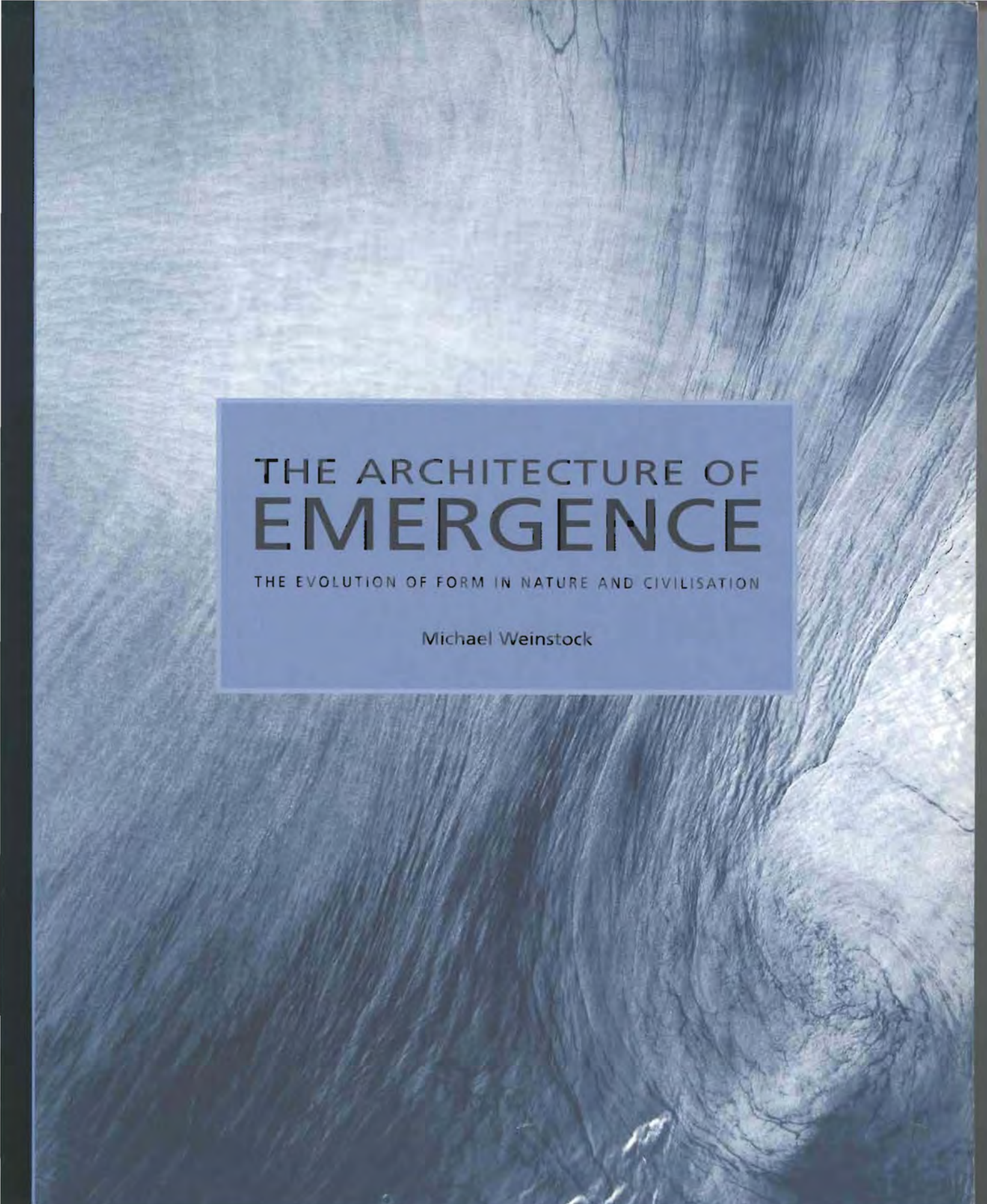
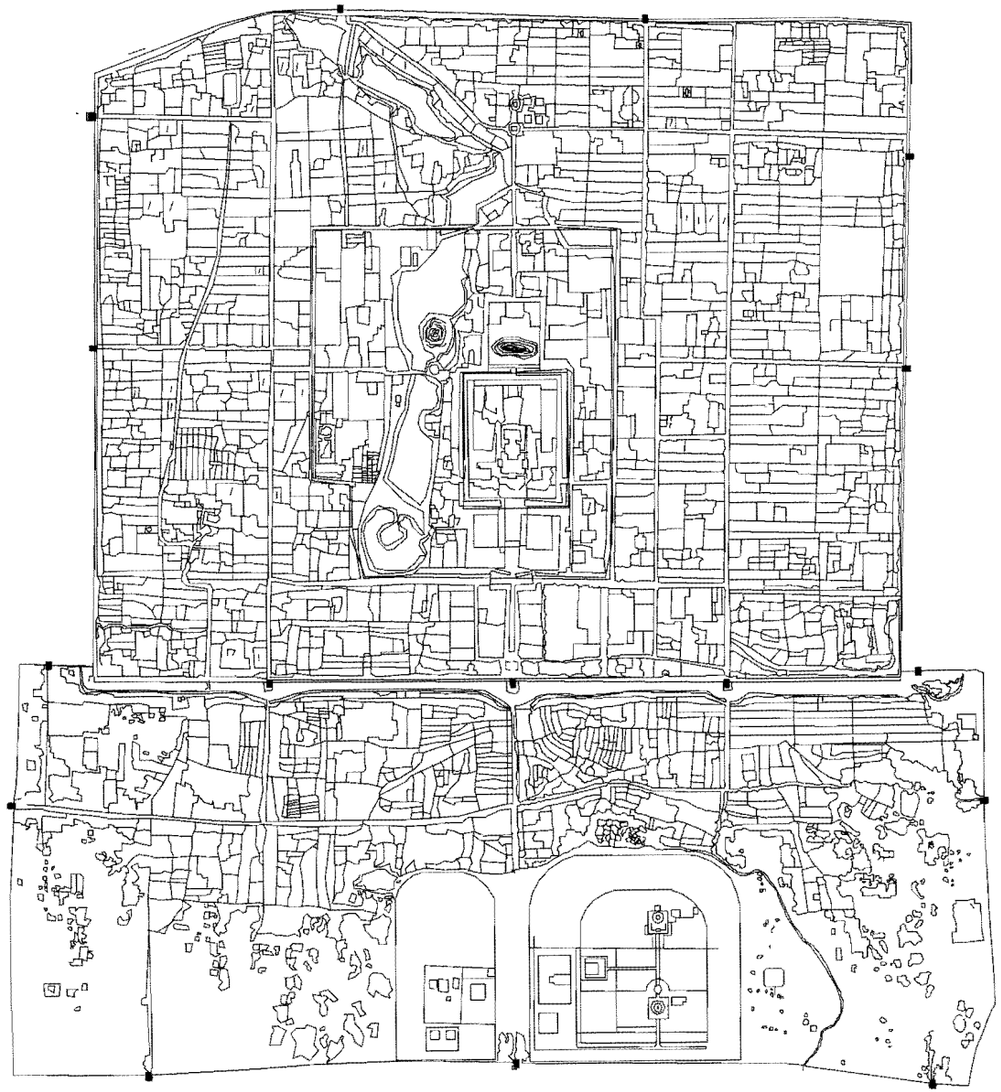


THE ARCHITECTURE OF EMERGENCE

THE EVOLUTION OF FORM IN NATURE AND CIVILISATION

Michael Weinstock



8.1 Beijing
The first city ever built by the steppe nomads, known as 'Dadu' or great city, conformed closely to the Chinese *Kao Gong Ji* model cities in plan and material construction, and is today part of Beijing. Travellers from the small dense cities of Europe, including Marco Polo, were astonished by the number of cities in China, the enormous areas enclosed within their walls, and the dense populations two or three times larger than that of any city in Europe.

The Forms of Information, Energy and Ecology

8

The integration of the collective metabolism of systems of cities into complex hierarchical systems acted as a positive feedback on the evolutionary development of information systems. Graphical and numerical notation, calculation and writing arose from the regulation of the fluctuating flows of energy and materials, and the complexity of the system increased commensurately. As more extensive and complex metabolic networks emerged, they have extracted energy and materials over regional and continental scale territories, with many periods of expansion to the critical limit of stability, and subsequent collapse and reorganisation. The evolutionary development of continental scale systems and the current worldwide system is strongly coupled to extensive modifications to the surface of the earth and to the ecological systems that live upon it. In consequence the interactions between the surface of the earth and the atmosphere at local, regional and global scales have been altered.

In humans, like all other living forms, information and the ability to extract energy from their environment are strongly coupled. The assembly of an integrated cultural system had reached a critical threshold of complexity more than 35,000 years ago. Complex spoken language, graphical arts in the form of cave paintings and engravings on shell and bone, and the beginnings of mathematics in simple lunar calendars were in use in most populated regions of the world. The information transmitted down through the generations was ecological and social knowledge, a set of instructions of how to live as member of the group or tribe, how and where to hunt and to gather, how to make weapons, tools, clothes and implements, and how and where to construct dwellings. Information enabled the metabolic, spatial and social organisation of the founding system to expand their numbers and flow across the surface of the earth. As humans dispersed into new climatic and ecological zones and adapted to them, new variations of the founding system arose. Seasonally and ecologically determined patterns of movement, inherited from the ancestral apes, also evolved to include long-term settlements of excavated 'pit dwellings' as winter residences, along with the use of tents and temporary structures in warmer seasons. Pit dwellings enabled modern humans to regulate their

collective metabolism in a great range of climates, and to expand into the very cold territories of the high northern latitudes. Adaptation to differing regional climates, topographies and ecologies emerged through variation in the timing and frequency of movements and residency, and morphological variations in the depth and size of the excavation and construction.

The variability of dwelling morphology and mobility strategies enabled anatomically modern humans to occupy and flourish in all the continents and islands of the earth. Knowledge of how to make a dwelling was passed down from one generation to the next, and incorporated into the set of skills, social and ecological knowledge of each family and tribe. The use of graphical arts in cave paintings predates written language by 20,000 years, and it follows that the use of drawing in construction is most likely to have arisen at the same time with the marking out of the 'plan' of the dwelling on the ground with pegs and cords. There was little differentiation between individual dwellings in areas with similar climate and ecologies. It is likely that when variations did arise they were produced by differing circumstances of climate, topography and material resources during the building process.

Human populations grew to the maximum densities that could be supported in the ecology within which they were situated. The lowest population densities were in the hot and wet tropical forest ecologies, where the minimum density is estimated to have averaged only one or two people per 100 square kilometres, but in more temperate regions where gathering and fishing were the main activities, population densities were much higher – averaging up to 90 people or more per 100 square kilometres. The energy gained from gathering tubers, fruits and grains, or hunting and killing animals, averaged between 10 and 20 times the energy expended in those activities. Hunting small animals had such a minimal gain that in many situations it resulted in an energy loss, but hunting large herbivores including bison and mammoths produced as much as a 19-fold return. The extinction of the megafauna was part of, but not the only modification, of ecological systems that human activities induced. The cutting down of trees for the construction of dwellings and for fuel, the use of fire to drive game and to clear land, and the extinction of megafauna produced permanent changes in steppe grasslands, in cool forests and in the warmer grasslands. As the populations of humans continued to spread and grow, the increase in gathering of grains altered the regime of natural selection and initiated the genetic changes in wild cereals that enabled the development of more systematic plant cultivation.

The world population is thought to have been about five million people 10,000 years ago.[1] Across the surface of the earth the peoples had increased their numbers to the maximum capacity of their ability to extract energy and materials from their home range. Within the mid latitudes the climate became increasingly arid and plant life diminished, so that fewer animals could be supported and in turn the sources of food available for humans were greatly reduced. As the extended metabolism of the founding system failed across large open territories, settlements and territories were abandoned, and the founding system collapsed. In five geographically separated and ecologically distinct regions the peoples migrated to the more ecologically favourable valleys of the major river systems[2] in Egypt, the Levant and south-west Asia, India, China and Peru. The flow of migrants increased the size and number of settlements, and accelerated the development of increasingly complex networks of links between them. Cities emerged, between 5,000 and 6,000 years ago, through a process of nucleation, condensing into nuclei within the extended 'metabolic' networks of the linked settlements in the river valleys.

The spatial, material and metabolic characteristics of the early cities were intricately linked to the ecological and climatic system within which they emerged, and to the regional variant of the common founding system from which they descended. Where climate and ecology were similar, their evolutionary development tended to be convergent, with approximately similar spatial patterns and material organisations. What was common to them all was the increasing ability to extract energy from their locality, to manipulate and transform materials, and the accumulation and propagation of information. Information systems arose from the recording and transmission of differentiated and fluctuating flows of energy and materials, and evolved as the metabolic system of cities increased in complexity. Variations also arose in the form and scale of individual buildings, in the inventory of building functions, in the spatial organisation of groups of buildings, and in the arrays of cities and settlements. As more extended and more complex 'metabolic' systems developed, the intensified flow of energy and materials acted as a positive feedback to the further evolutionary development of energy and information systems.

Land-based nomadic systems, evolved from a variant form of the founding system, also exhibited common material characteristics and seasonal mobility patterns as they developed and expanded across ecologically marginal territories in Africa, Eurasia and Siberia, and Northern America. The principal vectors of interaction

with the systems of cities were trade and war. They transported information and high value items across local and regional territories, and in doing so diffused cultural values. In many regions and particularly in north-east Asia, they also developed advanced strategies and technologies of systematic warfare.[3] A significant variant system arose from the intensive use of river craft that extended the metabolic activities of the systems of cities along the Nile, the Euphrates/Tigris, the Indus, and the Yiluo and Huang He rivers of China. Maritime nomadic systems coevolved with the development of sailing ships capable of longer coastal and sea voyages around the Mediterranean, the Indian Ocean and the South China Sea. As extended arrays of cities and their colonies were established, linked by maritime and land-based nomadic systems, the flow of energy and materials intensified at a regional scale. The quantity and complexity of information to regulate the flows through the expanding systems increased accordingly.

CITIES AND INFORMATION SYSTEMS

The evolutionary development of scaled plan drawings may be inferred from the stone statue of Gudea,[4] currently in the Louvre, which is known to be a little more than 4,000 years old. The seated figure has a tablet on his knees on which is inscribed the plan of a temple, along with a graduated scale rule. The plan is orthogonal, and defines a thick wall with buttresses, appropriate for the brick construction of that region and time. Gudea's robe has an intricate inscription that includes an account of the construction, and the distant source of materials such as cedars from Lebanon and stone from northern Syria. Two inscribed stone cylinders have also been found that document the construction.[5] Scaled plan and elevation drawings were also used in Egypt. One of the few surviving drawings on papyrus, known as the Turin papyrus, sets out the front and side elevations of a shrine at Ghorab. The elevations were drawn in black ink against a red grid, suggesting the method of transferring the drawing at full scale to the stone block. Few papyrus drawings survive, perhaps because only important drawings were made on the fragile and expensive papyrus and leather surfaces.[6] Most construction drawings were made on temporary plaster surfaces or on flat timber panels as working templates during construction. Site measurements were made with a cord knotted at 12 equally spaced intervals, a flexible 'ruler' also used by the city surveyors to mark field boundaries.

In Mesopotamia, Egypt and in China the first forms of systematic writing arose about 5,000 years ago, at the same time as the emergence of cities. In Mesopotamia small clay tablets had been in use for at least a thousand years to record quantities and transactions of grains, livestock and materials. The inscribed signs were stylised but recognisable pictorial representations such as of ears of wheat, or bundles of reeds. Abstract symbols were developed when reed styluses became widely used to press marks into the fresh clay. The resulting written language is known as cuneiform.[7] Egyptian hieroglyphs emerged around the same time, developed through a similar process of gradual abstraction from pictograms. Writing systems of this kind are referred to as logographic systems, and include Chinese and its descendants.

By 3,500 years ago in Mesopotamia, Egypt and China, mathematics had developed to include many geometrical constructions and arithmetical computations. In Mesopotamia detailed surveys of land, property boundaries and parts of cities were recorded on clay tablets as, for example, the map of the city of Nippur[8] that is annotated in cuneiform. Other fragments that survive from the Turin Papyrus show a large Egyptian map indicating the recording of topographical and geological characteristics. The papyrus is extensively annotated and it was probably made in preparation for an expedition to quarry for stone and gold.[9] The Mayan glyphs and other written languages from Mesoamerica emerged a little later, but quite independently. The collapse of the system in the Supe valley and Caral in Peru resulted in abandonment, and the migration of people to the north. The later development of the Inca notational system, manifested in textile strands, threads and knots, known as 'quipu', may have first emerged in Caral. It is not known at present if the 'quipu' system equates in complexity to fully developed writing systems. It has been argued that the development of 'quipu' is analogous to cuneiform, originating as a system of accounting records and evolving into a unique three-dimensional writing system.[10]

Phonetic writing, in which symbols represent the basic sounds or phonemes of spoken language, and syllabic writing in symbols which represent syllables, emerged from the evolutionary development of logographic writing. Today, all writing systems are combinations of logograms and phonetic symbols, augmented by 'silent' or unspoken signs known as 'determinatives' that are used to resolve ambiguities.[11]

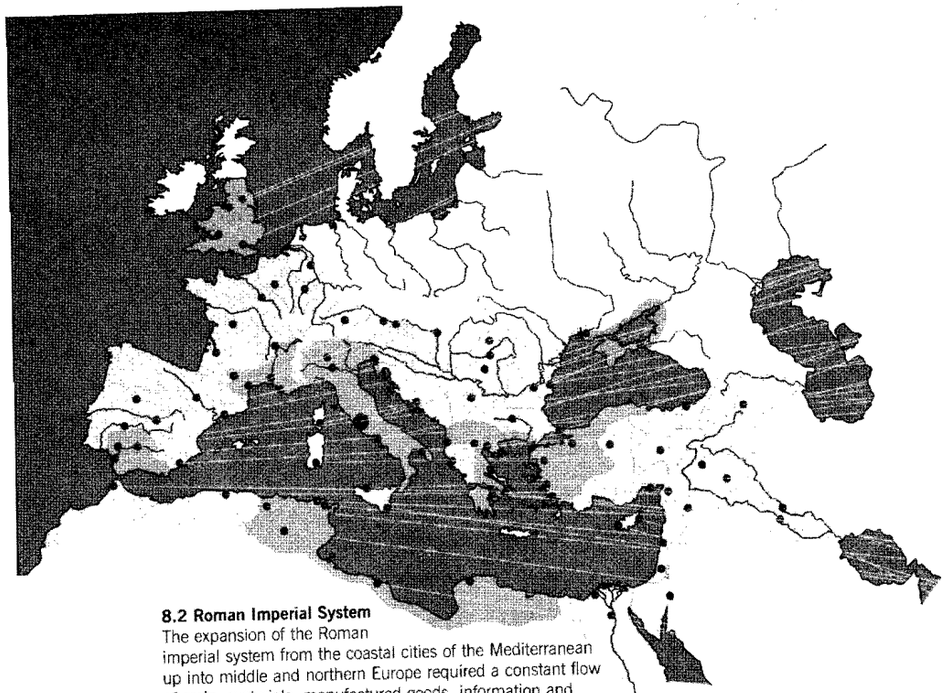
In Mesopotamia, Egypt and China the use of writing was limited to professional bureaucrats and scribes. The Greek alphabet of 24 letters, developed from Phoenician consonants and extended by the innovation of signs for vowels, arose approximately 3,000 years ago and is still in use today. It has been used to

write other languages, and many other alphabets are descendants, most notably Latin. A significantly larger proportion of the population used written language in the Greek system, although the majority of the population were not literate. Written specifications, or *syngraphai*, described the building, with sufficient information for the craftsmen to understand its form, dimensions and materials and method of construction. The general spatial arrangement of dwellings was long established, and widely known. As in Mesopotamia and Egypt, drawings used in Greek construction were made at full scale on the ground to set out the building to be constructed, or on temporary flat surfaces of plaster or timber as working templates. The master craftsman or architect set out the geometries on the site, and important details were first made in wood or clay at full size. These three-dimensional templates or prototypes were known as *paradeigm*, and precise measurements were taken from the *paradeigm* to the material construction. The Naval Arsenal at Piraeus, the port of Athens, was built 2,300 years ago as a store-house for the rigging and sails of 400 triremes. A stone tablet was incised with the complete specification for the building, including the foundations, site and dimensions, and the size of the stone blocks from which it was constructed.[12]

The archiving of information arises from data that is metabolically significant and ecologically contextualised. Information grows exponentially as populations increase, and greater quantities of energy and materials have to be extracted from the surrounding environment. The development of systems for the collection, storage and redistribution of energy and the manipulations of material was strongly coupled to the evolution of information systems, of administration, governance and the regulation of energy and material flows through the system of cities. Written language emerged from the evolutionary development of its antecedents: spoken language, drawings and material archives. Writing and specialised construction drawings coevolved with systems of cities, and enabled the accurate transmission of greater quantities of more detailed information over larger distances and longer durations. The establishment of distant colonies enabled cities to expand their populations beyond the energetic and material constraints of their local topography and ecology.

Metropolitan or 'mother' cities developed increasingly complex information systems, that in turn enabled the further development of systematic transformations of materials for the construction of artefacts, buildings and cities. Information flowed back to the colonies, accelerating their local expansion and increasing their complexity in turn. Increased complexity required higher levels of organisation, increased numbers of specialists to process, manipulate and to communicate greater volumes and more kinds of information, and they had to be supported on the surplus production of energy and materials in the system. Complexity consumed energy, and each increase in complexity required a further increase in the flow of energy. The process of finding, developing and collecting more energy and materials over greater distances and larger territories required an increase in information processing and consumed yet more energy. The emergence and subsequent evolutionary development of information systems and the systems of cities were strongly coupled, each acting as positive feedback on the expansion and growth in complexity of the other.

The systems of cities within the latitudinal band of the Levant and south-west Asia, the eastern Mediterranean and North Africa[13] all had had similar developmental sequences, with initial phases of rapid increases in population and city size, together with rapid accelerations of the flow of energy, materials and information through their systems. Although there was pronounced variability of climate 2,500 years ago, the overall trend had been a fall in temperatures across southern Eurasia, and the colder, wetter climatic regime extended as far as China. At the same time, the northward shift in the monsoon belts reduced rainfall in the subtropical latitudes and induced extended periods of drought. Sea level fell by 1 metre as more and more water was taken up into the expanding ice sheets.[14] Lower temperatures and changes in the global pattern of precipitation, varying in duration from decades to several centuries, produce substantial ecological changes. It is argued that these climatic variations are coupled to the deep ocean circulation, and so have a similar periodicity, occurring approximately every 1,500 years or so.[15] In the less ecologically favourable locations, expansion slowed and then ceased, and territorial contractions began, followed by declines in populations and migrations. In the most arid and ecologically stressed locations cities were abandoned. In Egypt, Mesopotamia, Crete, Greece and south-west Asia there was an irregular series of contractions and expansions, prolonged periods of famine and warfare that induced large migrations, but in China the systems of cities developed slowly but continuously, expanding the number of cities and doubling the population.



8.2 Roman Imperial System
The expansion of the Roman imperial system from the coastal cities of the Mediterranean up into middle and northern Europe required a constant flow of grain, materials, manufactured goods, information and people from the Mediterranean region. The flow back to Rome from Europe was precious metals in the form of captured treasures, money and the people who were enslaved. At its maximum extent the system included 60 million people.

THE IMPERIAL SYSTEMS OF ROME AND CHINA

The imperial[16] systems of Rome and Han China extended over continental scale territories of approximately 6 million square kilometres each, and by 2,000 years ago almost half of the world's population lived in either one or the other system.[17] Their trajectories through time were similar; they arose, expanded and collapsed at more or less the same time. Each system developed the largest cities of the world in that period, with in excess of half a million urban residents. Both imperial systems developed and extended over climatically and ecologically varied territories; the Roman system expanded from the Mediterranean northwards up into the cooler and wetter temperate latitudes of Europe, and the Han Chinese system expanded to the south from the cooler Loess Plateau down into the warmer and wetter climatic regime of southern China. They were linked by an extensive network of overland routes, now known as the Silk Road, that began in Chang'an in China and connected Asia and India to the Mediterranean regions. People, together with materials, manufactured artefacts, information and diseases flowed along its 8,000 kilometre length, and through the many trading cities that emerged and expanded along its routes. Both systems developed from antecedent systems within their region. The increase in complexity of imperial systems relative to their antecedent systems was characterised by an increase in differentiation, requiring an extended social order with more specialised occupations, and a more complex network to collect, process and disseminate more kinds and greater quantities of information. Both the Roman and the Han Chinese system developed many new techniques of material transformations, and built many more different forms of buildings than their antecedent systems.

THE ROMAN IMPERIAL SYSTEM

By 2,000 years ago the city of Rome had a population estimated at 500,000 people resident within the city[18] reaching a total of as many as 1 million over the extended urban area some 200 years later. For centuries before the imperial system was created, Rome had already expanded beyond the capacity of its hinterland to feed its citizens and to provide fuel for its industries. It had conquered and controlled the coastal cities of the Mediterranean, and grain flowed from Egypt and North Africa, Sicily, and Sardinia.[19]

The expansion of the imperial system up into middle and northern Europe required constant flows of grain, materials, manufactured goods and people from the Mediterranean region. The flow back to Rome from Europe initially was precious metals in the form of captured treasures, money and people who were enslaved. The continual rebuilding and enlargement of the harbour and granaries at Ostia and Portus during the imperial expansion suggests that grain and materials flowed from Egypt and other fertile territories to Rome, and were shipped from there to the mouth of the Rhône in southern France, and from there by river and overland to all the territories of the imperial system.[20]

The city of Rome had developed from a group of settlements arrayed around a small valley on the floodplain of the Tiber River. Each of the settlements expanded from their small hills down into the valley, eventually coalescing into a continuous urban form. The single-floor brick houses with internal atria and courtyards were variant forms, descended and modified from the courtyard antecedents in Greece, Crete, Mesopotamia and Egypt. In the early centuries this was the dominant form of dwelling in the city, as it was for its antecedents. As the city grew and developed over time, a new form of dwelling emerged, multi-floor buildings that occupied a whole city block. Known as *insulae*, the simplest

form consisted of two parallel rows of repeated modules of single chambers, built from brick and extending from the street to the inner space between the rows. Other blocks consisted of parallel rows of two- or three-floor modules, and the most spatially complex had four rows arranged in a rectangle around a paved inner courtyard. Many were six or more floors high, although the legal limit was 21 metres. There were many variations in the spatial, material and structural organisation of the courtyard *insulae*.[21] The number of rooms in the blocks suggest that the occupation of these city block 'apartment' buildings was very high, and there are many records of fires and structural collapse, often attributed to poor building technique, the difficulty of pumping water higher than one or two floors, and the general lack of water in the city.

The Severan Marble Plan of Rome shows the ground plan of every building and block in the city, with a level of detail that included the smallest alleyways and staircases. The marble, also known as *Forma Urbis Romae*, was carved about 1,800 years ago and is known to have been approximately 18 metres by 13 metres when complete, with a scale of 1:240.[22] It is known that detailed surveys were made of all the buildings within Rome, and it is suggested that a more detailed annotated copy existed on sheets of papyrus. Roman maps were made to scale, and were used to record dimensions, ownership and building taxes. Analysis of the plan suggests that the courtyard *domus* with an internal atrium, once the general dwelling for all the population, persisted as the form of dwelling for the rich minority, and that the courtyard *insulae* apartment buildings became the most common form of dwelling for the mass population. The map also shows clearly that the urban blocks were very mixed, with no clear segregation of rich and poor into separate districts, nor of commercial buildings from residential.

There are a few surviving medieval copies of Roman surveyors' manuals. Although often poorly made, the copies that survive include surveying and measuring techniques, town plans, and theoretical sections on astronomy and applied geometry.[23] Surveyors also played a significant role in the establishment of new colonies; choosing the site, drawing the plans for the new city, setting out and allocating the plots of land, and making written records. The Roman army was the principal vector of urbanisation of all the territory under the imperial system. There was one language used in the army, Latin, and the flow of information from Rome to the furthest periphery, and from all regions back to Rome was through the army. The standard plan of the army camp was universally applied, although variations arose according to the local topography. A ditch and a wall enclosing a rectangular area of 20 hectares or so was constructed, either of earth with strong timber facing for temporary camps or of stone and brick for permanent fortresses. Two main streets were set at right angles to each other and around the intersection were set out the main administrative building, the hospital and the granaries. Each quadrant was subdivided by streets, with 15 barrack buildings in each quadrant, each legion having a nominal strength of 6,000 men divided into centuries. As people and goods, food and materials flowed into the camps and fortresses, buildings accumulated outside the walls, often extended for a kilometre or more and eventually developing into large towns. The Roman military origin of many large European cities can be seen in the street patterns that have persisted until today, as in Strasbourg, Cologne and Vienna.[24]

Maintaining the flow of grain, materials and information over the enormous distances to the northern and eastern frontiers was immensely expensive and very slow. When the expansion by conquest was over, the energetic costs of the imperial system rose and the returns began to decline. Once the system had expanded to its maximum extent, changes in climate and ecology accelerated the fall in energetic returns. Prolonged droughts in the eastern Mediterranean reduced the agricultural capacity of even the most fertile agricultural lands, which had already been exhausted by the intensity of cultivation and overgrazing. The cultivation of additional but less fertile territories was required to compensate, requiring more energy input for increasingly diminishing returns.[25] Throughout the imperial system local grain and livestock surpluses were used to supplement the flow from Rome, imposing an oppressive tax regime that required a larger and more expensive bureaucracy to administer. The complexity of the system was increased, by doubling the size of the army and the government, which was paid for by debasing the silver currency with 'base' or cheaper metals and massive inflation. When the climate became rapidly cooler in the high latitudes of northern Europe and Asia, the returns from livestock and grains diminished in ecologically marginal lands that had also been overgrazed and intensively cultivated. The demands for energy extraction placed on the provinces were so high that they could not be met. The oppressed provincial populations were alienated and reduced by migrations, while marginal lands were abandoned throughout the northern territories of the system and the people migrated to the south.[26] The army was increasingly unable to defend the enormous length of the frontiers against mass migrations and, in some areas, hostile invaders. The geographical extent of the imperial system began to shrink back until a little more than 1,500 years ago the city of Rome was conquered and sacked.

THE HAN IMPERIAL SYSTEM

By 2,000 years ago the population of Luoyang was similar to that of Rome, approximately 500,000 people,[27] and the total number of people within the entire Han imperial system was also similar to the Roman system at 60 million. The system extended from the tropical southern coast up to the Great Wall that had been built close to what is now the edge of the cold arid Gobi Desert. The Han system emerged from the collapse and reorganisation of the previous and short-lived Qin system, of which Chang'an, also known as Xi'an, had been the administrative capital; it later became the capital of the first or Eastern phase of the Han imperial system. The antecedent Qin system had unified the separate warring feudal states of China, although once that was accomplished it lasted only another decade.[28] The construction of the Qin mausoleum, the massive necropolis[29] of the first Emperor Qin Shi Huang, is now known for the 'terracotta army' of ceramic figures, of which more than 8,000 have been excavated to date. The construction of the Great Wall of China was completed during this phase of the imperial system, connecting and extending by thousands of kilometres the existing short sections that had been built by smaller independent states to defend against the incursions of the nomadic tribes of the steppes. Flood control and irrigation systems were already comprehensive, having emerged very early in China, and Qin extended the systems, with a new navigable canal connecting the Yangtze and Pearl Rivers, and new reservoirs and irrigation channels. Road construction and their dimensions were standardised, as were weights and measures, and the forms of written language with what is now known as the 'Qinzhuan' font. Military conscriptions involved a very high percentage of the population, and the tax demands, to be paid in labour on the construction of the Great Wall and in grain, were so high that they could not be met without mass starvation. It has been estimated that more than 60 per cent of the total output of all the population was required to keep the system functioning. The energetic demands of the Qin system could not be met and the system collapsed.

The Han imperial system inherited and developed the administrative system, and an imperial academy was established to train government officials, who had to undergo a formal examination. A two tier, central and local, administration was developed in order to minimise the expense of supporting a professional bureaucracy over the huge area of China. Metallurgy industries were nationalised, taxation was reduced and 'labour' conscription for government projects was limited to one month in each year. The population expanded very rapidly. As in the Roman system, a professional army of mass infantry was developed. Both the Han and Roman armies built roads and bridges as they moved during wars of conquest, infrastructures for the movement of people, food and materials. Armies also generate and manipulate vast quantities of information. Civil administration and the flow of information, energy and material were accelerated in both systems by the military. Mass migrations were also used to populate new colony cities in uncultivated lands and to integrate them into the imperial system.[30]

Information for the organisation and construction of cities was set out in the manual *Kao Gong Ji* which translates as *The Records of Examination of Craftsmen*. The manual may have originated in the Qin system, but it was revised and extended during the early Western Han system. It was widely used for the examination and assessment of craftsmen of all trades, guidance on the manufacture of artefacts such as weapons and musical instruments, and the building of dwellings. It has instructions on how to survey and level the ground, set out the square plan according to the cardinal points with a length of 1,200 metres per side, organise the internal subdivisions of the city, and orientate and position all of the principal internal buildings and structures.[31]

The walled cities of the Han imperial system were 'descendants' of the cities that emerged on the northern plains thousands of years earlier. The city of Chang'an, a few kilometres north-west of the modern city of Xi'an, was built on the site of ancient settlements, and has been continuously occupied and rebuilt many times over the 7,000 years since.[32] In the first centuries of the Han imperial system, sometimes referred to as the Eastern Han, it was the capital city. It was approximately square in plan, with massive rammed earth walls enclosing an internal area of 10 square kilometres that was divided into 160 interlocking walled courtyards of varying sizes, three larger walled courtyards of many tens of thousand square metres, and an orthogonal street pattern organised on north to south and east to west axes.[33] The spatially and functionally differentiated organisation, with separate areas for dwellings, granaries, arsenals, manufacturing workshops, foundries and kilns, is clearly descended from much earlier cities, such as Erlitou and Zhengzhou, although it was very much larger and had an extensive inventory of building functions. The northern and western outer walls had to be rebuilt according to the course of the river, and so were irregular in plan. When the capital was moved to Luoyang in the east, the population of Chang'an and its immediate surroundings declined substantially for several centuries. Luoyang, the capital of the later Eastern Han system, extended between the Mang Mountains and the Luo River, and was rectangular

rather than square in plan with the long axis running north to south between the mountains and the river. The area enclosed by the rammed earth walls was 10 square kilometres, similar to Chang'an. There is scant archaeological evidence of Luoyang at this time, but it is thought that there was a significant amount of unoccupied land within the enclosure during the Han period.[34]

Most cities were set out and built on the northern side of fertile river-banks on land that was already cultivated, so that large cultivated areas were enclosed within their walls. Lakes were always constructed and this enabled walled cities to have an internal supply of food and water, a significant advantage especially in the semi-arid regions of northern China and in times of warfare when the city gates had to be closed for extended periods.[35] The internal organisation of the walled cities into a differentiated series of interlocking walled courtyards of varying sizes and an orthogonal street pattern was not necessarily fixed over time. The materials used for construction were rammed earth and timber, strong but relatively easy to construct or remove, and with a limited lifespan. In consequence, courtyards within the city frequently needed to be rebuilt, offering opportunities for reconfiguration. Chang'an and Luoyang were rebuilt many times over the following millennia, in response to changes in the course of the rivers, to demographic and political changes, and after destruction in warfare.

The total population of the Han imperial system had risen to 60 million and covered a vast territory. The quantity of information generated, manipulated and disseminated to regulate the system was immense. Although the geographical extent of the Han system was similar to that of the Roman system, four times as many professional administrators were employed. The rivers of China are orientated mainly on the east/west axis, making the flow of grains and livestock, raw materials and manufactured artefacts comparatively easy. However, movements on the north-south axis had to be by road, requiring more human and animal labour and so a higher energy cost. The energetic costs of the system continued to rise, and higher taxes were imposed. Excessive taxation and continuous warfare and incursions on the northern boundaries led to widespread social unrest. The rapidly cooling climate across the northern steppes began to diminish plant and livestock returns, inducing widespread famine and migrations to the south. Communication between the remote northern Xiongnu, Xianbei and Qiang provinces and the capital cities on the central Loess Plateau became irregular and eventually hostile. The Han imperial system collapsed, and fragmented into warring independent states.

COLLAPSE AND REORGANISATION

A thousand years ago the population of the entire world is thought to have been 310 million people, only marginally increased over the previous millennium.[36] The climate was then in the middle of the 300 year warming[37] that is sometimes referred to as the 'Medieval Optimum'. Very dry conditions prevailed across the mid latitudes of the Mediterranean region and southern Europe, south-west Asia and east Africa, and the south-west regions of North America, and strengthened the seasonal monsoons in eastern Asia.[38]

The middle centuries of the previous millennium had been much cooler and very dry across the high latitudes of the Northern Hemisphere. Polar and steppe grasslands are particularly sensitive to small changes in climate, and in dry cold conditions vegetation dies back and new growth is restrained. The nomadic system had evolved in these, and in other, ecologically marginal lands as a variant of the founding system, and their interaction with systems of cities had developed in two principal vectors, trade and war. In north-east Asia the nomadic peoples had developed formidable strategies and technologies of systematic warfare,[39] and as the resources in their homelands declined, waves of migration southwards persisted for hundreds of years. Large movements of armed nomadic peoples into the northern territories of the Roman and Han imperial systems, coupled to the diminishing ecological resources in those territories already under stress from the increasing energetic demands of the imperial systems, triggered a cascade of failures in both systems. The effect of local failures in the systems increased the stresses on the parts of the system to which they were connected, and where there were more connections the further the effects were transmitted. The more complex a system is, the more connections it has, so that what may appear to be a series of independent and unrelated localised failures act as negative feedbacks that amplify and accelerate the decline and collapse of the whole system.[40] Warfare, famine and plague caused severe population decline in both regions; both systems fragmented into separate autonomous and less complex systems, with reduced flows of energy, information and materials. The outcome of the collapse in China was quite different to that in Europe and the Mediterranean.[41]

In China, cooler conditions and changes to the pattern of rainfall had persisted for more than half of the previous millennium,[42] but although the flow of energy and information through the cities and settlements on the central plain of the Loess Plateau and in the south was diminished, it did not break down completely. The independent smaller states were gradually brought back into the

system, the invasions of nomadic peoples were contained, the plague did not recur and the imperial system was reassembled and reorganised over a period of some 300 years. As the climate began to warm again towards the 'Medieval Optimum', the strengthening monsoon rains increased agricultural returns substantially, populations expanded, and the flow of energy through the system intensified. A new and much larger city of Chang'an was set out and built south-east of the former Han city. The walls enclosed an area of 84 square kilometres, within which more than a million people lived.

The use of timber for construction and for making the charcoal used as industrial and domestic fuel, and the clearance of land for agricultural use, coupled to climate change, resulted in deforestation and soil erosion at a regional scale, encouraging the spread of savannahs and the extinction of many animal and plant species. The Loess Plateau was once a flat terrain with extensive forests and grasslands, but by the end of the Han imperial system deforestation and changes to the hydrology had accelerated such extreme erosion of the soil that the topography was entirely changed. Thousands of years of human occupations, culminating in the increasing intensity and quantities of energy and water resources extracted during the densely populated Han and successor systems, produced the very steep low hills and valleys and the low water table that characterise the Plateau today.[43]

In Europe and the Mediterranean, the Roman imperial system had been reorganised into two autonomous parts, conventionally referred to as the Western Empire and the Eastern or Byzantine Empire, each with its own Emperor and administration. In the western Mediterranean lands and over all the former territory of the Roman system in Europe, the eventual outcome of the collapse was the emergence of small independent walled cities and fortified towns with sufficient local territory and local connections to be self-sufficient.[44] The medieval feudal pattern, and ultimately the pattern of today's small nation states of Europe, emerged from the collapse and fragmentation. The Eastern system persisted for a thousand years after the fall of Rome, gradually ceding territory and shrinking until only the capital city of Constantinople itself remained. It has been argued that this may be the only example in human history of a system of cities extended over a very large territory, that when faced with declining resources of energy and material chose to reduce the complexity of its organisation and the flow of information, and to revert to a simpler system.[45] The centralised administration was progressively reduced, local militias replaced the professional army, and cities were abandoned.

A thousand years ago the Islamic imperial system had expanded from the original and principal city of Mecca in the Arabian peninsula, to Damascus in Syria and Baghdad in Persia, around the northern rim of the Mediterranean as far as Cordoba and Granada, to Fez in Morocco in North Africa, and up into Asia as far as Samarkand. Under the administration of the Abbasid Caliphate it extended over a greater geographical area than the Roman and Han imperial systems combined, to more than 13 million square kilometres, but with only half the density of population. Existing inhabited cities that had been extensively rebuilt by the Roman imperial system, such as Alexandria, Cordoba and Damascus, were again expanded and incrementally rebuilt. The recombination of successive and distinct spatial and social orders is still evident today. New cities such as Al-Qahirah and Madinat as-Salam, now known as Cairo and Baghdad, were set out and built as fortified walled cities, and imperial libraries were established in both cities to translate and preserve Persian and Greek texts. Baghdad grew rapidly, with a million inhabitants. Within it the library, the 'House of Wisdom', developed into what today might be described as a scholarly research institution, collecting, translating and systematising key ancient and current texts from all across Europe and Asia, and then generating new forms of knowledge. The first organised institution, the Al-Nizamiyya – what today might be called a university, offering free education for the populace – was also founded in Baghdad and the model was adopted by many other cities within the system.

The beneficial warming of the climate across the temperate latitudes of Europe and Asia was coupled to reduced rainfall and increased aridity over the eastern Sahara, the highlands of Ethiopia, around the eastern rim of the Mediterranean and the lands to its east. The consequent ecological stress reduced agricultural returns and diminished the flow of energy through the Islamic system. Although overland caravan and maritime routes extended as far as the more ecologically favoured territories of China, the very long distances prohibited the bulk flow of grains and livestock. Similar difficulties arose to those experienced by the earlier Roman and Han imperial systems: vastly expanded territory, diminishing resources and increasing complexity of the administration required to regulate the flow of information, energy and materials over very long distances. Theological disputes and war between rivals fragmented the system into increasingly independent regional territories, each bounded to their particular regional ecology.

The intensity of energy extraction around the whole Mediterranean region and south-west Asia also contributed to pronounced ecological changes that persist today. Forests provided timber for charcoal making, for the construction of buildings and ships and for the artefacts of war and fortifications. Deforestation had resulted in scarcity of timber all around the southern and eastern Mediterranean before the Roman and Islamic imperial systems,[46] but by 1,000 years ago the entire region was deforested, with depleted and eroded soils. The scarcity of forest resources resulted in intense competition and local warfare between cities and systems of cities, and in turn increased demand. Soil depletion and erosion diminished the energetic returns from agriculture, reducing the population that could be supported so that intensification of agricultural production was necessary. In turn, intensification further increased the depletion of nutrients and further accelerated erosion. Climate and water supply are modified by the metabolic activities of trees, and in the arid and semi-arid regions the cutting down of trees and clearance of forests eliminated the ameliorisation of episodes of drought, and the deserts advanced. In areas with moderate seasonal rainfall, such as the northern shores of the Mediterranean, the leathery shrub and small tree ecology, known as 'maquis', replaced the forests and persists today.

In North America, the changes to the global climate had an even more severe effect. A series of droughts, each at least one and some more than two decades long, occurred all across the southern plains and south-western region of North America. The climate of this region was hot, with a fluctuating pattern of low rainfall. The soil had few nutrients, so even with flood irrigation agriculture could not be intensified. Once the trees had been cut down for fuel and construction and the soil exhausted in a particular location, the people abandoned their settlements and moved to a new site. This system requires a large territory to support a small population that moves and resettles every two or three decades. Over time, the whole region was deforested, erosion accelerated and the soil exhausted. On the Great Plains, as in the Sahara, the dying back of vegetation produced a positive feedback that accelerated the process of desertification and increased the persistence of droughts over time. The long droughts and the consequent ecological changes substantially reduced the agricultural returns of the Anasazi, Mogollon, Hohokam and Patayan peoples, and led to the substantial decline of their populations. Over three centuries of drought there were successive waves of abandonment of the *Pueblo* settlements,[47] and the migration of the people to the more ecologically favourable valleys of the Colorado and Rio Grande rivers. The marginal soils and aridity persist across the entire region today.

The series of severe decadal droughts also had a pronounced effect in the Central American region of southern Mexico and the isthmus connecting the North and South continents of America. The Mayan system had expanded its population to about 5 million people across the region, close to the maximum that the system could support. Agriculture had been intensified by stepped terraces, raised fields and irrigation canals, but further intensification was constrained by the absence of domesticated animals for food and transport systems, and by the lower food energy in the main crop of maize compared with rice or wheat. Individual cities were thus limited to the resources available within a radius of two or three days' walk from the centre. As all materials had to be moved on human backs and all heavy work such as ploughing was done entirely by humans, there was a much higher ratio of human energy invested for lower energy returns than in Europe and Asia.[48] A greater percentage, up to 80 per cent, of the population was involved in agricultural work. The energy flow through the Mayan and other Mesoamerican systems, was in consequence very closely matched to the energetic demands of the cities and settlements. The limestone karst terrain with very few rivers and the long-term regional pattern of fluctuating rainfall made the supply of water a particular problem for cities. In consequence most were built on or close to naturally occurring sinkholes that were lined with plaster to make large cisterns that collected water from extended plastered catchment surfaces. However, the quantity of water stored was rarely sufficient to last more than a year or so, and as a result the series of decadal droughts had a severe effect on the agricultural and water resources of the cities. There were numerous small cities, closely packed together and often competing for favourable agricultural territories but with few links between them. Although written language, numerical and graphical information systems were advanced, and trade in small high value items had reached a regional scale, localised but prolonged warfare between cities was common.[49] Flows of information, energy and material between cities never did develop into a larger and more complex system to distribute resources across the region. Deforestation and soil erosion further accelerated the diminishing returns from agriculture, and city after city was abandoned across the densely packed south of the region. The minimal presence of human occupation over the last thousand years has allowed the tropical forests to expand and today they cover almost the entire region.

THE SLOW RISE IN COMPLEXITY

The climate began to change yet again 500 years ago, entering a three-century long period of intermittently cooler temperatures that persisted until about 200 years ago. The regional and local effects were strongly differentiated, and the lowest temperature and least rainfall occurred in different places and at different times. For example, the coldest century in Europe occurred some 200 years before North American conditions cooled, by which time warmer conditions had returned to Europe. Knowledge of building materials and material manipulation for manufacturing processes was widespread throughout Europe, the Mediterranean region and right across Asia. Building plans and specifications were commonly produced only for larger buildings, were quite standardised, and clearly descended from the systems developed thousands of years earlier. Buildings were still marked out on the ground with ropes as they had always been, and drawings were usually produced during the construction of buildings to resolve difficulties of fabrication and assembly of what were becoming increasingly more complicated details. Evidence suggests that few drawings were necessary, and those that were required were full scale 'working' drawings on plastered floors or wood panels.[50] In China, south-west Asia and the Mediterranean region each craft guild kept their own private sketchbooks with notes on the processes of construction, but European books or texts for the coordination of the many trades and fabrication processes for building construction were rare. Few European examples have survived, and those that have suggest that the cultural diffusion of information from China and from the descendants of the ancient systems of the Mediterranean and south-west Asia took place over centuries rather than decades. Mathematics, surveying instruments and drawings had arisen and developed with the emergence of systems of cities at least 5,000 years before, and had slowly evolved since then. The first systematic use of machines for the mass printing and dissemination of information were the woodcut and moveable character printing presses that were widely used in China several centuries before they appeared in Europe. Mechanical printing systems began to evolve very rapidly about 500 years ago in Europe, enabling the systematic 'mass' production and distribution of books, maps and manuals.

The population of the world had risen to 500 million people, an increase of two thirds over a period of 500 years. The increase is remarkable, as the combination of pandemics of plague that swept across Europe together with the sustained warfare of the expansion of the nomadic peoples of Asia through China to the Mediterranean resulted in more than 100 million deaths. The plague, sometimes referred to as the 'Black Death', is thought to have originated in the widely distributed 'wild' populations of gerbils in the semi-arid region of Central Asia. The vector of transmission between rodents, and from rodents to humans, was the bite of a flea that had abandoned an infected host animal. There is a clear relationship between climate, cities and the dynamics of the plague. Both the host rodents and fleas greatly increase their numbers during warm springs and wet summers, initiating an acceleration of plague events.[51] Cities and settlements have always had large populations of rodents, in many cases thought to equal or exceed the number of humans, and once the transmission of the disease from 'wild' rodents to 'urban' rodents has occurred, the chances of human infection increase exponentially. When the outbreaks of plague in cities occurred, people fled to seek refuge in uninfected cities or settlements, spreading the disease further. The flow of people along the extensive multiple overland and maritime connections between Asia and Europe accelerated the spread into western Europe, where it is estimated that a third of the population died. The enormous expansion of agriculture in Europe was halted, as the population fell and energetic demands reduced, farms were abandoned and the forests began to grow again over what was once cultivated land.

In Asia, the nomadic people of the Asian steppes and deserts had greatly expanded their numbers during the ecologically favourable centuries of the 'Medieval Optimum'. As the steppes began to cool and dry again in the latitudes sensitive to monsoon variability,[52] crop failures and famine were widespread. Right across northern China ecological pressures on the greatly expanded populations induced yet further waves of migration to the south. In the semi-arid regions of the steppes, the social and military organisation of the nomadic system had increased in informational complexity, and the dispersed tribes were united under a single ruler or 'Khan'. Driven south into the more economically favourable territories they conquered all before them, including the imperial systems of China and Islam.

Within one generation the Mongol system extended from the Pacific coast of Russia, right through Asia and into Europe as far as the river Danube. It became the largest land-based system ever, covering 33 million square kilometres and with a total population of over 100 million people. However, the nomadic system had always either traded with or been predatory towards cities and settlements, and had not developed informational systems for the long-term

occupation and regulation of their metabolism. Once the limit of territorial expansion had been reached, the Mongol nomadic system split into four semi-autonomous regional systems that were rapidly absorbed into the more complex systems of information of the territories they occupied. In consequence the process of acculturation modified the nomadic system. In China, the nomads adopted many of the cultural patterns of the imperial system, and were in turn transformed by them. The first city ever built by the steppe nomads, known as Dadu, or great city, conformed closely to the Chinese *Kao Gong Ji* model cities in plan and material construction, and is today part of Beijing. Travellers from the small dense cities of Europe, including Marco Polo, were astonished by the number of cities in China, the enormous areas enclosed within their walls, and the dense populations two or three times larger than that of any city in Europe. The imperial system of China progressively reduced overland trading contacts, recalled their large fleets and effectively closed its borders to the rest of the world for hundreds of years.

Further to the east, at Angkor on the flat floodplain of the Siem Reap River in Cambodia, the urban population had expanded to over a million people. The array of settlements was similar in many ways to that of the Maya, with many small cities without any obvious hierarchy. The polycentric system with multiple 'suburbs' extended over a land area of more than 1,000 square kilometres, integrated by an irrigation system of ponds, reservoirs and canals with built up banks to cope with variability of the monsoons.[53] The system had developed to the maximum level of complexity that could be supported by intensive irrigated rice agriculture. The extensive land clearance deforested the land and accelerated erosion, and the increasingly intensive agriculture required to support expanding populations over centuries depleted the nutrients in the soil. When the latitudinal shifts in the monsoons induced the prolonged cool and dry conditions, it led to accelerated agricultural failure, which ultimately caused widespread famine. The population declined rapidly, and much of the city and its multiple suburbs were abandoned.

In Europe 500 years ago the network of cities, towns and villages that exist today was substantially completed. As the population began to increase rapidly after the plague, the area of land needed for cultivation increased accordingly, reversing the growth of forests over abandoned agricultural land, and accelerating the deforestation of much of Europe. Most dwellings were built of wood, and construction in brick or stone required enormous quantities of strong timber as scaffolding, and the processes of transforming raw materials into even the most basic components of buildings, such as brick, ceramics and metal, all required timber or charcoal fuelled furnaces. It is thought that the largest quantities of all the timber cut from the forests were consumed as firewood for domestic cooking and heating. The development of professional navies and merchant fleets consumed the best quality timber such as oak, larch, ash and beech.

The population of the city of Venice, located between the Eastern Roman empire and the Islamic empire, is estimated to have been as large as 150,000 or so, at the time when the population of Rome had fallen below 50,000, and even the largest city of the Eastern Roman empire, Constantinople, had a central population of no more than 200,000. Venice evolved from Roman settlements on marshy islands at the mouth of the river Po, and sits on millions of oak and larch piles. Over the centuries the forests upriver of the city were cut down to supply the piles, the structural frames of many of the buildings, industrial processes and domestic heating, and for export around the Mediterranean. The rapid erosion of the cleared land and the riverbanks increased flooding and silt deposits in the lagoon.[54] Ships had been constructed in Venice, like other port cities in the western Mediterranean, for at least a thousand years before the building of the Arsenal. The Venice Arsenal was an extensive municipal shipyard within which the systematic fabrication of trading vessels and warships was organised. Craftsmen worked in teams – each specialised in one part of the sequence of construction – using standard pre-shaped timber components. What we now think of as the assembly line logic of industrial manufacturing originates in shipyards, and the shipyard systems were themselves descendants of the organisation of the shared assembly and fabrication of pit structures, dwellings and larger building constructions that had evolved over tens of thousands of years. The Venice Arsenal employed over 16,000 people on its production line 500 years ago, and is reputed to have completed one ship a day.

The form of the Venetian merchant ship or galley was a descendant of the Egyptian and Roman galleys, and still made use of oarsmen. The carrying capacity of ships had increased only marginally from the Roman galleys, but the speed, reliability in adverse weather conditions and the sheer number of ships greatly accelerated the flow of materials and manufactured artefacts through Venice and the Mediterranean region. The evolutionary development of ship design and construction was strongly coupled to a rise in the complexity of

information and the emergence of new modes of representing and disseminating it. Venice was the centre for the first systematic mass production and dissemination of printed information, replacing handwritten manuscripts with books and charts of which thousands of copies could be produced in a single 'print run'. Developments in the forms of ships constructed in Portugal and other Atlantic cities made ships faster, sturdier and capable of a much greater range than the oared Venetian galleys. Construction systems for deep-water ships coevolved with the development of maps, charts and navigational instruments, and had a significant effect on the systems of cities in Europe, enabling their colonial expansion across the continents of the Americas and Africa. The emergence of three-masted sailing ships, with greatly increased sail areas and more sophisticated control systems that enabled them to sail closer to the wind, allowed longer voyages along the coast of Africa and around into the Indian Ocean, across the Atlantic to the Americas, and into the Pacific to complete the circumnavigation of the world. Changes to the form of sailing ships over the next three centuries included increases in size, speed, carrying capacity, and the development of armed ships with accurate gunnery and greatly extended range. Lisbon and Oporto, Amsterdam and Antwerp, Paris and London expanded rapidly to become the largest cities, each with extensive maritime systems through which materials from across the world flowed into Europe, and from where information flowed out.

Maritime systems continued to develop, with systematic mass production of great numbers of ever larger and faster sailing ships, more precise navigation, and professional navies. The capacity to move substantial numbers of people and material across the oceans enabled military excursions and the subsequent colonisation of the Americas. The indigenous people had not developed resistance to viruses that were common in Europe, such as smallpox and influenza, and these diseases spread rapidly through their populations with catastrophic consequences. The total population of North and South America was estimated to have been about 60 million people, similar to the maximum numbers in either the Roman or Han Chinese empires. The densest populations were the Aztecs and the Incas; they were able to support a high population density through intensively irrigated agricultural systems, complex information systems and social organisation. Within a century of the first contacts, however, the demographic collapse was complete, with the population reduced by 90 per cent.[55] In the absence of people, forests began to expand over the abandoned settlements and cultivated lands.

ENERGY, INFORMATION AND COMPLEXITY

A century ago the world population was calculated to have exceeded 1.6 billion (1,600 million), more than three times as many as the number of people alive in the world when the first Europeans made land falls in the Americas. As the existing networks of systems of cities in Asia, Europe and the Mediterranean were connected to each other by a greatly expanded maritime system to the Americas, new forms of fuel energy and information emerged and the interconnected global system was increased in complexity. Successive waves of migrating people flowed from Europe, particularly Spain, Portugal, England, France and the Netherlands. The expansion of settlements and cities in North and Central America accelerated and prolonged the flow over successive generations.

The energy resources of the systems of cities had not changed since they emerged between 5,000 and 6,000 years ago. Biomass in the form of wood and crop residues, human and animal muscles, flowing water and wind were the primary resources. Wood, and later charcoal, provided the source of heat for cooking, the heating of dwellings in winter and for the transformation of materials to be used for construction and manufacturing such as brick making, metallurgy and ceramics. Human and animal muscles were also used to drive water wheels and other mechanisms for lifting water. The lever, wedge, pulley systems, wheel and axle, and the endless screw provided amplification of muscle power in all these activities. River and sea-going craft driven by wind energy, usually supplemented by human muscles, were also in widespread use. Variations and developments in form, size, numbers and efficiency occurred in differing climatic regimes and ecologies, as did their recombination into more complex mechanisms and larger and more complex irrigation systems, manufacturing and construction processes. Nonetheless, the set of energy resources did not change until the expanding populations and consequent increase in demands for timber and charcoal were already surpassing the limits of supply in the extensively deforested territories of North America, Europe and Asia.

Fossil fuels contain more energy per unit of volume than wood and charcoal. The use of fossil fuels occurred first in Europe where localised and small-scale use of coal from surface outcrops is thought to have begun about 2,000 years ago, but it was not until 100 years ago that the burning of coal (and some oil) equalled the use of wood, charcoal and crop residues. Coal requires relatively little processing beyond the difficulties of extracting it from ground, but it did require

a whole new infrastructure of increasingly rapid distribution systems that connected sources and cities, principally canals, railways and steam powered shipping, each with their own specialised buildings and artefacts, that made the fast transportation of coal and other bulk materials possible. The final elements in the new physical infrastructure were the power stations to burn the coal to generate electricity and the 'grid' or extended cable networks to distribute it. The full transition from local systems to national and continental scale systems had taken four generations[56] in Europe and North America, and in other parts of the world it took perhaps a generation or two longer. There are still some parts of the world where, either by circumstance or choice, wood and charcoal persist today as primary energy sources. Oil and gas have followed similar trajectories over time, each taking more than two generations to implement and deploy. All three energy sources are simultaneously in use today, augmented by hydroelectric and nuclear systems, but coal still supplies almost one third of all the energy used in the world.

The ability to extract and deploy energy from 'high density' fuels coevolved with an equally significant acceleration in the velocity of distribution of information, in the variety of its forms and in quantity. The full implementation and deployment of the newly emerged information networks had a similar multi-generation trajectory over time, and the new networks did not replace older distribution systems but added new velocity and greatly enlarged capacity. The forms of information had been greatly expanded over the previous century, with systematic studies of all natural phenomena leading to the development of new domains of knowledge and new disciplines. Naturalists, explorers and experimental investigators of all kinds gathered measurements, made surveys and analysed data statistics, refined instruments and made taxonomies that provided the foundation for new sciences. New forms of communication networks emerged, giving open access to information to many more people, as national postal services became interconnected across continents by railways and between continents by faster and more regular shipping. Newspapers, encyclopaedias, instruction manuals and books of all kinds were rapidly distributed across continents and oceans. Information encoded in electrical impulse, the dots and dashes of Morse code, was almost instantaneously transmitted along continental scale networks of cables by the telegraph, and telephone and radio had begun to expand from their initially small and localised use. Analog calculating machines such as the water-powered astronomical clock described in the *Book of Knowledge of Ingenious Mechanical Devices*[57] had been known in the Islamic system. Analytical engines and machines that could read data from cards patterned with holes, perform calculations and regulate other machine processes in manufacturing industries and for large data projects such as national census had evolved to become widespread 100 years ago.

New material processes were enabled by the phase change in energy and information systems. The construction materials for manufacturing artefacts of all kinds had changed little in more than 5,000 years: wood and other biological materials, brick, and stone and their derivatives. Bronze and iron artefacts and weapons had also been produced for more than 2,000 years. The systematic mass production of iron and steel coevolved with the new infrastructures of energy and information, each acting as positive feedback and intensifying the development of the others. Fuel and food energy, people and materials flowed in increasing volumes and accelerating velocity through the networks of the extended and increasingly connected metabolisms of the global set of systems of cities. The subsequent development of oil and gas, synthetic materials, television and digital computation, each with their respective infrastructures and networks has added complexity to the system, overlaying but not displacing the systems within which they emerged. They also followed similar trajectories over time, taking more than two generations to implement and deploy.

A hundred years ago the number of cities had rapidly increased in North America, and across the world there were at least 16 cities that had more than 1 million citizens. London was the largest at that time with more than 6 million citizens. London, New York, Paris, Berlin, Vienna, Tokyo, Beijing, St Petersburg and Moscow were each the centre of very large imperial systems with extensive land and maritime networks of connections to subsidiary cities and settlements. Europe was intensively urbanised, with more than half of the population living in urban areas. North America and Japan became similarly urbanised within one generation. Asia and Africa were predominantly rural, and remained so until very recently. In China today about one third of the population live in cities,[58] but in Europe and North America four out of every five people do. As the world population has grown exponentially, existing cities have expanded out over their adjacent territories, and new cities have been rapidly built. Over the last century, despite two periods of systematic warfare at a global scale, and several smaller scale but decade-long interregional conflicts, the global system has become increasingly connected over greater and greater distances. There are very few cities in the world today that could survive unchanged on disconnection from the global network, or its failure.

Ten years ago the world population had increased to 6 billion, an increase which had significantly more than trebled in just 90 years. The number of cities with over a million citizens had increased from 16 to more than 450, with uncounted numbers of smaller cities with their own subsidiary settlements. The geographical distribution of extremely large cities, commonly known as 'megacities', reveals the pattern of population growth and city expansion was accelerating most rapidly in Asia, India and South America. Tokyo, for example, had more than 35 million inhabitants at that time, more than half the number of people in either the Han or the Roman imperial systems but concentrated into a tiny fraction of their geographical area. Seoul, Manila, Delhi and Mumbai, Mexico City and São Paulo, and New York each had 20 million or more, and Shanghai, Guangzhou, and Beijing, Osaka, Jakarta, Calcutta, Karachi, Cairo and Los Angeles each had more than 15 million citizens. In some regions cities of varying sizes and densities have become so numerous that there are no distinct territories between them, and they have coalesced into one continuous regional scale urban configuration, commonly referred to as a 'megalopolis'.[59] The largest tend to be located on river deltas, such as the Yangtze River region in China that now has more than 80 million inhabitants. Many more are expected to emerge in Asia within the next generation, and the consolidation of already dense regions in Europe and North America is also likely to continue.

City forms almost everywhere have been modified by the increasing proportion of the physical infrastructures required for the mass movements of energy, information and materials, and people too move greater distances more frequently and at greater velocities than 100 years ago. Cities have become increasingly similar, convergent in the forms of their material and their metabolic organisation, with identical high velocity networks of energy and information that flow across continents and oceans. This is as true of motorcars and mobile phones as it is of clothes and computers, of skyscrapers, suburban homes and shopping malls, of cities, 'megacities' and the regional scale urban configurations of 'megalopolis'. As cities across the world have become increasingly interconnected, and new cities are rapidly built and connected, the complexity of the whole system increases in consequence. The increased size and connectivity enables increased flows between the systems of cities, but it also allows failures and perturbations to travel further and faster from their local origin.

COMPLEXITY AND ECOLOGY

Humans, like all other life, have to extract energy from their environment to generate and maintain their forms, and to reproduce and propagate their descendants out into new territories and down through time. In consequence there are no ecological systems on the surface of the earth that have not been modified in some way by the effects of the extended metabolisms of human societies. The founding system of civilisation used fire to clear land and drive game, cut down trees for fuel and the construction of dwellings, and the extinction of megafauna on three continents induced changes in steppe grasslands, in cool forests and in the warmer grasslands. As human populations expanded across the surface of the earth, the gathering of grains altered the regime of natural selection and initiated genetic changes in wild cereals. These genetic changes, together with the domestication of animals, enabled the development of systematic agriculture. After cities emerged between 6,000 and 5,000 years ago, the increased quantities of energy and materials extracted from their environments began to substantially modify ecological systems over more extensive territories. Food and fuel energy and materials for construction and the manufacturing of artefacts flowed from networks of settlements to the cities. Information flowed back from the city to the settlements as data in the forms of accounts and encoded in transformed materials, such as bricks and ceramics, timber, artefacts, tools and implements. As the system of cities expanded and developed over time the flows became more complex, generating more complex social organisations in the cities, more kinds of and greater quantities of notation and calculation, and more specialists to process that information. As the number of specialised occupations grew, more intensive cultivation was needed to support them, generating extensive irrigation systems, and the modification of ecologically marginal territories was greatly increased. Over time ever more extensive and complex metabolic networks were developed, drawing energy and materials over regional and continental scale territories. The evolutionary development of the metabolic systems of cities has been episodic and irregular, with many periods of expansion to the critical limit of stability, and subsequent collapse and reorganisation. The emergence and development of the systems of cities is strongly coupled to extensive deforestation and the spread of savannahs, the extinction of animal and plant species, soils exhausted of their nutrients, silted river courses and accelerated erosion of the land across Asia, North Africa, Europe and America.

Human modifications to the surface of the earth and to the ecological systems that live upon it have altered the interactions between the surface of the earth and the atmosphere at local, regional, and global scales. The progressive deforestation over three continents and many thousands of years has reduced the transpiration of water up into the atmosphere and altered the storage of water in the soil. It also changed the albedo of the surface, allowing more heat energy to be absorbed by the land. Systematic intensive agriculture has further accelerated these modifications.[60] Additionally, the chemical composition of the atmosphere has been modified, by black carbon (soot) particulates from the burning of timber, charcoal, crop residues and fossil fuels which have added increasing amounts of carbon dioxide and other greenhouse gases to the atmosphere, enabling it to retain more heat energy.

The emergence and development of the coupled high density fossil fuel and equally high density information systems has enabled increasingly rapid acceleration in the rate of growth in human populations over the last two centuries. Half of all humans alive today live in cities, although the geographical pattern is uneven; in Europe and North America this figure is four out of every five people. Existing cities are expanding and new cities are being built, connected and integrated into the world system of cities. The flow of information and energy has accelerated accordingly, the population of the world is rapidly expanding and the complexity of the world system continues to increase. The energetic expense of complexity in the system continues to accelerate, with increasingly greater numbers of people in specialised roles to generate and process the flow of information, and in manufacturing, constructing and maintaining its physical infrastructure. The most densely populated regions of Asia, Europe and North America now consume biological materials at more than twice the rate at which the ecological systems of their own regions can regenerate. They are now dependent on the resources of other regions to meet the deficit in the flow of energy and materials required to support their preferred patterns of consumption.[61] In turn, the increased demands on other regions limits their capacity to expand their own populations. More than half of all the fuel energy consumed in the USA and Europe today is currently imported from other regions, and the dependence on energy imports in Asia is accelerating. There are many indicators that suggest that the system is close to the threshold of stability. Systems that have evolved close to their maximum capacity are poised at the critical threshold of stability and are consequently very sensitive to social, climatic and ecological changes. A local failure may trigger a cascade of failures that amplify each other right across the world and so trigger the collapse of the whole system.

1 Data from *The World at Six Billion*, Population Division, Department of Economic and Social Affairs, United Nations Secretariat, 1999.

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