et al. (eds.), *Complexity Perspectives in Innovation and Social Change*,
Methodos Series 7, DOI 10.1007/978-1-4020-9663-1_4,

the speculative nature of the story that follows. Yet we firmly believe that, in very general terms, this scenario is correct, and that further research will vindicate us.

We first give examples of the kinds of abstractions, and the hierarchy of conceptual dimensions necessary for prehistoric human beings and their ancestors, to conquer matter, i.e. to conceptually understand, transmit and apply the operations needed to master the making of a range of objects made out of stone, bone, wood, clay and other materials. Some of the abstractions that had to be conceived in this domain resemble those that Read et al. refer to (and may therefore have been transposed from one domain to another), while others apply to this domain alone, and had to be truly 'invented'. It is then argued that such 'identification of conceptual dimensions' is a process that underlies all human activity, and we look a little closer at how that process relates to invention and innovation.

Lastly, we shift our attention to the role of innovation, information processing and communication in the emergence of social institutions, and in the structural transformation of human societies as they grow in size and complexity. In particular, we look at the role that problem solving and invention play in creating more and more complex societies, encompassing increasing numbers of people, more and more diverse institutions, and an – ultimately seemingly all-encompassing – appropriation of the natural environment. To illustrate this development we will focus on the origins and growth of urban systems, as we have done for the ISCOM project as a whole.

## 3.2 Why did it Take Us So Long to Become Inventive?

Human beings and their precursors have lived on this Earth for several million years. In their current guise (*Homo sapiens*), they have roamed over its surface for around 195–160,000 years. For the great majority of that long time-span, our species moved around in small groups, using very basic tool-making techniques to ensure modest success in defending itself and obtaining the necessary foods for its subsistence. Although there are clear signs of innovations from at least 50,000 years ago, the rate of innovation increased dramatically from about 10,000 years ago. From that moment on, in a relatively short time, human beings have managed to upend the balance between themselves and their natural environment, and gain something approaching control over many environmental processes. The history of our species therefore raises three interesting questions:

1. How did the species survive for so long with a minimal toolkit to defend and nourish itself, and under a wide range of natural circumstances?
2. Why did it take so long to 'invent' and accelerate innovation?
3. Why did innovation increase so rapidly, once that point was reached?

Clearly, the long-term survival of the human species depended, and depends, on the adequacy of human behavior with respect to the environment. Most human behavior was of course routine, and well-adapted to known circumstances, but whenever people encountered unknown phenomena, they initially suffered until they learned how to deal with them. If that took too much time, the consequences were dire. Learning and adaptation constituted the key to survival (as they do now!).

For much of human history adaptation was favored by the fact that people lived in small groups, had an essentially mobile lifestyle, and roamed over large territories. Their capacity to extract the necessary resources for survival may have been lower than at present because highly efficient extraction technologies were not available, but the small size of the groups and the large size of groups' territories made it possible to gather sufficient food to survive on, and the mobility ensured that if a group could not do so in one place, it had a good chance of finding another, better, location before it was too late.

All in all, for a very long time, human populations thus lived within fairly narrow constraints, surviving on whatever the land offered and moving on when that was not enough. The major areas of invention and innovation concerned the immediate interface between people and their environment: tools and procedures to enhance the impact of human actions, and to extend the range of resources that could be used. Examples of such innovations are the control over fire, the manufacture of clothing and weapons, the construction of shelter, etc.

However, that does not explain why this way of life persisted for so long. If, in the last 10,000 years, the species managed to increase so dramatically the rate of innovation, why did it not do so before? One could argue that external perturbations forced the species to accelerate learning, invention and innovation. But, if external perturbations are at the origins of the acceleration of invention, why did this not happen during earlier or later periods of (often much more drastic) transformations of the external circumstances under which human societies lived? And why, once the threshold had been crossed, could invention and innovation accelerate exponentially, independent of external circumstances? There must have been other factors at play.... It seems to us that the answer to both these questions lies in the fact that achieving a certain level of development of the human conceptual apparatus was the necessary and sufficient condition for the acceleration of invention and innovation. The next section of the current chapter will be devoted to answering the second of the three questions: "Why did it all take such a long time?" (cf. Wobst, 1978).

## 3.3 The Earliest Tool-Making and the Conceptualization of Three Spatial Dimensions

In the last chapter, Read et al. called this threshold "the innovation of innovation," and argued that, in the realm of kinship relations, crossing it essentially entails attaining the capacity to abstract and generalize locally-made observations to a much wider realm that includes unobserved situations. Here, we are going to extend that argument to the domain of the relations between people and matter, because *in this realm, we can assign dates to some of the steps involved, and we can thus substantiate the claim that it did indeed take a very long time to innovate innovation*. In the process, we will point to the invention of other conceptual dimensions and operators that were needed to 'conquer the material world'.

For most of human history, there is only one category of artifacts that allows us to monitor the development of human cognition: flaked stone tools. In what follows, we will base ourselves on Pigeot (1992), as well as on a more extensive paper one of us has written on this topic some years ago (van der Leeuw, 2000). Pigeot has presented us with an outline of the development of human cognition as reflected in the ways and means for knapping stone tools. In essence, she argues that one may distinguish five stages in the development of the techniques to make stone tools: the conceptualization of (1) the point, (2) the angle, (3) the edge, (4) the surface and finally (5) the volume (Figs. 3.1–3.4).[2]

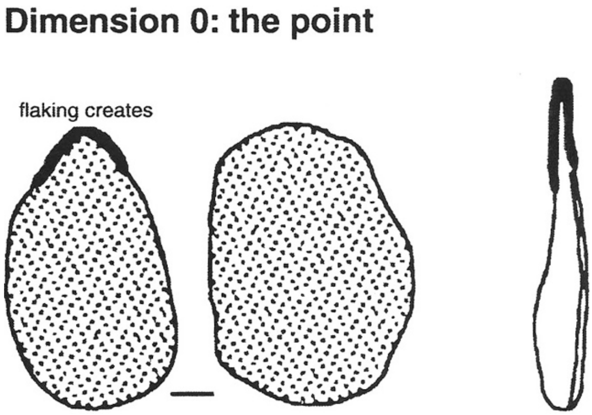

**Fig. 3.1** The cognitive capacities of the preliminary stage (after Pigeot 1991)

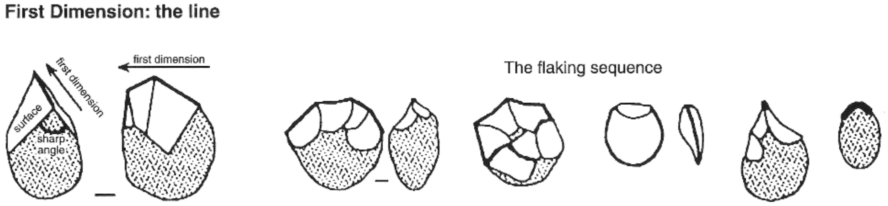

**Fig. 3.2** The cognitive capacities of the first stage (after Pigeot 1991)

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[2] Inevitably, since the publication of this paper, colleagues have disputed some of its finer points of technology, as well as the relatively simple chronological sequence in which Pigeot cast the ideas. But for the purposes of our argument here, these points are less relevant than her final conclusion – that by the end of the Paleolithic, flint-knappers had mastered the conceptualization of objects in three dimensions.

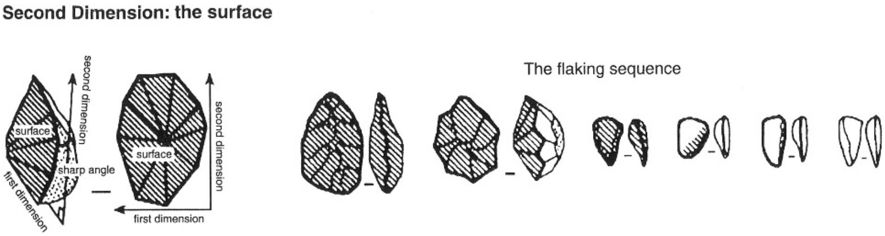

**Fig. 3.3** The cognitive capacities of the second stage (after Pigeot 1991)

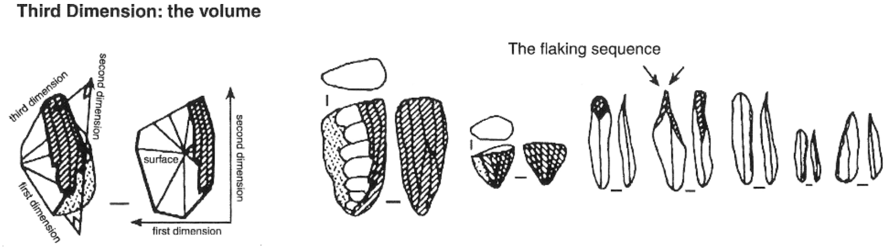

**Fig. 3.4** The cognitive capacities of the third stage (after Pigeot 1991)

## *3.3.1 The Concept of Points: The Very Earliest Tools of Primates and Humans*

Fundamental for all deliberate tool making is the capacity to invert causal sequences in the mind (“A causes B, therefore if I want B to happen, I have to do A”), transforming an observation into a deliberate action (e.g., Atlan, 1992). Humans share this capacity with many primates. Both are therefore theoretically able to manipulate (aspects of) the material world.

Primates and early humans use stone tools both actively (as hammers, or as objects to throw) and passively (as an anvil, for example). These uses may be combined, for example, in cracking nuts or bones. Like human beings, primates are therefore aware of certain properties of their tools, such as their weight, their hardness and their resistance to shock, as well as of the motions they can execute with them.

Finally, primate tools and the earliest human tools are very much alike. Both show the impact of blows, because flakes have been struck off at that point, which in turn indicates that the angle at which these stones hit each other was smaller than 90°. But there the similarities end. Primates never learned to conceptualize either the *point as an abstract object*, or the *angle as a relational concept linking two lines or planes*. As a consequence, they are not able to deliberately shape the tools they use. In this, they are different from (proto) humans.

### *3.3.2 Thinking in One Dimension: Edge Tools*

As early as two million years ago, the first collections of broken pieces of stone are identified as tools. Although it is not sure that they have actually been deliberately shaped, they share one feature: that of a (cutting) edge. To make such objects deliberately is presumably a sign that some conceptual capacities have been developed. The first such tools, the so-called choppers and chopping tools, show that several adjacent flakes have been removed deliberately by hitting the stone with another one. In each case, the toolmaker focused on sharpening only (part of) the tool's edge. In so doing, he followed the original shape of the stone; there is no attempt to achieve control over the whole shape. Nevertheless, the alignment of blows shows a degree of deliberation and choice in the way stones were hit, and shows that tool preparation has moved from a point-based conception towards a line-based conception (Fig. 3.1). Moreover, the fact that, at this point in time, both one-sided and two-sided flaking occurs, confirms that the angle has been conceptualized. The edge occurs where it best suits the natural form of the pebble.

Finally, although both the object from which a flake was removed and the flake itself may be used in further actions, from the toolmaker's perspective they are viewed differently. The former may be further modified by flaking, and is therefore the true object of the toolmaker's attention, while the latter is not – it is a by-product rather than an object.

### *3.3.3 Thinking in Two Dimensions: Surface Tools*

At some point in time, our ancestors extended their linear conception of tool-making by removing flakes all around the edge of a pebble or stone, making what Pigeot calls 'discoïdal tools.' By thus closing the knapped line onto itself, they implicitly defined a plane or surface. The next conceptual step concerned the transition from defining a surface by instantiating its perimeter to defining an edge by instantiating the surface within it, transforming such tools from objects consisting of an edge flanked by two planes into objects consisting of two planes between which one finds an edge. Identifying the transition is a question of reconstructing the sequence in which the tool is made: has the maker first sharpened the edge of the tool and then taken large flakes off both surfaces, or has he done the reverse? In practical terms, this does not change the shape much, or the function or the effectiveness of the resulting tool, but the conceptual step is a major one for the toolmaker. It implies a move from a tool conceived in terms of one-dimensional conceptual objects (edges) to one conceived in terms of two-dimensional conceptual objects (surfaces). Once that step has been taken, tool making becomes inherently a matter of dealing with surfaces. Around 250–300,000 years ago, this leads to the development of a special technique (called 'Levallois,' see Pigeot, 1992, p. 184–186, and Fig. 3.2) in which the removal of one flake is at the same time the preparation for the removal of the next one. In the process, the makers substantively increased control over the shape of their products.

### *3.3.4 Thinking in Three-Dimensions: Tools Conceived as Volumes*

Whereas the Levallois technique exploits the stone by knapping on two crosscutting planes and creating flake tools with one edge where two planes meet, the Upper Paleolithic knappers work at the intersection of *three* planes. They create long blade tools with three edges, at each of which two out of the blade's three planes meet (Fig. 3.3). The Upper Paleolithic nucleus is thus a volume in the true sense; it is prepared in different ways, but it always consists of three crests that guarantee an optimal exploitation of the nucleus because the flaking reduces the volume everywhere in turn (Boëda, 1990). Pigeot adds that the volume that is thus defined is exploited on the smaller of its surfaces, so that the volume literally is more important than the surface, and the management of the core volumetric rather than planar. A volumetric conception of tool manufacture is attested in the Gravettian and Magdalenian traditions (c. 27,000 and 13,000 years ago, respectively). It is conceptually and economically very efficient, and it involves the simultaneous mastering of new knapping techniques, such as soft percussion flaking, which increase control over the way flakes and blades are removed from the core. As a result, a completely new range of small blade-based stone tools is invented (see below).

### *3.3.5 What are the Conceptual Advances So Far?*

Depending on when one assumes the above collective learning process to have started, it seems to have taken human beings and their ancestors one to two million years (or more) to achieve true volumetric conceptualization of the manufacture of stone tools. At that point in time (say, 20,000 years ago), they acquired the capacity to conceive of *each volume as constituted of an infinity of surfaces, each surface of an infinity of lines and each line of an infinity of points, and vice versa*. This has important implications. As long as the object (tool or flake) is conceptualized in fewer than three dimensions, but in reality exists in all three, full manipulation of matter is impossible. It is only when all three dimensions of material objects are conceptualized that full control can be achieved over the making of stone tools. A threshold is thus crossed, which, from this time onwards, allows for a major acceleration in the development of human control over matter.[3]

But in the process of acquiring the capability to conceive of and to make stone tools in three dimensions, our ancestors had also acquired a number of other conceptual tools. One of these is the *capacity to plan and execute complex sequences of actions*. As long as individual flakes are being removed from a tool to create an edge that follows no predetermined pattern (as is the case for many of the earliest tools), there is little or no anticipation. The controlling feed-back loop at most relates the removal of a flake *to the past*, to the removal of the last one. And even when the edge comes full circle, the result of blow $n+10$ is rather under–determined by the result of blows n to $n+5$ (Pigeot, 1992, p. 182). When the Levallois technique is

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[3] For an extended discussion of the above developments, as well as those pointed to in the next few pages, see van der Leeuw (2000).

introduced, this approach changes radically. Now, the knapper has to look several steps ahead *into the future* in evaluating the results of past actions, so that each removal prepares the way for future steps. Initially, the span of such control loops[4] is relatively short. However, in the case of the industries that use a truly volume-based approach, the preparatory phase is quite elaborate, involving the creation of a strike platform, as well as the preparation of the surfaces from which the blades are to be removed. Once all that is done, the blades are removed one after the other without intervening reshaping. From the sequencing point of view, this implies a stringent separation between 'preparation' and 'exploitation' of the raw material. The Levallois technique is thus an early instance of a *manufacturing sequence in which the total process is divided in different phases that are not interleaved*. Being able to conceive and manage such sequences in turn testifies to the fact that the toolmakers developed the conceptual capacity to link different steps in a process together in such a way that one might speak of a plan. Their repeated use of the different knapping sequences has made it possible to identify the steps involved, and, to some extent, the cause-and-effect relationships between them. But what does this require at the conceptual level?

To *identify* cause-and-effect one must have inserted a control loop between observations and conceptualizations. To *(re)create* a transformation at will, the individual must be able to retrieve the whole sequence associated with the desired result, to 'wind it back' to its beginning, and to 'replay' it in the appropriate order. To *understand and manipulate* the dynamics of cause and effect, the individual must be able to play such sequences backwards and forwards in an interactive way and to retrieve (parts of) sequences that are associated with any of the stages of transformation or actions concerned. Moreover, such understanding also requires the capability to observe differences between manufacturing sequences, and to generate variations by mentally or physically inserting operations or modifying them. *That in turn requires the capacity to mentally associate different strings of events, for example, on the basis of an assessment of similarities and differences between the transformations and/or the products at certain stages*. It requires full conceptualization of all the steps and their interconnections, hidden and apparent, so as to be able *to anticipate all different parts of the manufacturing sequence*, and to create the right conditions for them to be implemented and controlled.

## 3.4 Creating a New Material World

From around 12,000 years ago, we clearly observe a drastic acceleration in the speed of invention and innovation. Many new categories of artifacts emerge, new materials are used, new techniques are introduced, and new ways to deal with aspects of the material world are 'discovered' in a comparatively short time – a span of a few

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[4] We will here use the term "control loop" instead of the more common "feed-back" or "feed-forward" loop because it seems to us that feed-back and feed-forward are always combined in monitoring the actions undertaken as part of a manufacturing sequence.

thousands of years. The acceleration is so overwhelming, that in that time-span, the whole way of life of many humans on earth changes: rather than live in small groups that roam around the Earth, people concentrate their activities in smaller territories, they invent different subsistence strategies, and in some cases, they literally settle down in small villages.

If we look forward in time from that point, the change is even more dramatic: within a couple of thousands of years more, people congregate in much larger groups, all kinds of new social institutions are instantiated, technological inventions explode and reach very different realms when people start building cities, communicate in writing, etc. All in all, it is clear that just before the beginning of the Neolithic, a threshold of innovativeness had been crossed. This section is in part devoted to the description of some of the conceptual tools acquired, but its aim is to answer the question what made this acceleration possible.

### *3.4.1 New Kinds of Tools in Stone, Bone, Wood, Etc.*

During the tail end of the Upper Paleolithic and the Mesolithic, we see a rather large number of important new techniques emerge almost simultaneously.[5] One such new development is the manufacture of a wide spectrum of smaller and smaller stone tools. These so-called '*microliths*' are very finely made, and show that the makers are extending their control over manufacture to finer and finer details, something that would not have been possible if these objects had not been conceived in three dimensions, and that the manufacturing sequences were planned in detail. It testifies to the *extension of the range of orders of magnitude of volume* manipulated by toolmakers.

As part of this process, we see an increasingly wide range of differently shaped objects, which implies that there is a increasingly close match between individual objects and the functions that they are meant to fulfill; that in turn suggests that tool-makers have acquired a *more versatile spatial topology*, and an improved capability to analyze the requirements their artifacts should meet in order to fulfill their intended function most effectively.

A closely related innovation is the introduction of *composite tools*, consisting of a number of microliths hafted together in objects of wood or bone. This phenomenon is interesting from the conceptual point of view, as it implies a certain *reversibility of scalar hierarchies*: not only are tools made by reducing a larger piece of stone into one or more small flakes, which are then retouched to give them the required shape, but such small pieces are assembled into something bigger.

Although it is unlikely that this moment represents the first use of non-stone materials as tools, one now observes the use of other materials (wood, bone, antler, etc.) alongside stone in new, composite, tools. Some of these tools fit the new, small

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[5] In archaeology, it is often very difficult to determine the sequence in which phenomena appear, in part because of either a lack of dates or because dates have a wide margin of error, but also because our record is often so fragmentary that it is very easy to miss the first manifestation of a phenomenon.

stone blades in larger objects made from bone, for example. The fact that such a wide range of new materials was used testifies in yet another way to the increasing innovativeness of human beings around this time, as it meant developing a wide new range of (motor and other) skills and tools to work all these materials.

### *3.4.2 The Introduction of Ground Stone Objects*

Alongside these newly emerging techniques, knapping of larger stone tools clearly continues. From about 10,000–7,000 years ago, however, these tools are transformed beyond recognition as toolmakers discover grinding. Grinding tools in the last stage of manufacture achieves much better control over the final shape and enables toolmakers to create shapes that until then had been beyond their capability. In many ways, this development caps and completes the mastery of stone-working at all scales. Objects such as Neolithic stone axes and adzes are first roughly flaked out of appropriately fine-grained blocks of stone. Next, they are refined, by removing smaller and smaller flakes. Finally, the toolmaker removes particles of infinitely small size by pecking or grinding. The resulting objects have a completely smooth surface, which can be as flat, rounded, or irregular as desired. *Control over the final shape is complete, as is the use of different scales of removal from the initial stone block – from very large flakes to individual grains*. That control leads, ultimately (in the British Late Neolithic, for example), to very highly standardized production of very large numbers of polished stone axes (cf. Bradley & Edmonds, 1993).

### *3.4.3 The Introduction of Containers*

The making of containers was invented anywhere between 12,000 and 9,000 years ago (depending on the material and the part of the world one looks at). Such containers occur in wood, leather, stone and pottery. In each case, the actual manufacturing technique is of course different, but the conceptual underpinnings are the same. They combine different innovations that emerge subsequent to three-dimensional conceptualization of artifact manufacture (van der Leeuw, 2000):

- The introduction of topologically fundamentally different objects, consisting of *solids around a void*. This requires the conceptual separation of the surface of an object from its volume, and making the distinction between outside and inside surfaces. Neither is conceivable in the absence of a true 3-D conception of objects.[6] In some parts of the world, gourds may have provided an example, and other natural containers may have served that function elsewhere. Nevertheless,

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[6] One craft in which the 'discovery' of such hollow shapes may have occurred is leather-working, where skins are removed from one kind of object (the animal), only to be transformed into another, differently shaped, object (the container).

the step from observing a natural object to re-creating it conceptually was an important innovation.

- The inversion of the sequence of manufacturing, *beginning with the smallest particles and assembling them into larger objects*. Basketry and weaving are examples of this. In each case, one assembles small linear objects (animal hairs or vegetal fibers) into longer and thicker ones that are subsequently assembled into two- or three-dimensional surfaces (cloth, baskets). Although in the case of pottery the smallest particles (the clay platelets) are found in nature, the earliest shaping techniques (coiling; shaping in a net) are closely related to basketry.
- One of the main advantages of such additive techniques over subtractive ones is the fact that one can *correct errors* by going one or more steps back in the procedure, making the correction, and then proceeding again. This presumes not only that control loops link the past with the present and the future, but also that, in this particular domain, *actions are conceived as being reversible*.
- In the case of pottery, the *separation between different stages of production* is also pushed a step further. Resource procurement, clay preparation, shaping, decoration, and firing occur one after another, and, during the whole manufacturing process, the maker has to keep all later stages in mind. The choice of raw materials, for example, is intimately linked to a pottery vessel's shape, function and firing conditions. Manufacture involves a large number of embedded control loops, and small variations early in the process do have major consequences later. It is therefore important that errors are easily corrected.

### 3.4.4 Inventing the Conceptual Tools to Conquer the Landscape

These conceptual advances also opened up completely new realms of problem-solving and invention, including the transformation of subsistence risks from a daily concern over which people had little control, to a seasonal or pluri-annual concern over which they had a little more control. That transformation was achieved by (1) a mobile lifestyle with the breeding and herding of domesticated animals, or the seasonal cultivation of wild plants, as principal subsistence strategy, or by (2) settling in one place, building houses, clearing fields, and cultivating domesticated plants.[7] In both cases, the result was *long-term human investment in certain aspects of the environment*, which cut off some hitherto existing options for flexible interaction with the environment, even as it opened up new opportunities for social and cultural development. As we will see, the concomitant 'inventions' are difficult to imagine without the conceptual changes in artifact manufacture that we discussed.

Gathering and hunting are essentially intermittent, almost instantaneous (albeit periodic) interactions between the various temporalities that rule the natural

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[7] The fact that different crops and different animals became domesticated in different parts of the world seems to argue against the spread of domestication as a 'technique,' but not necessarily in favor of independent invention. The invention of different subsistence activities may simply have been enabled by the changes in the conceptualization of space and time.

environment and the rhythms of human subsistence needs. As the human beings concerned need only to be at the right time in the right place to feed themselves, such ‘culling’ only requires descriptive knowledge in which space-time can be represented as strings of (favorable or unfavorable) encounters between people and the landscape. It suffices to include the season in such descriptions to make them effective as subsistence ‘manuals.’ Herding, cultivation and domestication, on the other hand, involve a longer-term, intimate symbiosis between humans and their food sources, in which people influence the natural processes. That presupposes the existence of certain conceptual functions at the spatial scale of the landscape and the temporal scale of years.

*Spatially* speaking, this requires a *two-dimensional map of the landscape* and, in the case of houses and cultivation, the conceptual distinctions between ‘*inside*’ and ‘*outside*,’ – marked by the walls of a house or the perimeter of gardens or fields – as well as between ‘*self* ’ and ‘*other*’ that is acquired as part of the conceptualization of kinship systems. But it also involves the extension of two-dimensional conceptualization of space to surfaces larger than those of tools, and the distinction between inside and outside that is characteristic of pottery-making.

*Temporally* speaking, in the case of cultivation clearance, planting or seeding are separated by several months, if not years, from harvesting a crop, whereas in the case of herding it takes years to build up a herd of sufficient size to entrust the survival of the group to symbiosis with a particular herd. We thus see the same mechanisms at work as in artifact manufacture: stretching of temporal sequences and temporal separation between different parts of a ‘manufacturing’ sequence.

We can infer there is also a *change in people’s relationship with time and space at the scale of the landscape*. During the Mesolithic, artifact distributions point to increasing circumscription of the areas within which each human group moves around. A little later (10,000–7,000 years ago, depending on the region), this may result in a settled lifestyle. In the absence of archaeological data, we must look to ethnography in order to understand the implications of these changes for people’s perception of time and space.

The Australian Aborigine use of ‘song-lines’ provides an example of mobile space-time perception. Song-lines are strings of chant sung while traveling through an unknown landscape. They allow the traveler to find his way by matching the song with what one sees while traveling. The landscape cannot be interpreted without the song, nor does the song make sense without the landscape. Individual song-lines are learned by rote, as people do not return to any area frequently enough to acquire the necessary knowledge by experience. The song provides a guideline through a landscape because it invokes time as an independent dimension to interpret space, stringing a series of punctual perceptions of space into a sequence.

In many sedentary cultures, on the other hand, spatial perception is encoded on a map. There are, again, two dimensions, but both are spatial. Three factors facilitate the transition. Firstly, settling down provides fixed points (settlements) around which a two-dimensional map can be organized. Secondly, frequent movement over limited distances replaces long-distance movement, so that every trajectory between any two points is observed from every direction, and the relationships between these trajectories can be memorized. Thirdly, settling down provides the temporal continuity of observation needed to unravel the respective roles of the spatial and temporal dimensions in observed changes. Together, these factors are necessary to enable people to develop two- and three-dimensional conceptions of the landscape.

### *3.4.5 The Impact of the Invention Explosion*

In conclusion, we would argue that the ‘invention explosion’ of the Neolithic is the result of the fact that human beings have internalized the conceptual apparatus necessary to conceive of space in four nested dimensions (0, 1, 2, 3) across a wide range of spatial scales (from the individual fiber or grain to the landscape), to separate a surface from the volume it encloses, to use different topologies, to distinguish and relate time and space, to distinguish between different sequences of cause and effect, and to plan, etc.

Together, these conceptual advances greatly increased the number of ways available to tackle the challenges posed by the material environment. That allowed them to meet increasingly complex challenges in shorter timeframes. Hence, it triggered a rapid increase in our species’ capability to invent and innovate in many different domains, substantively increasing humans’ adaptive capacity. It is as if, rather suddenly, human beings had achieved an exponential increase in the dimensionality of the conceptual hyperspace (‘possibility space’) that governed their relationship with the external world. This afforded them a quantum leap in the number of degrees of freedom of choice they had in dealing with their material and ideational environment.

But the other side of the coin was that these solutions, by engaging people in the manipulation of a material world that they only partly controlled, ultimately led to new, often unexpected, challenges that required the mobilization of great effort to be overcome in due time. The fact that, in the process, human societies invested more and more in control over their environment (such as by building infrastructure), anchored them more and more closely to the territory in which they had chosen to live. The symbiosis that thus emerged between different landscapes and the lifeways invented by human groups to deal with them eventually irrevocably channeled the ways in which the societies concerned could interact with their physical environment, driving them to devise increasingly complex solutions, with more unexpected consequences resulting. Overall, therefore, increasing control over the material and natural environment was balanced by increasing societal complexity, which was not always simple to keep under control.

## 3.5 Invention, Innovation and Collective Problem Solving

In the remainder of this paper, rather than attempt to outline, necessarily very poorly, the innumerable individual conceptual inventions made by humankind since the innovation threshold has been crossed, we will assume that the process of invention and problem generation accelerates from the Neolithic onwards, and focus our attention at the aggregate level, investigating the processes that were triggered at the level of whole societies by the crossing of the invention threshold.

Returning with the benefit of hindsight to the questions asked at the beginning of the paper, we can now answer them by describing the emergence of the human species as a dominant player on Earth as a bootstrapping process in which humans slowly gained an edge over other species and over their physical environment by using the faculty that distinguished them from all other species: the capacity to learn and to learn how to learn.[8] That capacity allowed them to categorize, make abstractions and hierarchically organize these abstractions, and, in so doing, to develop their capacity to identify and solve problems by inventing suitable conceptual tools. They learned various kinds of (symbolic and other) means to communicate among themselves, and they increased their capacity to transform their natural and material environment in many different ways and at many spatial and temporal scales.

A 'shorthand' description of this bootstrapping process as it occurs in any individual looks more or less like this:

1. A trial-and-error process identifies conceptual dimensions that summarize observations and experiences in a particular domain, so that these can be stored and transmitted in an economic and efficient manner;
2. The more such dimensions are available, the more questions can be asked, and the more answers found, further increasing the available know-how to solve emergent problems;
3. The human capacity for abstraction allows increasing numbers of conceptual dimensions, questions, and functional domains to be conceptually and hierarchically linked, thus structuring and increasing the connectivity between different domains of knowledge and understanding;
4. This leads to a continual increase in the density of identified conceptual dimensions in the cognized 'problem space' of the individuals involved, and thus gives those individuals an immediate edge over others, as well as over their non-human environment.
5. In the longer term, each solution brings with it its own unexpected challenges, requiring more problem-solving, and a more costly conceptual and material infrastructure to survive.

Ultimately, human survival in the early stages was because no dependencies emerged between the human species as a whole on the one hand, and any specific set of environmental conditions on the other (even though individual groups did depend on particular environments). Human beings were, in the true sense, omnivorous,

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[8] Their capacity to process information is genetically encoded, but the information they process, and the ways in which they do so, is not. It is socio-culturally and self-referentially developed and maintained.

living in the widest possible range of environments, and using in each environment the widest range of available resources. They invested little or nothing in their environment, and took from it whatever they could use. Their social organization, in small groups, put minimal pressure on the environment, allowed a huge range of different ways to survive, and operated with minimal overhead and maximum spread of risk. In short, and in systems terms, the species survived because the coupling between human groups and their environment was extremely loose.

Both the slow start and the subsequent acceleration in the innovation process are, in our opinion, best explained by looking at invention and innovation as a process occurring at the level of the group, rather than the individual. It seems reasonable to assume that there are in every group a number of inventive individuals, and that there is, therefore, an average 'invention rate.' For much of prehistory, however, population densities were very low, and encounters incidental, so that the transmission of inventions was irregular and its rate of loss was high. For innovation to take off, the interactivity among individuals had to exceed a certain threshold, attained by bringing more people together in the same place for longer periods. The circumscription of mobility and/or an overall increase in population were therefore a necessary part of the process leading to increased invention and innovation levels. To enable either, it was necessary to have sufficiently dependable and storable foodstuffs, and that, in turn, required certain innovations.

Once the conquest of the material world was made possible by the invention of conceptual tools such as described above, the coupling between humans and their environments became much tighter, initiating a true co-evolution between the two. That coupling increased investment in specific environments and subsistence strategies and concomitantly increased the risks involved in any individual survival strategy. The problems that emerged prompted a search for solutions, leading to more problems, etc. A control loop emerged between innovation and population density growth that was responsible for an exponential increase in both, over the last 10,000 years. That control loop is summarized in the following box (cf. van der Leeuw & McGlade, 1993; van der Leeuw & Aschan-Leygonie, 2005):

> Problem-solving structures knowledge → more knowledge increases the information processing capacity → that in turn allows the cognition of new problems → creates new knowledge → knowledge creation involves more and more people in processing information → increases the size of the group involved and its degree of aggregation → creates more problems → increases need for problem-solving → problem-solving structures more knowledge . . . etc.

The result of this loop is the continued accumulation of knowledge, and, thus, of information-processing capacity, enabling a concomitant increase in matter, energy and information flows through the society, and, therefore, the growth of the number of people participating in that society. We will discuss the relationship between these flows in the next part of this paper.

## 3.6 The Emergence of Complex Societies

In archaeology and anthropology, although the boundaries between them are not very sharply defined, we distinguish between the small-scale ‘gatherer-hunter-fisher societies;’ the larger, but still relatively homogeneous ‘tribal societies’ in which there are few structuring institutions based on any form of power or control, simply because the size of the societies (hundreds to a few thousand people) does not require such institutions; and the so-called ‘complex societies,’ which encompass tens of thousands of people or more, and in which control becomes a problem that is solved by the creation of ad-hoc institutions.[9]

On this topic, our ideas run somewhat counter to established, energy-based, theories that argue that in order to establish such societies, the first requirement was to institute subsistence strategies that could yield a food surplus, so that those ‘in power’ would not have to provide their own subsistence, and could harness some of the population at least part of the time to invest in collective works, etc. Instead, in our opinion, the emergence of such societies is linked closely to the problem-solving control loop we have just discussed.

We would argue that, because matter and energy are subject to the laws of conservation, they could never have played the role of driver in the emergence of complex societies. Matter and energy can be transmitted and stored, they may feed people and provide them with other necessary means of survival, but they cannot be shared. They can only be passed on from person to person, and any fortuitous constellation of people that only processes energy and matter together will therefore immediately lose structure. In other words, flows of matter and energy alone could never have created durable human social institutions, let alone complex societies. Information, on the other hand, is not subject to the laws of conservation, and *can* be shared. It follows that the coherence of human societies is due to the exchange of information, which, by spreading similar ideas, links more and more individuals into a network of shared meanings. In effect, human societies are held together by expectations, by institutions, by world-views, by ideas, by technical expertise, by a shared culture! The larger and more complex the society, the more information is processed by its members, requiring an ever more sophisticated information-processing apparatus if the members of the society are to act in concert.

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[9] In practice, it turns out to be difficult to assign precise limits to these different categories, and there is, therefore, an important debate in the discipline about whether these categories are ‘real’ (e.g., Feinman & Neitzel, 1984). We have chosen to maintain them for simplicity’s sake because (a) we are not involved with the detailed distinctions between these categories, and, (b) we are not, here, trying to determine the position on this scale of any individual society. We use the terms in an indicative manner, to point out different parts of a continuum.

This does of course not mean that there was no need for any surplus to provide food and other resources for those people who were executing tasks for the group as a whole. Surplus was necessary, but the ability to procure a surplus was not sufficient for the emergence of complex societies. For such societies to emerge, the people involved must have been sufficiently interactive over considerable periods of time to understand each other, divide tasks and duties, and in general terms organize their society in such a way that everyone has a role, that the society has a stable subsistence and resource base, that there are institutions in place to deal with potential or actual, internal and external conflict, etc.

The multiplication of the number of people interacting together, and of the different kinds of tasks to be fulfilled in various contexts, very quickly did place considerable strain on the communication channels of such groups because the information load increased somewhere near geometrically, or even exponentially, when the number of people increased arithmetically (Mayhew & Levinger, 1976, 1977; Johnson, 1978, 1982, 1983).

With the technical means available, the only way to solve such problems involved reducing the time necessary for communication, making communications more efficient by eliminating error and noise, and inventing ways to communicate by other than oral means. That process must therefore have been going on almost everywhere in complex societies. We see the tangible results in the emergence of increasingly large interactive groups, which occurred in all complex societies in one form or another, once certain thresholds of population size were reached (van der Leeuw 1981). The emergence of towns and cities is among the most prominent consequences of this trend.

## 3.7 The Emergence of Towns

How did towns and cities emerge? The topic has been studied in many different archaeological contexts (China, the Indus valley, Mesopotamia, Crete, Etruria, Yucatan, etc.). The principal conclusions of such studies are that the emergence of towns is not related to any particular environment, as they emerge in many different ones, deserts, temperate plains, and tropical jungles among them. All one can say is that in the earliest cases, these environments did not facilitate the communication between large numbers of dispersed villages.

It is noteworthy in all the different archaeological contexts in which towns and cities emerged, – China, the Indus valley, Mesopotamia, Crete, Etruria, Yucatan – they never emerged singly. Rather, they always constituted clusters that differentiated themselves from their rural environments at around the same time. This reflects the fact that they are, in effect, always part of a network of exchanges and communications that links their immediate (rural) hinterland with other towns (and their hinterlands) farther away. It is thus not surprising that archaeologists always find trade goods in early cities – goods that sometimes come from hundreds or thousands of kilometers away. Moreover, if one corrects for the particularities of local geographical circumstances, such networks have a very specific spatial structure that is linked to spatiotemporal constraints in the transport of goods, energy and information both locally (from town to hinterland and *vice-versa*) and among the towns themselves (Reynaud, 1841; Christaller, 1933; Berry, 1967 and many others; for a summary, see Abler, Adams, & Gould, 1997).

Similarly, there appear to be recurrent regularities in the relation between the position of a town in the urban hierarchy and its size (Crumley, 1976; Johnson, 1981; Paynter, 1982, and many others). These regularities generally are explained by the fact that for a complex society to operate coherently, a number of administrative, commercial and other functions need to be fulfilled for all members of the society. Some of these functions are invoked only rarely, but others much more frequently. In order to optimize the overall effort involved in meeting these needs, the frequently invoked functions are present in every town, the rarely invoked ones only in one town, and, for those in between, the number of towns where they are present is dependent on the frequency with which they are needed. As a result, it is argued, town size and town rank (in the hierarchy) scale according to a Pareto or Zipf distribution.

There do not seem to be any external causes for the emergence of towns and cities that one could point at, as they emerge at different times in different regions, and do not emerge at times of particular climatic or other environmental stresses. That has led many urbanists, as well as some archaeologists, to hypothesize that towns and cities emerge spontaneously, due to a process of auto-organization (e.g., Pumain, Sanders, & Saint-Julien 1988; Durand-Dastès et al., 1998). One possible scenario has been elaborated by van der Leeuw and McGlade (1993, 1997).

How did towns and cities affect communication? Van der Leeuw and McGlade (1993, 1997) present us with a detailed discussion of this question in abstract, dynamic terms. We will here summarize it very briefly, and in terms that are more accessible. First, towns concentrated people in space, thereby reducing the time needed to access most information, especially when, within such towns, people were exercising similar activities, and, therefore were most closely involved with each other in everyday life. Secondly, the towns soon became foci of attention for those in the society who were not living there – as marketplaces, they became an important source of goods and information for the surrounding countryside. In the process, trading tokens and, eventually, money were invented as means to communicate and store value and to facilitate material exchanges. Thirdly, in all urban societies we see the development of writing (or some similar means of accounting and communication, such as *quipu's* in Peru), which, on the one hand reduced the error rate in communication, and, on the other, enabled communication by non-oral means. Fourth, in such early towns we see the development of an administration – i.e. institutionalized channels of communication and conflict resolution (e.g., Wright, 1969).

Ultimately, the conjunction between the absence of external drivers towards urbanization on the one hand, and the fact that towns and cities facilitate communication in a major way on the other, convinced us to ascribe the emergence of urban systems to yet another nexus in the development of information processing and communication networks in human societies. But as we have seen above, this interpretation challenges a considerable body of extant theory that ascribes the emergence of towns in terms of economies of scale in providing subsistence and other resources for the populations concerned. We would therefore like to devote some space to countering these arguments.

### *3.7.1 The Role of Energy in the Dynamics of Complex, Urban Societies*

As biological organisms, individual human beings require that they continually dispose of sufficient energy and matter to stay alive. According to biologists' calculations, that takes about 100 Watt per person. Yet in the developed world today, the average energy consumption per person is of the order of 10,000 Watt, two orders of magnitude higher (IEA 2006). With what we know about the subsistence and lifestyle of most hunter-gatherer people, it seems highly improbable that this increase occurred before the Neolithic. If it began at that time, as it may in some societies that were blessed with sure and plentiful resources, it must still have begun very, very slowly, because there was nowhere to spend or invest that energy. Human exertion may increase the total energy intake of a society somewhat, but could not possibly be responsible alone for a hundredfold increase. Such an increase is only imaginable in the context of a substantial increase in infrastructure of the kind that uses large amounts of wood or fossil fuel, animal energy, or water or wind energy. Those conditions did not come into existence until the emergence of complex, urban societies, several millennia later (around 7,000 years ago). It has therefore been argued that the emergence of towns is in fact driven by economies of scale in energy procurement, transport, and use (Bettencourt, Lobo, Helbing, Kühnert and West, 2007).

In our opinion, this is not so. Assuming an average yield in energetic resources per unit of surface, growth of the urban population would have meant that foodstuffs and other resources would have had to come from further and further away, rapidly leading to important increases in the cost of transportation of these resources. We would therefore argue that the transition towards urbanization is not driven by economies of scale in matter and energy provision, but, that said transition is very costly in energy terms. *Rather than a driver, energy usually must have been a constraint that limited urbanization and the growth of complex societies*. The need to ensure that enough energy and matter reached every member of an urban society must have pushed people towards attempts to solve problems of energy acquisition, distribution, and use.

Not much could be done in the domain of energy *acquisition*. Until the agricultural revolution, the available subsistence resources do not change much: essentially, they are products of agriculture, forestry, hunting and fishing, the breeding of animals and the collection of plants. Until the introduction of fossil or artificial fertilizer in the 19th century, all are essentially dependent on solar energy, and their maximum yield per acre is therefore limited. The available forms of energy also remained essentially the same until the industrial revolution. They included human and animal labor, hydraulic, wind and solar energy, wood, and (to a very limited degree), coal. The cost of acquisition and the yield of these energy sources did not change enough for any society to dramatically increase its *per capita* food or energy resources (except by appropriating resources accumulated over time by others, such as in the case of conquest).

In the *distribution* of these resources, on the other hand, there was room for energy savings. In contrast with biological organisms, the channels for the flows of energy and matter are not 'hard-wired' in human societies. Therefore, sharing information creates the channels through which matter, energy and information are processed and distributed, whether these channels are material (e.g., roads, cables etc.) or remain virtual (e.g., exchange networks such as the *kula* (Malinowski, 1922)). There is great flexibility both in the organization of the networks and the forms in which matter and energy are distributed. Therefore, between the Neolithic and the Industrial Revolution, many improvements in the efficiency of matter and energy transport (such as the introduction of slaves, beasts of burden, wheeled carts, boats, roads, etc.) helped alleviate the energy constraint on urbanization.

Other savings were made by *reducing energy use*, for example by improving crops, reducing crop losses and ameliorating agricultural techniques, redesigning clothing, inserting glass in windows, improving pottery kilns and fireplaces, inventing more efficient tools (levers, pulleys, etc.) to assist in building, and so forth. Finally, as we have seen above, major energy savings were achieved by minimizing the cost of information acquisition and transfer. The organization of regular markets, for example, reduced the time spent in finding appropriate items or information; the introduction of coins and money facilitated the exchange and transmission of value; and the invention of bookkeeping and writing reduced the cost of long-distance communication of information (and increased its efficiency).

All of these savings, though, were not enough to facilitate the growth of truly large cities, such as Rome. This growth required the invention of new techniques to *harness more energy.* Many of these techniques were essentially of a social nature, serving to enhance the control of few over many: feudalism, slavery, serfdom, wage labor, taxation, administration, and so forth. However, as Tainter argues (1988), all the complex societies based on these kinds of harnessing techniques were in the end not sustainable in the absence of fossil energy. The counterpart of this argument is visible with our contemporary eyes: since the industrial revolution, and in particular since the introduction of fossil fuel, cities seem to grow almost exponentially, and no limit seems in sight.[10]

In summary, the observation that the growth of towns goes hand in hand with economies of scale in energy use is correct, but the conclusion drawn from it is not: *these economies enabled urban growth by alleviating the energy constraints, but they did not drive it. Quite the reverse, energy savings were forced on urban societies to meet the growth of societies that was driven by economies in communication and information processing*. Towns emerged and grew as a way to deal with the fact

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[10] Half the world's population of c. 6 billion people currently lives in towns and cities, and 80% is expected to live there in twenty or thirty years!

that more and more people were involved in a society's problem solving, leading to increasing diversification and specialization, and therefore to an increasing dependency on frequent interaction and communication. Because town size fundamentally was limited by the need to distribute energy to all inhabitants, much inventiveness was invested in finding ways to do more with less energy. Once fossil energy was domesticated, social systems could, and did, grow without constraint, to the point that we now use 10,000 watts per person on average. Of these, 9,900 watts are invested in our society's infrastructures, and only 100 in our own survival! Finally, it is noteworthy that where it took human beings 200,000 years or more to remove the conceptual constraints on dealing with matter, they removed the energetic constraints in less than 8,000 years. That is in itself a remarkable acceleration, to which we will return.

### *3.7.2 Complex Societies as Webs of Networks*

In what follows, we have chosen to represent human societies as organizations whose existence is dependent upon flows of matter, energy and information that meet the needs of the individual participants by distributing resources throughout the society. Material and energetic resources are identified in the natural environment, transformed by human knowledge such that they are suitable for use in the society, and again transformed during use into forms with higher entropy. These forms can then be recycled, or excreted by the society. The first kind of transformation increases the information content of the resources, whereas the second one reduces their information content. Indirectly, therefore, the information content (or information value) is a measure of the extent to which the resource has been made compatible with the role it fulfils in the society.

Channels for the distribution of energy, matter and information link all individuals in a society through one or more networks. In the smallest of societies, there is essentially one, kinship-based network. Kin relations determine social contexts and exchanges of genes, information, food and other commodities, etc. In complex societies, on the other hand, the networks are many, and are functionally differentiated: kinship, friendship, business relations, and clubs do all constitute social networks. But in such societies, we also have networks of different kinds, such as distribution networks for communication, gas, electricity, fuel, ice, food, etc. Sometimes the channels for information and matter and/or energy are the same, but that is not necessarily so: electricity, petroleum and coal are transported, processed and delivered in different ways. The same is true of virtually all goods in everyday life that we do not collect or process ourselves. We conclude that the 'fabric of society' consists of flows through multiple networks, held together by different kinds of (information) relations, and transmitting different combinations of the three basic commodities (energy, matter and information). In Chapter 5, White introduces the concept of 'multi-net' to refer to the sum of these networks.

How did these all-important networks emerge? It follows from our basic premise that they emerged through a continued exchange of information, matter and energy that eventually allowed different people at least partially to share perspectives, ways of doing things, beliefs, material culture, etc. The recursive communication underlying this process both facilitated shared understanding among individuals, and drew more and more individuals into a network in which they could communicate and share more easily, and with less risk of misunderstanding, than they would experience with non-members of the network. There was thus a decided adaptive advantage to being part of such a network. Moreover, when the recursive communication remained below a certain threshold, it kept people out of the network because they could not sufficiently maintain their alignment.

What is the nature of such networks? In a network, nodes (actors, towns, hubs) are linked by edges (links) of different kinds (reciprocal, non-reciprocal, symmetric or asymmetric, etc.). We can define a network between any number of components, at any scale, linking any two phenomena (such as people to objects, to functions, to ideas) or serving the transmission of any conceivable commodity. Thus, there are networks of scientists, networks of administrators, networks of pipelines or cables, or roads, etc., but also networks of ideas, principles, artifacts, etc. For each network, both the relations between nodes and the nodes themselves must be defined *ad hoc*. In the case of self-structuring networks such as most social networks in society, one would also have to elicit or define what the thresholds are for sufficiently intensive participation that nodes may be included among the membership.

Like everything else, the nature of these networks can, and does, change. In most complex societies, not only do the actors in the network change, but so does the function of the network. Let us illustrate this with reference to the link between a potential resource, such as a vein of a particular kind of ore, and a society. As soon as a prospector (who has a certain kind of knowledge) identifies a promising geological formation, he or she creates a link between herself or himself and the potential resource. That link is purely informational. Once (s)he gets his (her) claim registered, and searches for funds to start exploiting the vein, there comes into being an embryonic informational (financial, legal, institutional) network that links the vein to other members of the society. In the next phase, that of preparing and beginning mining, a material network is instantiated by linking the mine to an existing road (or rail) network, and, subsequently, to electricity and/or telecommunication networks. From the start, however, the operator will hire mining personnel, tapping into a whole set of new networks (kin and business relations between the workers). Provided the mine is successful and the product can be sold, the mine will be linked into an industrial network that transforms the raw material into a number of finished products. That, however, presupposes that the society itself has not only identified the ore as a potential resource, but has been structured to use it as such, by the emergence of an industrial chain that can transform the resource into something considered valuable to the society. In a short time, the mine has become a node in a large number of functionally different networks that integrate it into the existing society.

In the case of an invention, the process is very similar. It also begins with a single person and a potential commodity or artifact, and links both into the society. But the process is much slower, as it entails, first, the spread of the underlying ideas into the society ("this box serves to telephone . . . it seems useful . . . I wish to use one"), so that the potential resource is recognized as an actual resource, and then the creation of the appropriate support networks (the communications towers, the dealers, the salesmen, the clients), etc. In either (and any other) case, though, the network is initially one of ideas, and, subsequently, may become material, energetic, communicative, or all three . . . .

The configuration of the network is closely related to its dynamics. In recent years, there have been a number of impressive studies looking at the relationship between these two aspects of the networks. In Chapter 5, White presents ways to formalize the interactions between nodes, and, on that basis, show how to define the structure and dynamics of large-scale urban networks.

## 3.8 Society-Environment Dynamics

We have seen that a society uses information processing to ensure that the necessary matter and energy reach all its members.[11] The matter and energy are found in the environment, while the information processing is found in the society. There is thus a control loop with matter and energy as input into the society, information as output (van der Leeuw, 2007). Maintaining a society's growth requires a continued increase in the quantity of energy and matter flowing through the society. Such growth is achieved through the identification, appropriation and exploitation of more and more resources. At the most abstract level, therefore, the flow of information (structuration) into the environment enables the society to extract from that environment the matter and energy it needs to ensure the survival of its members. The dynamic is driven by the information-processing control loop that aligns more and more people into a connected set of social networks, thus at once increasing the degree of structuration of the society and the number of people involved.

In order for the whole to function correctly, the rates of information processing and those of processing energy and matter need to be commensurate. If not enough information is processed collectively, the society loses coherence; people will act in their own immediate interests and the synergies inherent in collaboration will be lost. Thus, for a center to maintain its power, it must ensure that there is an information-processing gradient outward from itself to the periphery of its territory. At every point in the trajectory between the center and the periphery, it must be more advantageous for the people involved to align themselves with what is happening closer to the center than with what is happening locally or further away.

Over time, such a gradient can only be driven by a continual stream of innovations emanating from the center towards the periphery. Such innovation is facilitated by the fact that, the closer one is to the center, the higher the density of aligned individuals, and thus the more rapid is the information processing. One could say that the innovation density of such a system is thus always higher nearer the center.

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[11] This is, of course, an idealized situation. Societies may have pathologies where these resources do not reach all of its members, unintentionally or deliberately (Rappaport, 1971).

Innovations create value for those for whom they represent something desirable, but unattainable. The farther one is from the center of the system, the more unattainable the innovations are (because one is farther from the know-how that created the value). In general, therefore, the value gradient is inversely proportional to the information–processing gradient. Value in turn attracts raw materials and resources from the periphery. These raw materials and resources are transformed into (objects of) value wherever the (innovative) know-how to do so has spread, thus closing the loop between the two gradients. The objects are then exchanged with whoever considers them of value, i.e. whoever cannot make them (or make them as well, or as efficiently).

## 3.9 An Example: The Expansion of Ancient Rome

To illustrate how this works in practice, we could look at the history of the Roman Empire (van der Leeuw & De Vries, 2002). The expansion of the Roman republic was enabled by the fact that, for centuries, Greco-Roman culture had spread around the Mediterranean coasts. It had, in effect, structured the societies in (modern) Italy, France, Spain and elsewhere in a major way, leading to inventions (such as money, the use of new crops, the plough), the building of infrastructure (towns, roads, aqueducts), the creation of administrative institutions, and the collection of wealth. Through an ingenious policy, the Romans aligned all these and made them subservient to their needs, i.e. to the uninterrupted growth of the flows of matter (wealth, raw materials, foodstuffs) and energy (slaves) throughout their territories, toward their urban centers and ultimately toward Rome itself.

The Roman Republic and the Empire could expand as long as there were more pre-organized societies that could be conquered. Once their armies reached beyond the (pre-structured) Mediterranean sphere of acculturation (i.e. when they came to the Rhine, the Danube, the North African deserts and the Middle Eastern Empires), that was no longer the case, and conquests stopped. Then they began major investment in the territory thus conquered. This investment consisted of expanding the infrastructure (highways, *villae*, industries) and the trade sphere (Baltic, Scotland, but Roman trade goods have been found as far a-field as India and Indonesia) to harness more resources. As large territories were thus ‘Romanized,’ these territories became less dependent on Rome’s innovations for their wealth, and thus expected less from the Empire. One might say that the ‘information gradient’ between the center and the periphery leveled out, and this made it increasingly difficult to ensure that the necessary flows of matter and energy reached the core of the Empire. As the cost of maintaining these flows grew (in terms of maintaining a military and an administrative establishment, for example: see Tainter, 2000; Crumley & Tainter, 2007), the coherence of the Empire decreased to such an extent that it ceased, for all intents and purposes, to exist. People began to focus on their own interest and local environment rather than their interest in maintaining a central system. Other, smaller, structures emerged at its edges, and there the same process of extension from a core began anew, at a much smaller scale, and based on very different kinds of information. In other words, the alignment between different parts of the overall system broke down, and new alignments emerged that were only relevant locally or regionally.

## 3.10 Networks of Cities Constitute the Skeleton of Large-Scale Societies

In such an overall flow-structure dynamic, cities play a major part. They are demographic centers, administrative centers, foci of road systems, but above all, they are the nodes in the network, the locations where most information processing goes on. As such, they are the backbone of any large-scale human social system. They operate in network-based 'urban systems' which link all of them within a particular sphere of influence. Such systems have structural properties that derive from the relative position the cities occupy on the information-processing gradient, and in the communications and exchange networks that link them to each other (Chapter 5). Although the role of individual towns in such systems may change (relatively) rapidly (Guerin-Pace, 1993), the overall dynamic structures are rather stable over long periods.

Because people congregate in cities, the latter harness the densest and the most diverse information processing capacity. Not only does this relatively high information-processing capacity ensure that they are able to maintain control over the channels through which goods and people flow on a daily basis, but their cultural (and, thus, information-processing) diversity also makes them into preferred loci of invention and innovation. Innovation (as represented by the number of people involved in research, the number of research organizations, the number of patents submitted, etc.) scales super-linearly with the size of urban agglomerations (see Chapters 7 and 8).

The super-linear scaling of innovation with city size enables cities to ensure the long-term maintenance of the information gradient that structures the whole system. This is due to a positive control loop between two of any city's roles. On the one hand, most flows of goods and people go through towns and cities. That supplies them with information about what is happening elsewhere and this again enhances their potential for invention and innovation. But the same connections enable them to export these innovations most effectively – exchanging some part of their information processing superiority for material wealth.

## 3.11 The Role of Cities in Invention and Innovation

In the last section, we alluded to the fact that cities are preferred loci of invention and innovation, but did not really elaborate. Although this topic will be dealt with in a more extensive way in other places in this volume (Chapters 6–8, 12), in order to round off our outline of the long-term evolution and role of human conceptual systems from Early Man to the present, we will devote a couple of pages to the role of towns and cities in generating innovations.

First, we must clear the terminological ground a bit, and look somewhat closer at how inventions become innovations. *Inventions* are essentially local phenomena in the social and information-processing network that constitutes a society: they involve one or a few people, and one or a few ideas. *Innovations*, on the other hand, involve the network as a whole, they are global phenomena, as they imply the spread of the invention to all potentially relevant parts of the network, and, while spreading, they expose the invention to many other forms of knowledge and ideas (which we will here call conceptual dimensions). These conceptual dimensions are themselves linked to possibilities and challenges that the original inventors were not aware of, or did not connect in any way to their invention.

### *3.11.1 When are Inventions Transformed into Innovations?*

The question we wish to address in this section is, therefore: *When are inventions transformed into innovations*? To investigate it, we will contrast unsuccessful inventions with successful ones. There are a number of 'classical' cases of inventions that were instantiated, but never transformed into innovations until very much later. Ironworking, for example, was first invented about a thousand years before it appeared as a common technique to make a wide range of weapons and tools (Stig Sorensen & Thomas, 1989; Collis, 1997), and Hero of Alexandria's steam engine in the first century BC was not used widely until it was reinvented 1,600 years later. In both cases, the conceptual and material tools and techniques were available to instantiate these inventions, but the societal and/or technological context was not such that the invention could spread. In the former case, the society was very hierarchically organized, and those in power (who controlled the bronze industry by controlling the sources of bronze) were not ready to allow a technology to emerge that they could not control (because iron was found, literally, in every bog or riverbed). In the latter case, in a society based on slavery, there was no demand for steam power . . ..

The contrast with the present is striking. The closer we come to modern times, the more clearly we can observe major innovations coming in waves that rapidly succeed each other. In such a wave, once an initial invention is transformed into an innovation (i.e. when the invention has become popular, changing the way people do things and think about them), this triggers a cascade of other, related, inventions/innovations so that, together, these innovations completely change one or more domains of daily life, trade and/or industry. Think of the introduction of printing, or, more recently, the development of the computing and biotechnology industries – with nanotechnology already on the horizon.

What makes the difference? Spratt (1989) summarized what it takes to get a relatively complex innovation, such as a car, 'up and running.' He outlines some of the many inventions and innovations that had to exist, and to be linked together in a single conception, before the first car came on the road. These go back several centuries, and his example shows very clearly that the emergence of an invention is highly context-dependent. Many of the contributing innovations were made in domains that had nothing to do with transport (such as the discovery of rubber and the invention of new manufacturing techniques for steel), and clearly were not driven by demand in the transport sector. Others, however, were indeed triggered when problems emerged that had to be solved for the car to work. In fact, his example shows beautifully that an innovation of such complexity as a car is not possible until a certain (high) density in cognized and conceptualized problem-solving tools has been introduced and instantiated in a society as a whole.

In other words, an invention can successfully be transformed into an innovation, and then trigger other inventions and innovations when there is a sufficient density of relevant conceptual dimensions in the ‘global’ network. These dimensions can be conscious or latent (waiting to be discovered), on the one hand to instantiate the invention (e.g., the necessary raw materials, tools, techniques to make it) and on the other to link the invention to a range of new functional domains to be explored and/or exploited. In the absence of such a sufficient density, for whatever reasons, the invention may not take off at all, or may remain alone without triggering a cascade. Both densities are, of course, closely related to the available density of connected ‘grey matter’ involved in information–processing.

### *3.11.2 How are Inventions Transformed into Innovations?*

Now let us tackle a more difficult question: *how is an invention transformed into an innovation*? According to current cost-benefit theory, that depends on whether there is (latent or conscious) demand for the invention, or, if there is not, whether demand can be generated within a relatively short time-span. In that theoretical context, there is an important distinction between the distant past and the recent period. We argue that in the distant past, once an invention was available, its transformation (or not) into an innovation was demand-led, but that in the present, many inventions are made into innovations at great cost, by advertising, by the creation of scaffolding structures, etc. Innovation in the modern world is deemed increasingly supply-led.

Although that distinction makes an important point, we wish to make clear that we do not believe that innovations are either completely demand-led, or completely supply-driven. After all, what is at stake is a match between an offer (an invention) and a demand (a need in the society), or between a solution and a problem: does the problem trigger the solution or does the solution make one aware of the problem? There is always a bit of both in the transformation of an invention into an innovation. The differences are, in our opinion, a matter of proportions. The important thing is that a match is made that is of sufficient relevance to the society to adopt the invention and generalize it, so that it may pose new problems and trigger new solutions (and *vice versa*).

However, there are some consequences for the frequency and structure of innovating. If demand were the limiting factor, generally, there would first seem to be an important percentage of inventions that never are transformed into innovations, simply because they are forgotten before anyone outside the circle of the inventor(s) notices them. The loss of inventions is probably more important than is the case when there is a deliberate policy of innovation (though it would be difficult to demonstrate for lack of information on demand-led innovations). Secondly, it would seem that in the supply-led case there is, at least to some extent, a ‘logic of innovation’ that it may be possible to retrace, whereas in the demand-led case that would seem absent because the process has too many degrees of freedom and resembles random walk. As a result, when the emphasis is on demand, it would seem that the overall rate of innovation is slower than when there is a strong supply-driven effort at innovation. That may also explain some of the acceleration in innovation that we have seen over the last couple of centuries.

But the very tentative way in which we have put these ideas testifies to the fact that, in our opinion, demand-led innovation merits much more study from the kind of perspective we have tried to open here. There is, as of yet, too much study of *either* innovation *or* the converse, tradition, and not enough of the *relationship between the two* (van der Leeuw, 1994). Yet it is in the interaction between what exists at any time and what is invented, that the emergence of innovations has to be explained. It is for that reason that we (Ferrari, Read, & van der Leeuw, Chapter 14, this volume) have tried to create a simulation model of the interaction between invention and the formation of a consensus about it, which would be a first step towards transformation of the invention into innovation.

### 3.11.3 What Is the Role of Cities In the Transformation of Inventions Into Innovations?

Getting back now to the relationship between cities and innovations, why, then, are cities essential to invention and innovation and *vice-versa*? In recent years, several important characteristics of cities have emerged that are of relevance here: high population density, demographic diversity, above-average interactivity among the city’s inhabitants, and accessibility from outside. We will briefly deal with each in turn.

The first of these, high population density, is critical, as described in detail in Chapters 6–8. One implication of high population density is a rich interaction structure, which increases the speed with which innovations can be propagated.

The high interaction level has a counterpart in the diversity characteristics of urban populations, particularly with respect to specialized competences and functionality. A study undertaken by ISCOM team members for 5,500 settlements in the southern half of France demonstrated very clearly that the resilience and growth of individual cities are, among other things, directly related to diversity in age groups, diversity in economic activities, and diversity in level of education of the population (ARCHAEOMEDES, 1999). We explain this by pointing out that the more diverse a population, the more encompassing is its potential ‘possibility space,’ i.e., the total set of potential domains and directions in which the town can grow through innovation. Thus, if an invention is made or brought into an urban context (either because the inventor, as often happens, moves to a city or because someone picks up on an idea), suddenly the problem space with which the invention is confronted is much wider, and the chances are increased that the invention triggers, or meets, more problems for which it can provide a solution . . . and that in turn enhances the possibility that the invention triggers a cascade.

In addition, high levels of interurban interaction within an urban system increase the innovative capabilities of these systems (Chapter 6). This increase points clearly to the fact that both the increased access to ideas and resources, and the capacity to favor the spread of innovations that come with these interactions are also important elements in the equation. It is that capacity which has, initially slowly but increasingly with explosive rapidity, led to what Ingold (1987) calls '*The Appropriation of Nature*:' the reduction of the complexity and diversity (biodiversity, spatial diversity) of our natural environment and the increase of human control over it.

## 3.12 Do We Need a Lesson From the Past?

We are aware that this paper has only begun to identify where we can, and must, scratch the surface on invention, innovation, and the history of our species that led us from life in tiny groups without man-made shelter and only a few stone tools, to a worldwide society of more than six billion people who live in an infinitely complex social and material culture, and in an environment that borders on the artificial. Moreover, our map of the places to be scratched is very fragmentary in coverage, and only has touched on a few of the scales at which it approaches different problems. Yet, we do believe that we can sketch some of the implications of our work for the future, and we do not want to end the paper without sharing some of them with the reader.

It took our ancestors of different subspecies hundreds of thousands of years to establish the conceptual tools to deal with matter, and thousands of years to do the same with energy. We currently are in the first years of the third of these revolutions, the information revolution, which will, by extrapolation, last a number of decades or even centuries.

The driving force behind these developments has been the interaction between problems and solutions, in which known problems beget solutions beget unknown problems. With each new invention, new conceptual dimensions were added to the existing arsenal, and the total problem/possibility space now counts an almost infinite number of dimensions. That in turn has exponentially increased the potential problems (or to use the softer term 'unforeseen consequences') that any innovation can trigger. As in the case of Rome, when the possibility space expands through inventions and innovations, the problem space expands even faster. In the end, therefore, the rate at which problems emerge overcomes the rate at which people can innovate to solve them, which causes crises and re-structurations (van der Leeuw, 2007).

Thus far, these crises and the need to restructure from the bottom up (as in the case of Rome, but also the Chinese, the Maya, the Indus, and other civilizations) have limited the overall speed of change in human societies. However, at present, we are on the threshold, for the first time, of innovations that depend on, and enable, reflexive intervention in our own systems. These innovations, moreover, occur at a scale and speed, and are of such a complexity, that the intuitive human apparatus to deal with new problems by using models from other domains may quickly become obsolete.

On the one hand, that may pose enormous dangers, for societies that completely get cut off from the traditions that have enabled them to maintain a degree of coherence. On the other hand, that may offer, for the first time, the opportunity to move away from the means by which most societies have survived thus far (i.e., by gaining control over, and destroying large parts of our environment). The challenge is unimaginable in scope.

We had better get used to and begin to deal with this challenge. One starting point might be to gain better knowledge of what drives innovations in our societies, so that rather than deal with the consequences of our innovation drive, we can begin to deal with that drive itself. This book aims to make a beginning with that task, by juxtaposing the acceleration of innovation and urbanization, trying to improve and formalize our descriptions of these twin phenomena, modeling them, and, thus, gaining a deeper insight in what drives them, what constrains them, and what might help us control them.

**Acknowledgments** The authors wish to acknowledge the pleasure of close collaboration with Denise Pumain, Geoffrey West, Douglas White, José Lobo and all the others participants of the ISCOM project over a period of four years preceding the publication of this paper. They also gratefully acknowledge the funding of the project by the Research Directorate of the European Union as part of its ICT (FET) program, under contract n° ICT-2001-35505.

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