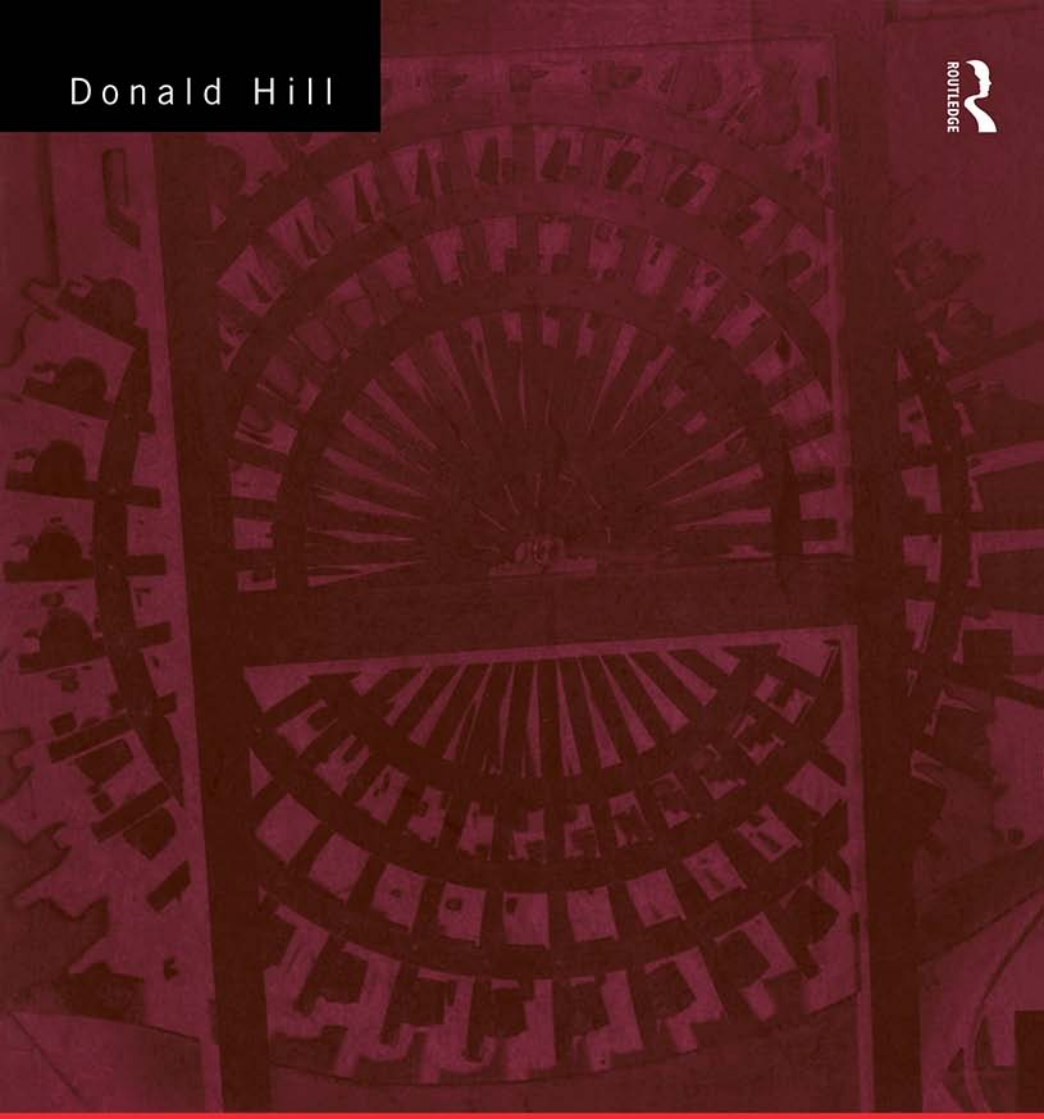
Donald Hill



A History of Engineering in Classical and Medieval Times

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London and New York

First published in Great Britain 1984 by Croom Helm
First published in the USA 1984 by Open Court

Re-issued in paperback 1996
by Routledge
2 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

Simultaneously published in the USA and Canada
by Routledge
270 Madison Ave, New York NY 10016

Transferred to Digital Printing 2007

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloguing in Publication Data
A catalogue record for this book is available from the Library of Congress

ISBN 0-415-15291-7

Publisher's Note
The publisher has gone to great lengths to ensure the quality of this reprint but points out that some imperfections in the original may be apparent

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To the memory of
Rose and Henry Hill

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Abbreviations

Only two abbreviations are used:

1. BGA means *Biblioteca geographorum arabicorum.* This is the title of a series of volumes of the works of Arab geographers published by Brill of Leiden. In the Notes and Bibliography, the details of individual volumes are given.
2. EI is used for *The Encyclopaedia of Islam,* 2nd edition, published jointly by E.J. Brill of Leiden and Luzac & Co., of London. The author, volume number and pages are specified in the Notes and Bibliography. The dates of the volumes are as follows: 1 (1960); 2 (1965); 3 (1971); 4 (1978); 5 — started 1979, but not yet complete. Supplement to volumes 1—3, started 1979, also not yet complete.

Transliteration of Arabic

The transliteration system of *The Encyclopaedia of Islam* has been followed, with three exceptions: 'j' not 'dj' is used for *jim*; 'q' not 'k' is used for *qaf.*

Consonants which are single in Arabic and double in Roman — e.g. 'kh' and 'sh' — are not underlined. Also, diacritical points under letters are given in authors' names in the Bibliography, but not in text or notes.

Acknowledgements

Figure 2.3, from Figure 1 in Norman A.F. Smith, 'Attitude to Roman Engineering and the Question of the Inverted Siphon', *History of Technology*, ed. A. Rupert Hall and Norman Smith vol. 1 (1976), courtesy of Dr Norman Smith; Figure 3.1, from Figure 2 in Norman A.F. Smith, *A History of Dams* (Peter Davies, London 1971), courtesy of Dr Norman Smith; Figure 6.2, from Figures 366 and 604 in *A History of Technology*, ed. Singer *et al.* (Oxford University Press, 1956), courtesy of Dr Trevor I. Williams; Figures 8.2, 8.3 and 8.8 are from Figures 14, 15 and 20 in J.G. Landels, *Engineering in the Ancient World* (Chatto and Windus, London, 1978), courtesy of Dr J.G. Landels; Figures 8.4, 8.5, 8.6 and 8.7 are from Figures 7, 54b, and 33 and 34 in Thorkild Schiøler, *Roman and Islamic Water-Lifting Wheels* (Odense University Press, 1971) — Dr Schiøler very kindly sent originals of these drawings and gave his permission to publish; Figures 8.9, 8.10 and 8.12 are from Figures 135, 138 and 142 in Al-Jazarī, *A Compendium on the Theory and Practice of the Mechanical Arts*, ed. A.Y. Hassan (Institute for the History of Arabic Science, Aleppo, 1979), courtesy of Professor A.Y. Hassan; Figure 9.5 from Figure 2 in Stanley Freese, *Windmills and Millwrighting* (David and Charles, Newton Abbot, 1971), courtesy of David and Charles; Figures 10.2 from Figure 29 in Derek de Solla Price, *Gears from the Greeks* (Science History Publications, New York, 1975), courtesy of Professor Derek de Solla Price; Figure 10.4 (a), (b) and (c) from Figures 1a, 2 and 3 in W. Hartner, 'Asturlab' in vol. 1 of *The Encyclopaedia of Islam*, courtesy of the Editors of *The Encyclopaedia of Islam*; Figure 7.3 from *The Astrolabe* by Harold N. Saunders (Bude, Cornwall, 1971) — Mr Saunders kindly supplied the drawing and gave permission to publish. The remaining illustrations were drawn by the author.

All the Plates were supplied by Dr Norman Smith, who also kindly gave permission to publish.

Preface

This book describes the important engineering achievements of the peoples of Europe and western Asia in the period from 600 BC to AD 1450. A large area and a long time; some omissions were inevitable. These include military engineering, which requires a book to itself, and also a wide range of devices, textile machinery for example, that were largely manually operated. Even so, a process of selection and condensation had to be applied to every chapter in order (it is hoped) to leave the essentials intact. This is a technical history of engineering — social and economic factors are referred to only when they can throw light upon engineering developments. The History of Technology is a discipline in its own right, and should not be seen simply as an adjunct to other branches of history. Certainly, historians working in other fields need the findings of historians of technology, but they should be able to rely upon those findings. It is useless to construct a model of 'technology and society' in a given culture, if the technological data used are faulty. One aspect of this work is concerned with origins and diffusions, and another with *what* was being originated and diffused. Considerable attention is therefore paid to descriptions of techniques and machines.

The task of the historian of technology has been eased in recent years by the publication of texts and translations of source material, papers and monographs on particular topics and a few very good works of synthesis. My researches have included all these types of material but, clearly, not everything that is available. There comes a point, in preparing a work of this nature, when a halt must be called to further research, otherwise the book would never be written. I have tried to treat the area as a cultural whole, since I believe it to be so. I have therefore paid more attention than is usual to Islamic achievements, in an attempt to present a balanced view of engineering developments in the classical and medieval period.

I acknowledge with gratitude the generosity of The Royal Society in furnishing me with a grant to assist me in the preparation of this

work. I wish to thank my friend Dr Norman Smith, of Imperial College, for providing me with illustrations and also for reading Chapters 3 and 4. His comments were very valuable, but the responsibility for any remaining errors or inconsistencies is, of course, mine. I am very gateful to Dr Thorkild Schiøler for sending me some of his own excellent drawings of water-raising machines, and for allowing me to publish them. Professor Derek de Solla Price, of Yale University, kindly allowed me to use an illustration of the Antikythera mechanism; for this, and for his advice and encouragement, I am sincerely grateful.

I also wish to thank my friend Professor Osker von Hinüber, of the University of Freiburg, for his advice on Indian culture and for providing me with books which would otherwise not have been available to me. I have found it a pleasure to work with the staff of Croom Helm, in particular Peter Sowden, and I thank them for their assistance, and for the quality of the production. I have found the library staff of the University of London and the Institute of Historical Research, both in Senate House, and of the Royal Asiatic Society consistently courteous and helpful. I am grateful to Dr John Watson of Great Bookham, who gave prompt and effective help when my health was jeopardised by pressure of work.

My dear wife Pat knows the depth of my feelings for her; this book could not have been written without her unfailing support and encouragement.

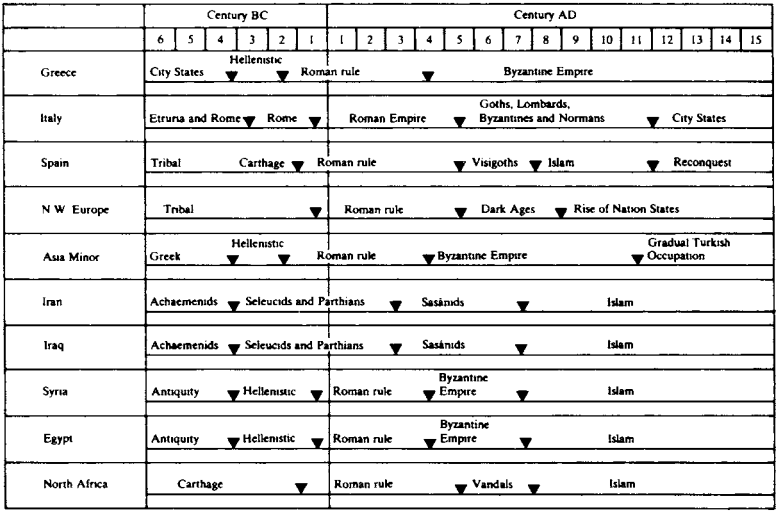
1 Introduction

The Background

A reference framework is required in order to locate events in time and space. With some contractions and omissions, Figure 1.1 shows the conventional divisions for the classical and medieval periods. Even before the birth of the idea of nationality, it is quite acceptable to refer to specific countries, such as Greece and Italy, whose boundaries are well defined. It is also usual to refer to areas in which there is felt to have been some degree of cultural unity — for example, the Roman Empire and Islam. Sometimes space and time are embraced by one image: the Roman Empire can mean either the first four centuries of our era or the area under Roman dominion. Used with care, these concepts have value for some historical purposes, but they can be very misleading. In the first place, we have to bear in mind the shifting of frontiers; in AD 750, for example, the Iberian peninsula was predominantly Muslim while Asia Minor was Christian — by 1450 the reverse was the case. Also, and this can be more serious, the conventional divisions are associated most closely with political and military realities, and often have little bearing on intellectual or social activities. When we think of Roman literature, the names of Tacitus, Virgil and Horace come to our minds, but in the richer, more populous East the languages were Greek, Syriac, Coptic and Aramaic. Most of the literary and scientific writings, in the eastern part of the Roman Empire, were in the first two of these languages. There can be no doubt, however, that the Roman period has distinctive features that justify its special place in history. The Romans were pre-eminent in the fields of organisation, administration, public works and domestic comfort. Their standards were not equalled in these respects until the nineteenth century.

According to convention, the Hellenistic Age began with the conquests of Alexander and ended with the death of Cleopatra. It therefore lasted for about three centuries — from about 330 BC to 30

Figure 1.1: Cultural Divisions



BC. During this period the Seleucids ruled in Syria, the Ptolemies in Egypt. It is often regarded as a period of stagnation, or even regression, between the glory of Greece and the grandeur of Rome. And this for an age that produced Archimedes, Theocritus and many major engineering works! There is, in fact, a strong case for prolonging the Hellenistic Age, for want of a better name, through the Roman Empire into Byzantine times and up to the advent of Islam. In the first centuries of our era great scientists such as Ptolemy, Pappos and Hero wrote in Greek in Alexandria, and there was also a thriving scientific tradition, with Syriac as its language, centred on Harran in northern Mesopotamia. Scholars from Harran were a seminal influence on the nascent science of Islam.

The concept embodied in the term 'Dark Ages', however, has some validity. The period from the fifth to the eighth century witnessed a marked decline in intellectual activity, and a falling off of standards in sanitation, water supply, communications and domestic comfort. The obscurity of the period is a serious drawback for historians, since the lack of written records means that for most subjects the only evidence comes from scanty archaeological findings. In the Byzantine and Iranian Empires, in this period, civilisation remained at a high level, but written evidence from these two cultures is very sparse. In 915 al-Mas'ūdī saw a large book dealing with the history of

the Sasānid kings and many of the sciences. The book was found in the royal treasury in Persepolis in 731 and was translated from Farsi into Arabic for the Umayyad Caliph Hishām bin 'Abd al-Malik.[1] No copy of this work has been found, but the reference to it implies that there was intellectual activity in Sasānid Iran. Indeed, we have firmer evidence for the existence of a scientific tradition in Iran in the foundation of a famous hospital and medical school in the city of Gondeshapur in Khuzistan. The transformation of Gondeshapur into an important medical centre was due to a group of Nestorian Christians from eastern Anatolia who had fled from Byzantine persecution. This probably occurred in the reign of Khusraw I (AD 531–79). Although there may have been some Indian influence, the teaching and treatment, which was based solely upon scientific medicine, was derived from the schools of Alexandria and Antioch, but it became more specialised and efficient. Gondeshapur was to be the foundation of Islamic medicine in the eighth century.[2] There are more written records from Byzantium than from Iran in this period, but many of these deal with theological and philosophical matters. For neither area, in fact, — and this applies to Byzantium in the centuries after the rise of Islam — is there much data about technology.

The Arab conquests of the seventh and eighth centuries changed much, particularly in the close cohesion of religion and daily life that is characteristic of the Muslim religion. The success of Arabic in replacing the original languages throughout North Africa and most of the Middle East, and becoming the vehicle for literature in the whole of the Muslim world was of tremendous importance in the upsurge of intellectual activity that began when the process of conquest and consolidation was complete. A further impetus was the translation from Greek, sometimes through the medium of Syriac, of many scientific and philosophical works. The conquering armies from Arabia were, however, small in numbers compared to the populations of the conquered lands, and a slow process of fusion took place, with Islam and Arabic becoming predominant while the Arabs were influenced by the cultural traditions of the conquered peoples. When, in the present work, the word 'Islam' is used, it is to designate the cultural area that was the result of this fusion. It is necessary to bear this definition in mind, since many of the great writers in Islam have been non-Muslims. In some ways the term 'Arabic' is more satisfactory, but it leaves out of account, for example, the great literary works written in Farsi. Also, in discussing technological matters, we

often have recourse to non-literary evidence. We can hardly call a mill built in Central Asia an 'Arabic' mill.

The standard of technology at any time depends mainly upon the demands of society. Where there are large urban communities to be fed, housed, clothed and provided with the raw and finished materials for commerce, we shall find technology applied to agriculture, communications and industry. The Arabic writers on geography in the tenth century describe a society in which the range of foodstuffs, the quality of textiles and indeed the standard of living in general were far in advance of conditions in Europe, and utilitarian technology was therefore relatively more developed. Courtly circles in Islam, not only in great centres such as Baghdad and Cordoba, but also in the courts of minor princelings, expected to be amused and given aesthetic pleasure by the production of ingenious devices, thus stimulating the development of fine technology, despite the apparent triviality of some of the devices. A further stimulus was provided by the requirements of astronomers for timepieces and for observational and computational instruments. (Astronomers, in fact, often made their own instruments.) Conditions were not propitious in Europe at this time. Populations were scattered in small communities and the ruling classes were largely illiterate. In the twelfth century European technology began to develop rapidly, along with the growth of cities and mercantile activity. In some fields, but not all, Europe had surpassed Islam by the close of the fifteenth century. The debt owed by Europe, in matters of technology, to Islam and other civilisations has never been fully acknowledged, and it is hoped that some of the material in this book will help to redress the balance. Nevertheless, it is undeniable that European technology has continued to develop from its medieval origins until the present day, while that of other cultures has not.

A close study of the interactions among technology, society and economic life is beyond the scope — and indeed the purpose — of this work. From time to time, however, connections will be indicated when these have a direct bearing on engineering developments. For example, the use of very large mills to grind corn for Baghdad is directly related to the fact that the population of the city, about 1.5 million in the tenth century, was a large net consumer of agricultural produce. It will also become evident that in certain places at certain times there were marked expansions in engineering activity, either in the scale of installations or in innovativeness, or both. We can identify the most significant of these:

Hellenistic world	330–30 BC. Machines, fine technology, irrigation.
Sasānid Iran	200 BC–AD 640. Civil engineering, irrigation.
Roman Empire	First four centuries AD. Civil engineering, surveying, water supply.
Islam	Ninth to thirteenth centuries AD. Water supply, irrigation, water power, fine technology.
Europe	Twelfth to fifteenth centuries (and beyond). Wind and water power, machines, mechanical clock.

Engineers and Artisans

The modern idea that the engineer is essentially an applied scientist simply does not hold water. It is true that in the last two centuries the engineer has had at his disposal a growing array of quantified scientific data upon which to base his designs, and that no engineer worthy of the name can ignore these data. Nevertheless, the execution of a construction project poses a number of problems that are unconnected with pure scientific reasoning. Some of these problems are not even of a directly technical nature: for example, the financial side of contracting and subcontracting with the accompanying measurement and valuation procedures. There are many other problems that are technical, but not directly related to science. An engineer needs to know the capabilities and limitations of men, machines and materials, and the restraints imposed by weather and soil conditions. Engineering science can assist in the resolution of some of these problems, but in the end we should expect our engineers to get their hands dirty — in the workshop or on construction sites. We should not be complacent, and assume that we have got the mixture of theory and practice exactly right. There have been enough failures in modern engineering to teach us a little humility. One might object, with some justice, that we approach the structural limits of materials much more closely than did the early engineers. So we should — with 4,000 years of their experience and almost two centuries of scientific analysis behind us!

In general, the classical and medieval engineers did not have a quantified, scientific basis for their designs. An exception to this

statement is the case of the five simple machines — lever, wheel, pulley, wedge and screw. Mathematical analysis of these machines had begun to take shape among the Greeks of the fourth century BC. Their results were by no means wholly theoretical. It is worth quoting in full what Bertrand Gille has to say about the greatest early worker in this field:

> Archimedes of Syracuse (*c.* 287–212 BC), greatest of all the ancient exponents of mechanics and one of the greatest mathematicians of all time, was the first of the long line of those who have promoted science by propounding practical and definite problems. Like Pythagoras and Archytas, like the Egyptian and Babylonian surveyors before him, and like Leonardo and Galileo after him, Archimedes was a geometer because geometry is a technician's science. His researches on statics revealed the fundamental principles relating to the lever and the centre of gravity. His studies were of great assistance to those who sought to construct purposeful machines. These geometrical investigations of Archimedes were important, since, if we may believe Plutarch (*c.* AD 46–*c.* 125), they enabled him to calculate, for example, the number of pulleys needed for lifting a given weight with a given force. He knew how to calculate mechanical advantage, than which there is nothing more important for all lifting-devices.[3]

There can be no doubt that the results of Archimedes and his successors such as Hero of Alexandria (*fl.* middle of first century AD) were applied to lifting devices, war machines, steelyards and so on. The difficulty with so many other problems in engineering is that their solution almost always demands the use of differential or integral calculus, which was not invented until the seventeenth century. Nor should we forget the difficulties of making calculations without the place-number and decimal systems. We also have to bear in mind that engineers and master craftsmen were often illiterate, at least in the sense that they could not read the languages in which the theoretical treatises were written. This probably applies to most of the master masons of Europe, some of whom may have read their own vernaculars, but not Latin. But in the use made by the master masons of geometry lies the key to the way of thinking of all the early engineers:

> It becomes evident that the 'art of geometry' for mediaeval masons meant the ability to perceive design and building problems in

> terms of a few basic geometrical figures which could be manipulated through a series of carefully prescribed steps to produce the points, lines and curves needed for the solution of the problems. Since these problems ranged across the entire spectrum of the work of masons — stereotomy, statics, proportion, architectural design and drawing — the search by modern scholars for the geometrical canons of mediaeval architecture is appropriate enough, so long as we keep clearly in mind the kind of geometry that was actually used by the masons. The nature of that geometry suggests that these canons, when recovered, will not be universal laws which will at last provide *the key* to mediaeval architecture; rather, they will be particular procedures used by particular master masons at particular times and places.[4]

It is precisely this kind of constructive approach that determined how a given problem was to be solved. The engineers had to know geometry, arithmetic and some trigonometry. They also had to understand the properties of materials and the way in which fluids and solids behaved in a certain set of conditions. Faced with a problem, they applied this knowledge to solve it in the most satisfactory manner open to them. For example, in bridge building it is desirable to keep the number of piers to a minimum. Piers are an obstruction to shipping, they are expensive to construct and they are more prone to failure than the superstructure. If semicircular arches are used for a large span they will be very high, so it became necessary to build segmental arches. To take another example, from mechanical engineering, the suction pump with horizontal cylinders and vertical suction pipes was developed by Islamic engineers from the so-called 'Byzantine siphon', used to discharge Greek fire from warships. In the earlier force-pumps the vertical cylinder had stood directly in the water, but clearly this was both undesirable and impractical with inflammable fluids. Both these cases, and many more could be cited, illustrate the solution of problems by practical thinking — the theory came later.[5]

The concept of specialisation is very recent. Of all the scholars whose names have come down to us, only al-Jazarī (late twelfth century) seems to have devoted his entire life to engineering. The others began their careers in a variety of occupations: Ctesibius (third century BC), according to Vitruvius, was a barber; Guido da Vigevano (first half of fourteenth century AD) was trained in medicine; Mariano Taccola (first half of fifteenth century AD) was an

artist and sculptor. Al-Bīrūnī (d. after AD 1050), probably the greatest scientist of medieval Islam, made astronomical instruments and studied mining technology. Although some of the wide-ranging studies of men such as these may have been decided by personal preferences, they were often obliged to follow the dictates of their patrons. No doubt there was an element of prestige in having learned men attached to one's court, but they were expected to earn their keep as physicians, astronomers, teachers, architects and engineers. Demarcation was unknown — they had to apply themselves to whatever matters were the concerns of their patrons at any given time. Versatility was normal, but it was also essential. It is hardly surprising to find that many of the engineers were concerned with devising and building engines of war — Archimedes, Vitruvius (first century BC), Hero, the Banū Mūsà (mid-ninth century AD), de Vigevano and Taccola — to name but a few. Many of the English medieval architects also built siege engines.[6]

Considerable discussion has taken place on the status of engineers in society at various times. (Here we are defining engineers as those who devoted at least part of their time to engineering.) It is well known that Plato and other classical writers had a low opinion of technology and manual work, but these activities were not so universally despised as might appear from these writers.[7] Indeed, it seems to have been quite usual for engineers to occupy a respected place in society. Frontinus (first century BC) was a highly-placed government official, the Banū Mūsà were the trusted advisers of a succession of Abbasid Caliphs in Baghdad, Taccola became an eminent citizen of his native Siena. The great architects of the Middle Ages, often appointed directly by the Crown, undertook the design, administration and supervision of construction on large public buildings. It is impossible, however, to make any general statement about the status of engineers, partly because we are considering a number of widely differing societies over a long span of time, and partly because the background, training and duties of engineers varied so greatly. We know that some of them, such as al-Jazarī and the English architects, were themselves master craftsmen who were highly skilled in the various engineering trades. Others, such as Frontinus, were simply civil servants who happened to be placed in charge of departments that were concerned with engineering matters. Between these two extremes lies the whole range of classical and medieval engineering. In dealing with the first category we can see quite clearly the difference between engineers and artisans — the

engineer was simply an artisan who had reached the top of his profession. It was often possible, at certain periods, for a master mason, carpenter or metalworker to reach a position of high responsibility.

It is of course obvious that there have always been large numbers of workers — skilled and unskilled — who never have risen high in the ranks of society. The question of the varying status of artisans throughout the classical and medieval periods is a topic of great complexity, which it is beyond the scope of this book to discuss in any detail. At certain times artisans, even if they were not actually slaves, were subject to strict control. In Imperial Rome the *fabricenses*, or armament workers, were branded on the arm so that if they deserted the factories they could be identified and returned.[8] When the Caliph's wazir, or counsellor, was constructing a bridge in Iran in the second half of the tenth century he conscripted the engineers and craftsmen from Isfahan.[9] On the other hand, the work of craftsmen was often well respected; in Iran the names of carpenters sometimes appeared as inscriptions on their products, for example the name of a certain Husayn b. 'Alī on a richly carved door made in 1428.[10] But for any kind of detailed study of the question, recourse must be had to works of economic and social history.[11] There is also one type of writing that is particularly useful for understanding the work of craftsmen in Islam. These are the books written for the instruction and guidance of the *muhtasib*, who was the official appointed by the ruler or his representative to supervise the affairs of the market. The duties of this official were wide ranging, since the market, or *sūq*, was the centre for commerce and industry in the city, and he was required to supervise its daily affairs: the maintenance of moral standards and religious observance; quality and quantity control over retailers and manufacturers; sanitation and water supply; checking the manufacture of building materials and the erection of houses. Usually an experienced craftsman was made responsible to the muhtasib for the maintenance of standards in his own trade. There is therefore a great deal of useful information in the *hisba* manuals about manufacturing and constructional methods.[12] Nevertheless, many of the trades practised in the Islamic, and indeed European, cities were not concerned with engineering and, in any case, we cannot readily define the relationships that existed between the engineers, and the craftsmen of the cities.

Nowadays there is a marked distinction between artisans who are based in workshops and factories and those who usually work on

construction sites, although there is of course mobility from one type of work to the other. For many trades, however, the type of skills demanded on construction are quite different from those needed in a workshop and this was equally true in earlier times. The type of woodworker who made ornamented furniture would not have been able to erect the timber falsework for a large masonry arch. The available evidence does indeed indicate that engineering workers formed a distinct group in classical and medieval times. Frontinus tells us, for example, that there were two gangs of slaves allocated to the maintenance of Roman water installations, one numbering about 240 men, the other 460. Both were divided into several classes of workmen: overseers, reservoir-keepers, inspectors, pavers, plasterers and other workmen.[13] In medieval England masons were often conscripted for Royal works, whereas for non-Royal buildings they were hired by the master mason.[14] In either case, it is probable that the same men were employed on a single site for a period of some years. Some classes of work did not demand large numbers of skilled artisans. For the excavation of canals in eleventh-century Iraq, for example, the engineers and surveyors established the lines, levels and profiles of the canals, and gangs of labourers worked under their supervision.[15]

Things are rather different in the field of fine technology. Al-Jazarī, who composed his excellent machine book in AD 1206, was clearly a master craftsman in his own right, who was capable of constructing large and small machines entirely with his own hands.[16] This consisted of metalwork of all kinds, including casting in copper, brass and bronze, soldering and tinning, sheet metalwork and so on. For his larger devices he would have needed the help of a labourer, and he may have trained apprentices, but otherwise he required no outside assistance. The treatise of Theophilus, written in the early 1120s, is the work of a master craftsman in paint, glassmaking and metalwork, although the engineering content of his work is much less than that of al-Jazarī.[17] The case of the Banū Mūsà, who composed their book on Ingenious Devices in Baghdad about 750, is rather different. These three brothers were prominent engineers and scientists, and their work shows a masterly use of differential pressures, but they make very little mention of the processes of construction, although the devices 'as built' are described clearly enough. It is possible, though by no means certain, that they did not make the devices themselves, but employed skilled metalworkers who worked under their direction.[18]

A Note on Tools

Man has been making tools for at least 2.5 million years and the stone tools in their last phase of development, the Neolithic, include most of the main types in use today. The advent of iron, however, was a very significant step in the history of tools, particularly with the discovery of hardening by carburisation and heat treatment, which led to superior edge tools of great toughness. These processes were discovered early and were fully utilised by Roman times. The basic kit of iron tools was available to Assyrian craftsmen in the eighth century BC and remained in use through classical and medieval times — the only major addition was the plane. But tools, within a given tool type, became very specialised. For percussion tools, for example, there was a complete range, from the heavy hammers used in quarrying and forging to the delicate hammers of the goldsmiths and jewellers.

The basic cutting tools were the axe and the adze — in the former the blade is parallel to the handle, in the latter it is at right angles to the handle. The heavy felling axe was used for clearing woodland, whereas the broadaxe was designed to convert felled timber to squared. It had a shorter handle than the felling axe with a heavier head, and was a two-handed tool. The adze was an indispensable tool of general utility for, in addition to surfacing, it was particularly useful for trueing and otherwise levelling framework such as posts, beams and rafters. Saws were originally designed to cut on the pull stroke but the modern practice of using the push stroke probably came into use towards the end of the Roman period as saws became more robust. A major contribution to saw design was noted in the first century AD by Pliny the Elder; the teeth of the saw were set — that is, alternate teeth were bent to one side or the other, so that a slot was created in the wood wider than the thickness of the blade. This helped to discharge the sawdust and also allowed the saw to run with less friction.

Chisels and gouges were made in great variety, from the heavy tools of the carpenters and masons, which were struck by mallets, to the more delicate hand-held tools of the woodcarvers. The Romans were the first definitely known users of the plane, the earliest examples coming from Pompeii. They appear to be without a pre-history, without even vague antecedents. The modern plane differs in detail, but not in principle nor in general appearance. The essential features of the plane are the wooden body pierced by a wide throat with a narrow slit in the bottom. The blade is held in position by a wedge tapped under an iron bar across the throat. The file is also used

for smoothing, and is more suitable for metalworking than the plane. The file's many tiny chisel-like teeth were produced by cutting with a small chisel-like hammer or with a hammer and chisel. After this treatment the file is tempered and quenched. Theophilus mentions files of square, round, triangular and other shapes. Specialised uses of the file included sharpening saws and cutting the teeth of gear-wheels.

Drilling and boring was done with simple awls and gimlets that push the material aside without removing it, with drills and with augers. The bow drill was invented as early as Upper Paleolithic times and it remains in use today in some parts of the world. A bowstring wrapped around the shaft imparts rotation to the shaft in alternating directions. The more complicated pump drill was developed in Roman times. A crosspiece that could slide up and down the spindle was attached by cords that wound and unwound about it. Thus a downward push on the crosspiece imparted a rotation to the spindle. A flywheel on the spindle kept the motion going, so that the cords rewound in reverse to raise the crosspiece as the drill slowed, and the next push down brought the spindle into rotation in the opposite direction. The basic auger originated in the Iron Age. It resembled a half pipe sharpened on the inside, along the edge, or both. It had a crossbar that could be turned with two hands. The earliest illustration of the brace-and-bit occurs in an illustration of about AD 1425.

The only early machine tool was the lathe, which was introduced into Europe by the Greeks in the seventh century BC, probably from the wood-producing areas of the Middle East. Most early machines were pole-lathes. This consisted of a bed with uprights in which bearings were installed; the work, roughly hewn to a cylindrical shape, was revolved in these bearings. A resilient pole projected over the bed, and a cord attached to its end was wrapped round the work and thence attached to a hinged board serving as a treadle. When the board was depressed the cord spun the work round in one direction; when the pressure of the foot was relaxed the bough sprang back, drawing the cord and treadle upwards and turning the work in the opposite direction. Motion was thus reciprocating, not continuously rotary, and this allowed the wood cut by the simple hook-tools on the down-stroke to be cleared on the up-stroke, thus avoiding clogging and loss of control.

Other tools, in use throughout our period, include tongs, pincers and pliers, engraving tools, and punches for doing repoussé work in sheet metal. Measuring and defining tools included the plumb line,

level, square and compasses. Some applications of these will be described when methods of construction and assembly are dealt with in subsequent chapters.

Notes

1. Abu'l-Hasan al-Mas'ūdī, *Kitāb al-tanbīh wa'l-ishrāf*, ed. M.J. de Goeje, vol. 3 of *Biblioteca Geographorum Arabicorum* (Brill, Leiden, 1894), pp. 106-8.

2. Aydin Sayili, 'Gondēshāpūr', *EI*, vol. 2, p. 1120.

3. Bertrand Gille, 'Machines' in Charles Singer, E.J. Holmyard, A.R. Hall and Trevor I. Williams (eds.) *A History of Technology* (Oxford University Press, 1956, reprinted 1979), vol. 2, pp. 629-57, pp. 632-3.

4. Lon R. Shelby, 'The Geometrical Knowledge of Mediaeval Master Masons', *Speculum*, vol. 47 (1972), pp. 395-421, pp. 420-1.

5. For the segmental arch see Chapter 4, for pumps see Chapter 8. The line of reasoning in this paragraph was generated in the course of discussions between myself and Dr Norman Smith of Imperial College, London.

6. John Harvey, *English Medieval Architects* (Batsford, London, 1954), pp. 22ff., 91, 150ff.

7. F. Klemm, *A History of Western Technology*, tr. Dorothy W. Singer (George Allen & Unwin, London, 1959), pp. 18-24.

8. W.H.G. Armytage, *A Social History of Engineering*, 3rd edn (Faber and Faber, London, 1970), p. 33.

9. Zakarīya bin Muhammad al-Qazwīnī, *Athār al-bilād* (Beirut, 1960), p. 303.

10. Hans E. Wulff, *The Traditional Crafts of Persia* (The MIT Press, Cambridge, Mass., 1966, 2nd printing 1976), p. 81.

11. Useful discussions of the subject will be found in N.J.G. Pounds, *An Economic History of Medieval Europe* (Longman, London, 1978), pp. 27-34, 71-9, and especially Chapter 4, 'Medieval Manufacturing', pp. 279-337.

12. One of the best (and most accessible) of the *hisba* manuals is Ibn al-Ukhuwwa. *Ma'alim al-Qurba fi Ahkām al-Hisba*, Reuben Levy (ed.) with Arabic text, notes and abridged English translation (Gibb Memorial Series, New Series, London, 1938).

13. Frontinus, *The Strategems and the Aqueducts of Rome*, ed. wth Latin text and English translations by Charles E. Bennett and Mary B. McElwain (Loeb Classics, Cambridge, Mass. and London, 1925, reprinted 1980), pp. 447-8.

14. Lon R. Shelby, 'The Role of the Master Mason in Mediaeval English Building's, *Speculum*, vol. 39 (July 1964), no. 3, pp. 387-403, p. 396.

15. Claude Cahen, 'Le Service de l'irrigation en Iraq au début du XIe siècle', *Bulletin d'etudes orientales*, vol. 13 (1949-51) pp. 117-43.

16. Ibn al-Razzāz al-Jazarī, *The Book of Knowledge of Ingenious Mechanical Devices*, tr. and annotated by Donald R. Hill (Reidel, Dordrecht, 1974).

17. Theophilus, *On Divers Arts*, tr. from the Latin with introduction and notes by John G. Hawthorne and Cyril Stanley Smith (Dover Publications Inc., New York, 1979).

18. The Banū Mūsà, *The Book of Ingenious Devices*, tr. and annotated by Donald R. Hill (Reidel, Dordrecht, 1979).

19. There is no comprehensive work on tools. This note is taken from the following: Richard S. Hartenberg, 'Hand Tools', in *Encyclopaedia Britannica*, 15th edn (1974) pp. 605-24 (with bibliography); R.W. Symonds 'Furniture: Post-Roman', pp. 221-58, and R.H.G. Thomson, 'The Medieval Artisan', pp. 383-96,