a guide for the perplexed

TOM HEATH
CHAPTER 3

the materials of construction

www.tomheath.org
What this book is not
This book is not intended to explain how the ‘design elite’, as Larson (1993) calls them, go about designing buildings. There are plenty of books by and about leading architects which seek to do this. However, these books do not seem to be much help to the beginning student facing that dreadful blank screen or sheet of paper.
This is not because these eminent people or their biographers are deliberately setting out to mislead anyone. No-one would expect a great musician’s musical biography to pay much attention to chords and finger exercises. Yet chords and finger exercises, or their equivalent, are essential parts of the preparation for any skilled performance, and architecture is a very skilled performance indeed.

What this book is
Sir Henry Wotton (1686), who gave the English-speaking world its most popular architectural cliché, ‘commodity, firmness and delight’, also gave his readers much practical advice. In writing about staircases, he says that what he is providing is a set of ‘vulgar cautions’, that is, advice designed to help people not to make elementary mistakes. This book is a book of ‘vulgar cautions’ for beginning architecture students.
The approach taken throughout will be found to differ from those of some other writers, partly because design is a large subject and will look different from different points of view, partly because of its resolutely practical viewpoint, and partly as a consequence of differences in values.

Extract from Chapter 1 Introduction
PROFESSOR TOM HEATH (1931–1998)
A graduate of the University of Sydney (B.Arch 1954), (M.Bld Science 1966), (M.Arch [Research] 1980), Tom Heath joined prominent Sydney firm of McConnel Smith and Johnson where he was a director for 15 years. In 1979, he left the practice to become Dean of the Faculty of Built Environment and Professor and Head of the School of Architecture Interior and Industrial Design at QIT, then QUT in Brisbane until 1990. He then became University Research Professor of Design and Director of the Research Concentration in Design and Construction Studies at QUT. At the same time he was editor of the RAIA journal *Architecture Australia* from 1980–1990. Heath was highly respected as an architectural theorist and wrote three books and over 200 papers on the theory of design. *Method in Architecture* (Wiley 1984) and *What if Anything is an Architect?* (Architecture Media Aust 1991), was followed by *Learning Architecture / Teaching Architecture: A Guide for the Perplexed* which was completed shortly before his death. His role as editor of *Architecture Australia* gave him the opportunity to be heard by the profession at large and through his editorials, he was a prominent voice. He was a foundation and active member of the Environmental Design Research Association (USA) and was inducted into the Design Institute of Australia Hall of Fame in 2007. His often perceived eccentric ways of a bow tie wearing academic, concealed an intensely private man who eschewed convention. His contribution to QUT was recognised by the establishment of the Tom Heath Gallery within the QUT Art Museum.

*Robert Riddell*

Extract from *Encyclopedia of Australian Architecture* (CUP)

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a guide for the perplexed

TOM HEATH

illustrations by Ray Jones

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The manuscript of this book was completed by my husband Tom Heath shortly before his death. In the process of producing and publishing the book, I was immensely grateful to receive valuable advice, encouragement and assistance from Tom’s friends and colleagues, and would like to specifically thank Amos Rapoport, Andrew Seidel, Wolfgang Preiser, Gordon Holden, Vesna Popovic, Jill Franz, John Simpson, Ian Close and Harry Nicolson.

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Special thanks to Ray Jones for his elegant illustrations throughout, and also to Jennifer Marchant, Heather Buchanan, Janelle Fenner, YE Ng and others for their assistance in the production of the book. The illustrations in Chapter 2 are based on original sketches by the late Paula Whitman.

Sipen
foreword
There have been various responses to a sense of dissatisfaction with architecture and architectural education. Some new fields have emerged to suggest solutions (e.g. Environment-Behaviour Studies, Design Methods and Participation). In my own field of Environment-Behaviour Studies, two attitudes can be identified. The majority tries for improvements within the existing paradigm, hoping to improve architecture, the profession and education incrementally – through a greater emphasis on research and users. I am a minority (possibly of one) and argue for a radical change, for a redefinition of architecture (as a science based profession not an art) and hence of the nature of design and education. As a result I rejected the core of architectural education, the studio, and have refused to teach studio or be involved with it for 40 years. Since my 1983 article about the topic I have become even more radical.

What then am I doing writing a foreword for a book on how beginning students in the studio might learn better and be taught more effectively?

What follows is an answer to that question.

I begin by admitting that my position is totally unrealistic (although, I believe, essential). Effectively, I have given up on architecture as it is. Tom Heath was ever the architect, and took a realistic position. While aware of the more radical positions, he believed that through research and incremental change things could be improved. In fact, Tom Heath and I had great debates when we met at conferences and late into the night when I stayed with him during visits to Brisbane and QUT. It was something we both enjoyed.

It was clear that anything Tom said had to be taken seriously – it was always the result of careful thought and thorough knowledge. This applies specially to this book which presents the full development of his ideas about how to improve studio education and bring it and the profession closer – a goal dear to Tom’s heart, reflecting who he was.

After many years as a director of a large Sydney practice (McConnell, Smith and Johnson), i.e. deeply involved professionally, he moved to academia. He became University Research Professor of Design at QUT, and became equally involved in academia. He did research and
not only taught and mentored students but thought deeply about teaching and learning. He also published, both papers and books. One was *Method in Architecture* (1983) in which he dealt with some of the theoretical issues explicitly omitted in this book although as he points out, these inevitably appear in the last chapter addressed to teachers. The second was *What, if anything, is an Architect?* (1991). In the present book he draws on his deep familiarity with both academia and the profession.

Another important thing: as an undergraduate, Tom Heath had been influenced by Andersonian philosophy. As a result he could approach issues intellectually, be analytical and develop a clear, logical argument. At the same time he managed to avoid the jargon, obfuscation and fashionable verbiage that marrs many philosophical and architectural writings. In this book the clarity of thought is matched by the crystalline clarity of expression: the use of simple language, a concise and very structured, easy to follow argument. This makes it of great benefit to read it, even if one disagrees with it, or parts of it.

One important aspect of research and scholarship is the extent to which it stimulates thought, questions, reactions and challenges readers (if they disagree) to formulate equally clear, cogent, logical and well-supported counterarguments. Consider two recent quotations from a single issue of the journal *Science* (Vol 326, Issue 5951, 16 October 2009). In the first (p336) a paper is described as ‘one of the most important – not because it is right – I think it is a little wrong – but because it acted as a catalyst to get people thinking’. The second, on pp368-369, reviewing a book says that ‘…fruitfully forces us to think in new ways about…’.

*Learning Architecture / Teaching Architecture: A Guide for the Perplexed* does that extremely well, as I will elaborate below.

I think of architecture as dealing with two major questions. The first is what should be done, i.e. what should any given environment be to be supportive of its users, and *why* – providing the research-based evidence for the decision. Then follows the second question – *how* should that environment be given material expression. I regard the first question as more important, but underemphasised, especially in the studio. Heath explicitly addresses only the second
question which of course remains essential (and it is the second question with which studio is currently largely concerned). Since not much is said about the first question, a major point of potential disagreement with my position disappears, because my concern is with how the first question can be made dominant, or at least given more emphasis.

Heath does an outstanding job in dealing with how to improve the way studio deals with the second question. He uses a most unusual and interesting approach by approaching the issue from two directions: first looking at how students best learn (the bulk of the book) using many research findings and, second, how particular ways of teaching could help.

It is a thoughtful, sophisticated, superbly reasoned and clearly expressed account of how architects approach design. It makes explicit what is typically either left implicit or obfuscated. It challenges the reader, student or teacher to think – to think hard, clearly and explicitly about what is being said and advocated, and about the nature of the evidence used. Ultimately that is what education (as opposed to training) is all about. It poses a major challenge for someone to write as good a book about the what and why of architecture as this is about the how, and about how a better job can be done in teaching and learning that aspect of architecture (and how the two can be brought together).

For me, reading is a form of dialogue with the author. Publications that I own (and student work) are much annotated – usually in red ink. As a result, when I retired, my PhD students gave me a red roller-ball pen. I still use it – and it was extensively used on the manuscript of this book.

These annotations showed me how this book has greatly clarified the nature of my position – the points of agreement, of disagreement (and where these are most acute), and my positions vis-a-vis the evidence cited. In effect, Learning Architecture / Teaching Architecture provides guidance, a road-map as it were, of how and where to identify counter-arguments and cite contrary evidence. It challenges one to construct what one hopes would be an equally clear, logical and well-reasoned argument (not an easy task).
From the first paragraph of Chapter 1, Heath clearly states his position, his starting point, his goals; the route followed and the decision points en route become clear as he proceeds point by point, using short, pithy, clear sections. One’s own thinking becomes structured and clear rather than global and inchoate.

In a book on the genetic bases of human behaviour by W.R. Clark and M. Grunstein (Are we Hard Wired? p239), it is said about a paper that it can be praised, rejected, welcomed or damned, depending on one’s position, but it cannot be ignored.

Neither can A Guide for the Perplexed be ignored, nor must it be. It is to be hoped that readers, whatever their position, will pay due attention and read it as though engaged in a high-level dialogue with someone very special.

Tom Heath died much too early. Personally I wish that he were still with us, and that he and I could continue to debate issues in person. This book, if read creatively and proactively, is the next best thing. We thus owe a debt of gratitude to his wife Sipen for the work she did to make this book available to us.

Amos Rapoport
It is an honor, indeed, to frame Tom Heath’s book.

I had the pleasure of meeting Tom first in 1972 in Leuven, Belgium, at a conference organized by the International Association of Empirical Aesthetics. Tom was a serious scholar in that topic area, and he contributed 3 books and over 200 articles to the field of architectural design theory over the span of 40 years. In Australian parlance, Tom was an aristocrat; i.e., a descendant of one of the early arrivals on that continent, and one with a distinguished record, both in architectural practice and academia.

Tom served as editor of *Architecture Australia* and was a founding member of the Environmental Design Research Association in the US. He served as Head of the School of Architecture, Interior and Industrial Design, as well as Dean of the Faculty of Built Environment at the Queensland University of Technology in Brisbane.

During my 11 lecture visits to Australia, I always made it a point to connect with Tom, whose vigorous academic pursuits and exemplary collegiate demeanor made him someone whom one would seek out to collaborate with. Starting in 1979 at the Educational Forum of Australian and New Zealand Schools of Architecture in Brisbane, Australia, I made the pilgrimage to Tom’s academic institution on many occasions, and had the privilege of staying at his Queenslander colonial style home.

The last time I met with Tom was at the 1996 annual conference of the Environmental Design Research Association in Salt Lake City. Were he still with us, he would have been an important contributor to our book *Designing for Designers: Learning from Schools of Architecture*.

I was sad to learn of his untimely death in 1998. It was an honor to have known Tom for so many years. We miss him. The present book is testimony to his serious commitment to scholarship in architectural education and to his critical mind set, which enabled him to separate fact from fiction in the field of architecture.

**Wolfgang F.E. Preiser**

Professor Emeritus of Architecture, University of Cincinnati
There are so many ways I want to describe Tom. I knew Tom over a period of about five years when I was a Visiting Professor for a part of each year at Queensland University of Technology. Tall, gaunt, always with a warm smile, enjoying a good joke, even a pun, he may have appeared to some as the quintessential patrician completely at home with tea, scones and cricket. Yet, I rarely saw him that way. He was thoroughly the gentleman and always a gentle man. I saw a dedicated teacher and a thorough intellect. He approached ideas, colleagues and students alike with thought, analysis, caring, humor and, I must add, a twinkle.

Tom believed it is now architecture’s turn. Well, so he mentioned to me. I’ll explain.

Today we nearly all think of physicians as a practicing scientist. But they were not always that way. In the 1930s, penicillin underwent one of the first random-trial drug testing protocols, introducing scientific experimentation, external to the daily event seen in a physician’s practice, into the knowledge base of physicians. However, we know that many general practitioners still do not understand the statistics that underpin the vast majority of the healing regimes they prescribe. It has been nearly eighty years and the progress has been very slowly evolutionary. Resistance to change is great. Yet, slowly, the practice of medicine has been changing from a practice-based knowledge to a research- or science-based knowledge. Some might call it glacially evolutionary.

In management education, the 1940s saw a turning point due to many developments occurring during and perhaps because of World War II. Management education was changing from practice-based faculty-member knowledge to research-developed knowledge. While some may lament that the pendulum has swung too far (and perhaps stuck), we nonetheless view management education today as research-based. We daily hear about metrics, research results and demographics in marketing and take them for granted. The seat-of-the-pants management approach is probably very much alive but its credence is severely diminished when confronted by contrary research results.

Tom believed that it is now architecture’s turn to begin the movement from a practice-based profession and discipline to an evidence-, research- and knowledge-based profession and
discipline. It is architecture’s turn to add to its glorification of designer-stars respect for measurable accomplishments and applications. It is architecture’s turn to change faculties from consisting primarily of successful practitioners to faculties consisting of researchers who can bring their research to bear on the practice of making better architecture and on improving the lives of those who inhabit those environments.

Like medicine and management before, Tom Heath believed this slow evolutionary process, even with its potentially significant flaws, had begun and he wanted to be one to leave a lasting contribution to such glacially hasty events. His first three books on method, the profession and aesthetics certainly made a mark.*

Yet, this book may be the most lasting. It will certainly be the most controversial. It was intended to provide entering architecture students with practical and fundamental knowledge that others before them have learned. The idea is that, if these approaches can be passed down, not forcibly rediscovered by every student, then the student’s intellect would be freed to move on to more challenging questions, to attain greater heights. Tom, after all, viewed the world as an intellectual world, trying to make sense of it through a process of both rational and creative thought. Through his career as an architect, a hospital programmer and designer, an editor of professional magazines, and as an academic, he mastered a highly rational approach.

This did not always please everyone, of course. Architects are taught to value, even revere, the grand art of the designer. But Tom knew that art history must be different from architectural history. And art and architecture could not be only examined similarly. After all, no one lives or works in a sculpture. Intellectually Tom knew that architecture can become its own form of art, but just as science was added to the art of medical practice and, with all the research in management, the art of the charismatic leader remains highly elusive to thorough examination, Tom also knew that as projects have become more and more complex and will continue to do so in future, art will remain in architecture but escalating rational abilities will be increasingly required.
I don’t think Tom would have described it as a conflict between the studio method of teaching architecture and the seminar. After all, anything can be done in either setting. His concern was just the growing need within the profession of architecture for increasingly substantive and rigorously developed knowledge for use in practice.

He probably knew that devotees of the studio method might have a problem with this book. Such devotees might argue that nothing should be explained and that the value of the architect was to discover or invent knowledge as appropriate to a project. Tom would disagree. He could not understand how standing on the shoulders of others, unless there was a good reason to ignore precedent and the knowledge of others, could be viewed as anything but positive.

To the student of architecture, use this book. It will save you time and free you to go further. Yet, nothing should be completely unexamined. If you have good reason to circumvent the principals stated here, then you know what to do.

To the practicing architect, you may enjoy this too. It may be a refresher you’d like to have in the office.

To the professor of architectural design, is there a way you could use this book to help your students move more quickly onto the complexity that is, after all, architecture?

To everyone else, enjoy this book. This may give you a clue about the simpler aspects of the problem architects face.

This book is a concluding contribution for Tom due in large part to the efforts of Sipen and a beginning contribution for this continuing discussion.

Tom was right. It is beginning to be architecture’s turn. To paraphrase The New York Times, those few architects who emerge to the level of fashionistas will remain on pedestals. At any given time there are 9-12 such people in the world.
The greatly innovative will realize that there is something in the future of architecture that will combine both the object and services into single packages. Yet, the overwhelmingly vast majority of successful, practicing architects will live fulfilling lives by providing professional services that honestly and directly try to improve the existences of those who utilize the environments they create.

It is to that last group that this book is dedicated.

Andrew D. Seidel  
Editor-in-Chief  
Journal of Architectural and Planning Research  
Toronto

Tom Heath had a very distinguished career in the practice, analysis and teaching of architecture. This unique book is testament to a career long passion for all of the facets and idiosyncrasies of a profession which has been endlessly written about. Most of this writing is about so called architectural ‘heroes’ or ‘signature’ buildings.

This is not one of those books.

This book, perhaps essentially written for students of architecture, will, because of the substance of its message, scope and thoroughness, also appeal to practitioners of architecture. It has the potential to confirm already established philosophies but is capable of, and likely to, I believe, inspire new ones. Tom considered the work of an architect akin to that of a midwife – properly executed it resulted in a wonderful outcome.

I consider myself fortunate, indeed privileged, to have known Tom. He invited me to join the Editorial Panel of Architecture Australia during his term as Editor 1980-1990. We met frequently for very enjoyable and informative sessions in the billiard room of Old Government House at QUT Gardens Point Campus.

This very important building has recently undergone a programme of significant restoration and adaptive-reuse under the skilful direction of Sipen.

I recall very fondly enjoying many lunches with Tom at a favourite restaurant near QUT, during which we had such fun, we must have seemed to others in the restaurant, like naughty schoolboys in need of parental discipline. Although not aware at the time, I later realized that during such occasions, typical of the man, he was testing ideas being explored in the preparation for the book.

Tom was a very private man, seemingly rather shy in company but with a subtle and disarming sense of humour. He was popular with his architectural colleagues, artists and
scientists, all of whom considered him to be one of them. These relationships have informed
the book and endowed it with a confidence of intellectual connection to all areas of creative
endeavour.

In recognition of his contribution to QUT, The Tom Heath Gallery within The QUT Art
Museum is named in his honour.

This is an important and scholarly book. I admire and commend Sipen for her vision and
determination to give it life.

John Simpson
The publication of books, articles and conference papers about comprehensive architectural education appears to wax and wane over time. For some time now there seems to have been attention given both to narrow topics on the one hand and overall architectural programme structure and degrees of integration with education for other disciplines on the other – both rarely delving deeply into the detailed scope and curriculum of primary knowledge and skill needed to design buildings. We may be in what can be interpreted as a period of wane in comprehensiveness. So the timing of the release of this book which addresses what Tom Heath considered to be the essentials of architectural education is significant in that it may help fill a gap in current discourse.

This book provides primary knowledge to the student of architecture that directly addresses buildings and their embodied architectural ideas combined with added dimensions of down-to-earth information and advice on how to apply knowledge. Heath writes that the book is ‘for use in the studio, as a practical substitute for experience’. The need for greater attention to primary architectural knowledge has been noted in the past. In a QUT colloquium on the knowledge needs for architectural practice, Jennifer Taylor observed a worrying dominance in architectural debate of secondary knowledge over primary knowledge. She saw secondary knowledge drawn from literature and social theory as easily leading to obfuscation and confusion.

While clearly not targeted at professional architects, the scope of the book is consistent with Heath’s editorials in the profession’s journal Architecture Australia during the 1980’s which addressed a very wide range of architectural topics. These editorials and other papers gained a reputation for their wit and seriousness, their rationality and their capacity to pare-down the topic to its essentials. He could capture your thinking in the first paragraph or so with a thoughtfully positioned proposition that you accepted or rejected. If you accepted it, even partially, then the clarity and structure of the rational argument that followed would leave you with little room for a different conclusion. The content of this book is mostly true to Heath’s style. It clearly positions itself at the beginning and it is explicitly structured into obvious chapters each with subheading topics containing clear, rational discussion and
information. But it is different from past works in one important respect. The reader can go into the book at just about any point and gain something valuable from it, without needing to start at the beginning and follow a line of argument. This was clearly intended by Heath, perhaps motivated by his understanding of how students are likely to access knowledge.

Neville Quarry in the foreword to Heath’s *What if Anything is an Architect?* a compilation of editorials, felt that the writings could be grouped under the three headings of: Demolition, Excavation and Construction of architectural beliefs and theories. Accepting Quarry’s groupings, this book squarely sits as a ‘Construction’ although there is also some demolition of what Heath considers to be false beliefs…he couldn’t help himself!

I worked with Tom Heath for nearly twenty years during which I learned much from him about theories of education. I respected his writings and advocacy and I find myself still using some of his aphorisms such as ‘if you are not writing coherently then you are not thinking clearly’. I frequently sought his advice, which he gave generously, and I bounced ideas with him and gave him draft papers that I had written for review. On one occasion he returned a draft with his copious hand written notes all over it, including one part that said ‘bullshit’ followed by a statement of points as to why I needed to re-think the piece. I was pleased with this, because out of deference to a colleague he hadn’t used the stamp marked ‘bullshit’ that he used for student essays, something not politically correct these days. Although there will be different views held from Heath’s about learning and teaching architecture, I think the reader of this book will find that there is no nonsense in it.

Here are Tom Heath’s final thoughts about how to de-mystify architectural education, a cause to which he devoted a considerable part of his life. This is true Heath. I welcome it and recommend it for the perplexed.

It is to the credit of Sipen that this book is now available.

**Gordon Holden**
Professor & Head, Architecture, Griffith University
Queensland
On first hearing that Tom Heath had energetically and meticulously penned *Learning Architecture / Teaching Architecture* and being asked to contribute to the book, I felt both privileged and apprehensive. Tom at the end of his life had the deserved reputation of intellectual driver within the School of Architecture at Queensland University of Technology. A five hundred page manuscript covering the wide gamut of issues embraced by learning and teaching architecture was bound to be a scholarly tome which would be difficult to appraise and honour here.

The manuscript thankfully offers refreshing reassurance from the very first page where Tom talks of ‘what the book is not’ and portrays it as book of ‘vulgar cautions’, and in a very easy-to-navigate format welcomes any teacher, student or those curious about architecture to want to read on.

The contentious and often opposing viewpoints surrounding architecture do not deter the author from either embarking on this ambitious undertaking nor proffering his own interpretations shaped and informed from his teaching experience. He confidently presents the pros and cons of various teaching tools and individual exercises alerting both teachers and students to the pitfalls of seemingly expeditious and easy learning modes.

He presents us with both the understandings and misunderstandings surrounding aesthetics, creativity, and inexpressibility as ideology, and even the ideologies of actually teaching architecture. His viewpoints are presented in bite size prose, well supported by references that allow the student and teacher to explore further. The book thus becomes the first and most important map (with many clues and links) to be scrutinised in the pursuit of a fulfilling architectural education.

Illustrated by Ray Jones, the book is an anthology of elegant, simple sketches akin to the itinerary for a ‘grand tour’ of influential and world renowned architecture. The buildings are thoughtfully chosen, some less well known and obscure but illustrating always the relevant message of adjoining text. They offer much more insight into seminal architectural
endeavour than could be gleaned through a haphazard sweep across the internet in search of short cuts to an architectural appreciation.

The manuscript was conceived almost a decade ago yet treatment of the theme ‘sustainability’ remains as relevant today despite the many changes that rapid technological advances have brought to the tackling of sustainable design. The tried and proven methods of passive design and thoughtful responses to local climatic conditions as well the appreciation of economic and political contexts influencing the processes of building are unequivocally articulated and thus ensure that this document provides a relevant and sound foundation for a student’s understanding of services and building technologies.

The book does not set out to be a curriculum for an architecture course however its thorough coverage of an extensive range of relevant topics along with suggested studio activities cannot help but form a basis for a credible and productive curriculum. If students and teachers did nothing more than to explore the many referenced authors and thereby reached their own conclusions about learning, teaching and aesthetic and creative appreciation they would build self-confidence in architectural discourse and expression that would serve them well in the company of experienced practitioners.

Tom Heath’s manuscript has turned into the most accessible of scholarly texts which dances with great agility from the pragmatic to the poetic and leaves the reader inspired.

I believe this book is destined to shape the lives of many a teacher and student and in turn, through their greater competencies, shape the better built environments of the future.

Phillip Follent
Queensland Government Architect
the materials of construction
Kaufmann house, ‘Falling Water’, Pennsylvania (1934–37)
Frank Lloyd Wright
The idea of technology

Technology in the architecture school

In most architecture schools, there are theoretical courses on various aspects of technology. Typically, there may be courses in structural theory, building construction, architectural science and building services. This chapter is not intended to be a substitute for such courses, or for the many excellent introductory books on these subjects. Its purpose is to help students to bridge the gap between such courses and the design studio (see 1.05 and 5.2.5).

However, technology is the subject of strong and conflicting values, among the general public and among architects. Students are likely to have formed general views of their own about technology before they enter architecture school. Once there, they will encounter professional views of the relationship between technological constraints and architecture. Such views are not always consistent and may well conflict with the student’s pre-existing views. Therefore, this introductory section is devoted to a discussion of technological values, or the idea of technology.

What is technology?

Technology is defined as the combinations of capital, labour, materials and machinery that can be used to carry out a particular task. These four things are sometimes called the ‘factors of production’. They are ‘the materials of construction’ in the sense intended in Mies van der Rohe’s aphorism ‘How shall we build, unless with the materials of construction?’.

Capital, labour and materials

Capital is here used in the narrow sense of money; it does not include plant and machinery or investment in the training of the labour force. Labour includes management and other knowledge workers such as architects and engineers, as well as skilled tradesmen and semi-skilled or unskilled labour. Materials include all the physical elements of the building, from raw clay (which might be used in pise construction)
through worked products like screws and plasterboard to elaborate pieces of equipment like refrigerators.

**Machinery**

Machinery refers to machinery used in the building process, such as bulldozers, cranes and electric drills, not to machinery that forms part of the building, like air-conditioning plant, which in this definition is part of ‘materials’. It includes devices that have been in use since the dawn of civilisation, like saws and chisels, as well as power tools. A more everyday view of technology might limit the concept to machinery, or perhaps machinery and materials. However, such a view can lead us to overlook the possibilities, and the importance, of substituting one element for another.

**Substitution**

To some extent, the four different elements that make up technology can be substituted for each other. A deficiency in one can be made up for by using more of the others. We would not today attempt to build the pyramids of Egypt without using large amounts of heavy machinery, but the ancient Egyptians did it by massive substitution of management, labour and capital. The more limited the resources available with respect to each of the four elements, the more the forms of buildings are subject to technical constraints. ‘Limited resources’ is a polite term for poverty.

**The bonds of poverty**

At many times in the past, technology was traditional and fixed. Even today in poor or remote areas there may be effectively only one way of building a particular type of building or buildings of any kind. Sometimes tradition is reinforced by law, as a way of giving expression to class structure or other social values. Under the Japanese Shoguns the construction and decoration of houses for different classes in town and country was fixed in this way, though towards the end of the shogunate, when people were growing richer, the law was often broken. The city of Santa Fe in New Mexico has regulations that require many buildings to look as if they were built of adobe (Gleye 1994). Architects and tourists often admire the visual consistency created by such limitations. The
people most concerned, however, often resent and resist, as the Japanese example shows. Such regulations in the modern world arise not from poverty but from attempts to control the aesthetic confusion created by riches.

**Embarrassment of riches**

Over a century ago Viollet-le-Duc (1872, 1987) wrote in his *Lectures on Architecture* that the increases of wealth and knowledge, and the accompanying changes in technology, were more than architects could cope with. The more knowledge that became available, the greater the learning and experience necessary to make good use of it.

Since then our material and intellectual wealth have increased enormously. The effect, as Viollet-le-Duc argues, is that technological choices are less and less clear-cut. If any one mix of the factors of production were clearly superior, in terms of current values, it would drive out the others. The reality is, as we will see, that different combinations have different advantages and disadvantages. Each then constrains our planning and aesthetic choices in different ways. Finding satisficing combinations can be a laborious task.

However, this embarrassment of riches does have one advantage. It makes it obvious that the selection of technology is a matter of values. The values of both architects and non-architects with respect to technology have been formed through the long history of modernisation and industrialisation and some of them have become part of the conventional wisdom.

**Architects’ values**

Architects’ values with respect to technology are confused and contradictory. Some architects perceive themselves as having a duty to innovate and to celebrate technology visually. Others support a return to a way of life thought to be simpler, more natural, and less damaging to the environment. These two sets of values originated in the nineteenth century and were somewhat uneasily mixed in the beliefs of the Modern Movement. Architects who take a ‘post-modernist’ stance often refuse to concern themselves with technology, which is supposed
to adapt itself to their artistic inspiration. Each of these attitudes is discussed in turn, before popular values with respect to technology are considered.

**Technical innovation and rationalism**

The idea of technical innovation as a duty originated in what is called architectural rationalism. The central belief of rationalism, architectural or otherwise, is that thought and action should be governed by a few ‘first principles’. Everything else can then be deduced from these principles. This belief can be traced back to Descartes (1637, 1979) in the seventeenth century. Viollet-le-Duc (1872, 1987), the leading exponent of architectural rationalism in the nineteenth century, quotes extensively from Descartes.

Viollet-le-Duc said that the first principles of architecture were ‘the programme’ or the intended use of the building, and technology. From Viollet-le-Duc these ideas passed to the Modern Movement. Viollet-le-Duc’s conception of technology was largely confined to structure. The Modern Movement added a belief in mechanisation. The Modern Movement conception of the history of architecture as fundamentally a history of technical innovations in structure was codified by Giedion in his *Space, Time and Architecture* (1941, 1949). The present-day inheritors of rationalist thinking, sometimes known as ‘hi-tech’ architects, have added services and their expression to structure and mechanisation as constituents of technology. The most striking example is the Pompidou Centre in Paris.

**Technological progress**

The idea of progress is in principle quite independent of rationalist views. However, the two became bound up together in Modern Movement thinking, partly under the influence of Marxist ideas. Architectural rationalism and Marxism have in common the belief that technology, or the factors of production, are first principles. Marxism added the belief that technology is a driving or progressive principle. Further, according to Marxist ideas, or at least some popular interpretations of them, history needed to be helped along. The
architectural application of this was that just as technology is a first principle for architecture, so architects should be the first principle, or prime movers, in the evolution of building technology.

**Criticisms of technological rationalism and progressivism**

Rationalism in general is subject to the criticism that it ignores the real multiplicity of values and causes that operate in the world. So far as architecture is concerned, something of this complexity is hinted at in the definition of technology given earlier. Historically, the patterns of capital raising, the skills and organisation of the workforce, the range of materials and their performance, and the amount and power of the machinery used in buildings have all developed continuously without any significant intervention from architects. Conversely, those works of architecture that are most often represented in the past as technologically innovative, such as the Sydney Opera House, the Pompidou centre and the Hong Kong Shanghai Bank, have in fact had very little influence on the subsequent development of building technology.

Technological change in modern societies does not arise from the actions of individuals, or even of professional groups such as architects, but from numerous interacting positive feedback loops. The institutionalisation of change in the modern world, through research, development and market mechanisms, has transformed and will continue to transform building as it has transformed every other form of production. With all this, architects have very little to do. For them to see themselves as heroes of technical progress is often misleading. Later a more credible role or set of values is suggested for them to adopt (3.1.34). To illustrate and conclude this discussion of the relationship between architects and technical innovation, one particular technological value that many architects have held strongly is briefly discussed: the industrialisation of building.

**Architects and the industrialisation of building**

The ‘industrialisation of building’ has been a persistent ideal of architects for almost a century. It was conceived as involving the mass
production, in factories, of large elements, making up a complete building. From time to time, this ideal has been supported by politicians and tried by industrialists. It provides a striking example of the failure of an ill-conceived idea, based on an over-simplification of technology.

Two images have helped enormously to popularise this idea. The Crystal Palace of 1851 is still often treated as the paradigmatic building produced by industrial methods (e.g. Elliott 1992). The use of then new materials, glass and iron, new machinery, some of it purpose-designed, and new methods of organisation of labour achieved a rate of construction that would be remarkable even today. In addition, the resulting building had a strikingly memorable form.

The second image is that of the car factory of the Fordist period. As recently as 1990, Martin Pawley complained that ‘From the very beginning car designers got everything right that building designers got wrong’. The success of the industrialised consumer goods industry in reducing prices and increasing variety has been a constant source of reproach to the building industry, which is perceived as having achieved much less.

**Why the ideal failed**

This ideal of industrialisation has not been achieved, despite many attempts, and there are reasons for believing that it can never be achieved (Russell 1981). Four main reasons can be given for this failure.

The first is that it was based on a narrowly economic view of buildings. Other values that influence the acceptance or rejection of buildings were disregarded. The Crystal Palace was adequate as a shelter for industrial exhibits, but for other applications it would lack resistance to heat transfer, noise and fire. Other, later, attempts at industrialised building suffered similar deficiencies.

Second, the hoped-for savings of money and time were seldom if ever forthcoming. This was largely because the analogy with consumer goods was faulty. Demand for buildings fluctuates much more than demand for consumer goods (Handler 1970). Investment in each unit of production is much larger, and investment is inherently uneven (Bon
Scraping of old models can seldom be afforded. For all these reasons, rates of production can seldom be maintained. Third, there are technical difficulties inherent in the production, transport and assembly of large pieces of buildings that add to the costs and detract from performance. These difficulties will be discussed in more detail in 3.5.32–36. Fourth, one of the reasons that industrialised building achieved political and administrative acceptance and was supported by some architects was that it was thought to offer the possibility of detailed control over behaviour through complete design of the environment (Habraken 1983). In this respect, large housing projects built by industrialised methods proved notably unsuccessful.

**Industrialisation of buildings: the reality**

Building has in fact been industrialised but not in the way that most architects expected. The raising and management of capital for building works has developed with capital markets generally. Over the past two centuries, there has been a very great increase in the number and differentiation of workers in management and design, and a corresponding reduction in the number of skilled workers on site. Most site work is now unskilled or semi-skilled and fewer workers are employed. This has been made possible by changes in materials and the increased use of machinery. While huge quantities of minimally processed material still make up the bulk of most buildings, and probably always will, finishing materials and fixings have grown enormously in sophistication and are now almost entirely produced off site. On-site processes are assisted both by heavy machinery such as bulldozers and cranes and by machine tools such as electric drills and screwdrivers.

Building has thus adopted relevant and appropriate industrial methods. Despite the forces that make for conservatism in the industry (3.1.32), there has been almost continuous and often radical change. If, despite all this change, the cost of buildings has remained constant or even increased in relation to the average income, it is not primarily because of the technological backwardness of the building industry. The major and continuing cause of the relatively high cost of buildings has been
changes in people’s values or standards. Standards, in terms of such things as space per person, quality of finish, and the provision of services such as bathrooms, lighting and air-conditioning, have risen dramatically throughout the twentieth century (see, for example, Lawrence (1987) on changes in housing values and standards).

**Looking backwards**

The second set of architects’ values with relation to technology can be dealt with somewhat more briefly. It has its origins in the writings of Ruskin on architecture (1849, 1890) and the Arts and Crafts Movement of the latter part of the nineteenth century. Ruskin and the leaders of the Arts and Crafts Movement saw industrialisation as having destroyed both the independence of craftsmen and the pleasure craftsmen found in their work. As a consequence, they thought, the quality of products had also declined. The Arts and Crafts Movement aimed at supporting and expanding hand production by skilled craftsmen, or artist-craftsmen. It failed in its main goals because the resulting products were too expensive for all but the rich to buy. It has, however, had enduring success through a continuing tradition of artist-craftsmen making household objects for enjoyment and use, even though economically speaking such things will always be luxuries.

The Arts and Crafts Movement has influenced architecture in several ways. The Modern Movement took over from Ruskin the idea that architecture should be ‘true’ to the means of production. This was interpreted as meaning that materials should be used as far as possible in their ‘natural’ state or that at the very least their properties should be understood and respected and that structure should be exposed rather than concealed. These issues will be discussed further in 3.2 and 3.5. Some themes of the Arts and Crafts Movement are continued in the contemporary support for regional architectures that make use of traditional materials, techniques and forms. Even in countries that offer a full range of modern technologies, some architects have chosen to restrict themselves to technology known before the industrial revolution. However, the choice of such pre-industrial technology tends to limit the architect’s clientele to the very rich on the one hand or to
owner-builders on the other. The recent pursuit of ‘sustainability’ in architecture has also drawn on the ideas of the Arts and Crafts tradition. The issue of sustainability is discussed further in 3.1.24–26.

**Giving up the struggle**

Meanwhile, the complexity and variety of available technology has continued to grow. It is now difficult, and perhaps impossible, to acquire an adequate knowledge of modern building technology solely by way of a combination of a few undergraduate courses and experience in practice. Architects who may in any case not have been much interested in technology have been further discouraged by the strong reaction against the rationalism and technological determinism of some Modern Movement writers. On top of all this, there has been a worldwide increase in the practice of suing architects for the cost of technical failures, whether or not such failures are due to negligent design or inadequate inspection. The resulting financial crisis has led many insurers to advise practitioners not to take any responsibility for the technical aspects of their work.

In the face of these pressures, some architects have responded by giving up the struggle. Technology today, they argue, is capable of producing any desired form. It is, they say, no longer necessary for architects to concern themselves with the technical means of realising the forms that they design or to take responsibility for them. On this view, architecture can be, and should be, practised as a pure art form. This response can be called ‘technological nihilism’.

**Some criticisms of technological nihilism**

It is doubtful whether architects should or can adopt this very narrow definition of their task. Such a position can all too easily be seen as combining arrogance with laziness and cowardice. Even on its own terms, such a course of action is not practical. The architect’s concept is abandoned to the mercy of others for its realisation. Architects and engineers who specialise in technical documentation or work for contractors or subcontractors will try to translate it into buildable form. Cost accountants will price it and suggest alterations. Manufacturers,
tradespeople and labourers will produce and assemble the parts. All of these individuals and groups will adapt the original form, as far as they dare, to their own values. The result will bear at best a broad and sketchy resemblance to the intention. Only by designing for and with the means of production can an architect hope to maintain the unity of a design in the final building.

**Popular values and building performance**

There has been surprisingly little research into lay expectations of the technical performance of buildings. Perhaps the answers are thought to be self-evident. Perhaps no-one wants to know. Architects certainly do not seem to take as much interest in these lay values as would be prudent. In the absence of research, it is still possible to make some reasonable inferences from building regulations, press reports, films and novels, and anecdotal evidence. We suggest that a list of the most important contemporary lay values in this area would include stability and safety, weatherproofness, health, comfort, durability, sustainability and economy. This set of values also seems to be quite stable historically and cross-culturally, though sustainability is new. Just as with principles of arrangement (2.4.1), these criteria of technical performance are neither entirely independent nor necessarily consistent with one another.

**The hierarchy of technical values**

Given that there is some such set of values and that they can conflict, we must expect that different groups will rank them differently, and that different circumstances will give rise to different rankings. This gives rise to a range of technical systems for realising the one building type. Houses may be built of load-bearing brick; they may also be framed and sheeted with timber. Different systems are also used for different building types. As with the set of values itself, the various hierarchies of values have been little researched. What follows is therefore somewhat speculative.

**Stability and safety**

Stability and safety of buildings appear to be universal values. This is
hardly surprising, but it is worth noting. Structural stability has prominent place in the oldest building regulations as in the newest (Petroski 1982, 1992). Likewise, elaborate and expensive precautions against fire are to be found throughout history. Notable examples are the stone vaults of Gothic cathedrals and the forms of construction required by the London Building Act after 1774 (Muthesius 1982). If anything, such concerns are greater today than in the past, as their successful exploitation in disaster films such as Towering Inferno shows.

Weatherproofness

Stability, health, safety, comfort and durability are all affected by weatherproofness. However, there are advantages in thinking about weatherproofness as a separate aspect of performance. Leaks, excessive sun penetration, windblown dust and so on can damage possessions. Even if they do no actual damage, they are widely regarded as evidence of bad building or bad design.

Health

Health is another widespread and perhaps universal value. The influence of buildings on health, and their design to promote health, is discussed in the earliest building manuals, such as that of Vitruvius, and in the even older Chinese writings on feng shui (see also 2.3.10). Avoiding mosquito- and water-borne infections was then mainly a problem of siting and orientation; today it is more a matter of the provision and design of services. We are more aware today of the dangers of toxic materials than the Romans were, but we also have more of them.

Comfort

Comfort, as before (2.4.22), refers here to thermal and acoustic comfort. There is evidence of a steady increase in the value placed on comfort from the latter part of the seventeenth century to the present (see, for example, Giedion 1948; Cowan and Smith 1988; Elliott 1992). However, the actual performance of buildings in these respects has somewhat declined during the twentieth century (see 3.3).
Durability

The durability of buildings has declined along with their comfort and for the same technical reasons. However, this has followed rather than gone against the tendency of popular values. People no longer expect buildings to last indefinitely. If the value attached to sustainability continues to increase, durability may once again become a significant technical value.

Sustainability

Sustainability is an extremely difficult topic. It is made all the more difficult because its difficulties have been glossed over and even deliberately concealed by the slogans and propaganda of opposing organisations. The global issues, such as the extent and reversibility of the effects of human activities on the atmosphere and on ecosystems, are still the subject of scientific controversy. Many predictions are speculative or based on limited data. Even to understand the various controversies often requires a knowledge of chemistry, biochemistry, ecology and atmospheric physics, which few if any architects possess. Probably the most that even a scientifically literate architect can say is that, if we care for our posterity, it would be wise to reduce the consumption of non-renewable resources, the production of greenhouse gases, the depletion of the ozone layer and other forms of environmental destruction.

The design, construction and operation of buildings can contribute to the achievement of these desirable goals. Technical means of reducing direct energy consumption in buildings are readily available. The environmental costs of producing and disposing of building materials are becoming somewhat better understood. More complex questions, such as the embodied energy of buildings and life-cycle energy analysis, are being addressed. (Embodied energy is the energy used in the total process of producing a building. Life-cycle energy analysis extends this idea to include energy concerned in operation, maintenance, renovation and eventual demolition.) Unfortunately, the more deeply the goals of sustainability are pursued, the more complex and difficult the issues become.
Complexities and contradictions of sustainability

Solar energy can be substituted for energy generated from fossil fuels for the purpose of heating water for houses and industry. This is straightforward. Other issues are less so. For example, how is the decision to be made between a concrete wall and a timber-framed plasterboard wall. The concrete wall generates ten times as much greenhouse gas (CSIRO 1996) but may last ten times as long. How, again, can the decision be made whether or not to use certain lightweight plastics, which will reduce the embodied energy of building but which are suspected of contributing heavily to the production of dangerous pollutants?

Sustainable values, like other values, may conflict. The following sections of this chapter have avoided (or, if you prefer, evaded) such issues and deal only with those that can be perceived as being straightforward.

The politics of sustainability

Even allowing for limitations of knowledge and value conflicts, the main obstacles to a rapid improvement in the sustainability of building practice are not technical but political. As things stand, more sustainable building methods are often also more costly. Without direct or indirect government subsidy, they are unlikely to be widely adopted. The use of improved building materials was shown in one case study to increase the initial capital costs by 6% (Oppenheim 1996). Without inducements, few owners are likely to accept such a premium. In the case of solar energy, the use of fossil fuels is still subsidised in many countries, while the use of solar energy is not. Naturally, the use of solar energy stagnates or declines. As a final example, the widespread use of known principles of energy-efficient design for houses will depend on changes to planning regulations (Lim 1997). Street layouts and landscaping must be designed to ensure that houses receive direct sunlight for solar heating and, so far as possible, an unobstructed wind flow for summer cooling.

Unfortunately, the costs of subsidising such improvements in the sustainability of building practice are immediate, while the benefits are
long-term. The capacity of democratic governments to plan ahead is usually limited to the time of the next election. Major and rapid change is unlikely until market forces and the popular will combine to overwhelm all opposition and raise issues of sustainability above party politics.

Economy

Buildings use relatively large amounts of capital, and capital is almost always scarce and expensive. First cost of buildings is therefore a constant and critical concern of developers and owners. The demand for low-cost construction obviously conflicts with other demands. Architects and builders are under constant pressure to ‘cut corners’ on aspects of the building that are invisible to or poorly understood by owners and occupants. The ill effects of such corner-cutting may not show up until years after the building has been occupied. Weatherproofness, comfort and the healthiness of the interior environment may all suffer. However, durability and sustainability are probably the main victims of the single-minded pursuit of economy.

Lifetime performance

It is sometimes argued that, in order to give considerations of durability and sustainability a look-in, the economics of buildings should be based on their lifetime cost and return, or lifetime performance. This involves calculating not only the initial cost but also the costs of operating, maintaining and refurbishing the building over its assumed lifetime, and the cost of demolition.

Unfortunately, such calculations are almost impossible. Future costs are unpredictable in themselves. For purposes of comparison they have to be converted to present costs, and this requires guessing future rates of interest, which is generally conceded to be impossible. Given the tendency, already noted, for standards to rise, the lifetime of buildings is also a matter of guesswork. Finally, any reasonable method of valuing the quality or performance of buildings requires information and management systems to support it (Pegrum and Bycroft 1989). Such systems do not yet exist, even for governments. In an economic
environment in which building procurement is more and more often at ‘arms length’, with neither the owner nor the occupier making any long-term commitment to the building, it seems likely that first cost will continue to be the governing aspect of economy. The most that can be hoped for is that new techniques of, for example, economising on energy consumption will be accepted if they can demonstrate a clear profit within, say, three years or less.

**Popular demand and the market**

The discussion of economy and lifetime cost draws attention to an important difference between buildings and consumer goods. Earlier (3.1.13) some reasons were given for believing that any analogy between buildings and consumer goods is unsound. Yet another reason for this belief is that the market for buildings does not work as proper markets for consumer goods are supposed to do. In a proper market there is continuous or at least regular production of competing goods among which buyers choose freely. The buyers’ choices send signals back to the producers, who adapt their products to suit the demand. The assumptions for a proper market are thus continuity of production, effective competition, and the ability of consumers to make relatively quick and accurate decisions about the quality of the goods on offer.

None of these conditions holds for buildings. The market for buildings notoriously suffers from a ‘boom and bust’ cycle. Demand greatly exceeds supply, or supply greatly exceeds demand. Production fluctuates correspondingly. Paradoxically, when production is at its peak, consumers have very little choice. Once supply exceeds demand, production drops dramatically. Consumers now have an abundance of choice. However, they are often unable to make wise choices because they lack experience, and also because, as noted in 3.1.27, buildings have relatively long lifetimes, and quick and accurate judgements of quality are therefore difficult. The feedback loop between consumer demand and building supply is thus often a very poor one. An important consequence of this is that communal action, in the form of laws and regulations, often has to be substituted for the action of the market in order to ensure that buildings meet popular expectations.
Building regulations

Building regulations represent popular values rather than the values of architects. As remarked previously, strongly and widely held values are often enforced by law or regulation. Laws regulating building are at least four thousand years old (Petroski 1982). The earliest regulations impose penalties, often very severe ones, for various kinds of building failure. Such prescriptive regulations were progressively introduced in most of the industrialised countries from the late seventeenth century. By the middle of the twentieth century prescriptive regulation had reached a high degree of complexity and sophistication.

However, prescriptive regulations were often opposed by architects and engineers, and also by manufacturers of materials, on the ground that they inhibit innovation. As a result, in the latter half of the twentieth century performance-based regulations have increasingly been substituted for prescriptive ones. Such regulations specify what the system or element must do rather than the technology to be used.

Technological values in normal architectural practice

In architectural practice, the choice of technology is often well constrained by the values of the various practices. Building regulations narrow the field considerably. Clients and their representatives are averse to risk and concerned about first cost (3.1.27–28). Contractors and tradesmen very reasonably tend to charge more if they are asked to use technology with which they are not familiar. Architects and engineers are well aware of all this. They also often prefer to reduce their own risks and cut their design time and costs by using established, well-understood technology.

The exceptions to these general rules are few but very well publicised. Indeed, it could be said that publicity is the reason for their existence. Such exceptions seem to occur when clients wants their building to make a symbolic statement about their technological up-to-dateness. This is a recurrent theme in certain kinds of building, for example buildings for transport and some industrial buildings. Issues of symbolism are further discussed in 4.3. In order to meet such demands
successfully, architects need an exceptionally broad and deep understanding of technology. Even more, they need the support of teams of engineering experts to collaborate with them in matching form to a set of technical constraints.

**Technological values in the studio**

This chapter makes a number of assumptions about the role of technological values and knowledge in studio work. The first is that, for the reasons given in 3.1.16–17, technical constraints should be emphasised rather than glossed over. The second, which follows from the first, is that insofar as students are allowed to make unrestricted use of technology that they do not understand, they are being trained inappropriately. The third, which follows from the second, and also from the discussion of normal architectural practice, is that the technologies used in beginning design exercises should be confined to those that are well established and conventional. As a consequence of these assumptions, the treatment of technology in the following sections is in terms of qualitative understanding and quantitative rules of thumb rather than engineering theory. The question of rules of thumb needs some further explanation.

**Rules of thumb**

The application of technological constraints in the design of buildings often involves chicken-and-egg paradoxes. It is impossible to complete even a sketch design satisfactorily without knowing the sizes and shapes of various technical elements. However, in many cases the sizes and shapes of those elements cannot be calculated until the general layout of the building is known. In order to break into this vicious circle, architects and engineers in practice use quantitative heuristics or rules of thumb. Properly used, such rules give an *approximation* of the required size that is not *likely* to be *significantly* upset by subsequent recalculation using more theoretically sound quantitative methods. ‘Significantly’ here refers to the impact on the plan and section, rather than to the impact on the technical elements themselves.
A possible criticism of the use made of rules of thumb in this book is that it may discourage students from attempting to grasp the developed quantitative theory of the various aspects of building technology. However, this danger can easily be overcome if teachers emphasise the limitations of rules of thumb, and students themselves understand that in order to go beyond the boundaries of the conventional they will need a much deeper understanding of technology. This in turn reinforces the importance of discouraging or actually preventing beginning students from basing their designs on advanced technology.

**Summary**

This section has put forward three main sets of ideas. The first is that, contrary to some conventional architectural values, architects are neither required nor in most cases particularly competent to advance building technology. On the other hand, there are practical difficulties in taking a backward-looking position. Architects, whether or not they are particularly interested in technology, need to understand and respect technical constraints. They also need to keep up with changes in technology. If they do not do these things, their buildings will not be realised as they intended.

The second set of ideas concerns lay or popular values. Clients, users and the general public have values that constrain the building process, partly through market processes but more importantly through regulation. Such popular values have not been sufficiently studied, and architects would be wise to pay more attention to them. Too often it seems that architects have chosen to oppose, rather than to support, expressions of these popular values.

Finally, it was argued that the system of constraints on building design and production results in most buildings adopting established, conventional building processes. This greatly reduces risks and makes possible the extensive use of rules of thumb in preliminary design. Such rules of thumb can help to bridge the gap between courses in technology and studio teaching, so long as their limitations are made clear.
The plan of this chapter

In the remaining sections of this chapter, the technical aspects of building are introduced under four main groupings. The first is the system of load and support, which provides stability. The second is the passive control of various forms of energy by buildings. The third comprises the services that are demanded in order to support the activities that go on in buildings. The fourth covers the building fabric, that is, the materials from which buildings are made and their assembly.

These four aspects of building technology are not entirely independent. A structural system must be realised in materials. The characteristics of the building fabric can affect the demand for services. Provisions for service distribution affect structure. Nevertheless, the four aspects can be separated for descriptive purposes, with some cross-referencing along the way.

Load and support

Structural theory and the design studio

The difficulty of bridging the gap between the teaching of technical subjects and the design studio is particularly obvious in the case of structural theory. Anecdotally it is well known that most architecture students view the making of structural calculations as a highly distasteful chore and gain little understanding of structural behaviour from it.

Many writers on structures have recognised that this is in part because architecture students prefer thinking in images to thinking in numbers. Accordingly, books on architectural structures have been produced that use a great deal of imagery, in the form of diagrams or historical examples or both to make their points (see, for example, Salvadori and Heller 1963, 1986; Mainstone 1975, 1983; Cowan and Wilson 1981).

In spite of these efforts, the knowledge gap is still apparent both in the studio and in practice. This may be because these writers have assumed that once students had the knowledge they would know what to do with
it. Studio teachers have perhaps made a similar assumption. This section does not attempt to teach structural theory. Rather, it proposes ways in which the knowledge of structural theory can be made applicable and used in the studio. It approaches this by asking what needs to be known about structure in order to be reasonably sure that a sketch plan is technically feasible.

**What do we need to know about structure?**

There are three questions about structure that a designer should be able to answer at the sketch plan stage. The first question is: what is the system of load and support? The second is: what will be the approximate size of the members? The third is: what movements can be expected and roughly how large will they be? Two other questions related to structure will be discussed in the next section: how will the structure resist fire? and what will the structure contribute to comfort?

**Loads**

Since this is not a book on structural theory, the division of types of load into dead and live loads and static and dynamic loads is not particularly useful. For the present purpose there are two kinds of load, vertical and horizontal. Vertical loads include the weight of the building itself and the people, equipment and goods in it, and some loads that come from outside, such as snow loads on roofs. Horizontal loads include wind loads and earthquake loads. Vertical loads need little explanation, with the exception of loading produced by movement of the foundations, which will be discussed briefly. Earthquake design is a specialised topic, beyond the scope of this book. In known earthquake zones, designing to meet the forces that earthquakes produce imposes critical structural constraints and will be the subject of detailed study. The wind, however, blows everywhere, and, since understanding its behaviour is important for every section of this chapter, it will be treated in some detail.

**Differential compression of foundation**

Differential compression of the foundation can be caused by the design of the building – for example if one part is very much taller that the rest,
so that there are big differences in the load on the foundation material. It can also be caused by variations in the kind of foundation material over the area of the building. Rock, gravel or compacted sand are less compressible than loam, clay or dune sand. See also 2.3.23 and 2.3.24.

**Moisture movement of foundations**

Clay soils are particularly subject to moisture movement, except where the clay is below the water table and therefore permanently wet. Water can actually be squeezed out of clay soils by the weight of a building, but this usually happens more or less evenly. However, in areas where there is a great variation in rainfall through the year or from year to year, the soil around the perimeter of a building founded on clay may dry and shrink more than the soil in the middle.

**Design and equivalent loads from foundations**

Either of the two kinds of movement just described has the effect of imposing a large equivalent load on the building, and if the building has not been designed to resist such a load it will crack badly or even collapse. A careful site investigation will usually reveal any such risks. Even the worst conditions can mostly be overcome by driving piles down to better material or constructing raft foundations stiff enough to resist the movement. However, such solutions are expensive. Where appropriate, it may be better to accept some constraints on the form of the building.

Thus, in cases of poor foundation material, low-rise solutions may be preferred to high-rise ones, if other constraints permit. An even height will be preferred to a variable height. It will be an advantage if the building can be broken up into pavilions or wings connected by light bridges. Rigid frame structures, space frames and shells, all of which react badly to any change of shape, should be avoided.

**Wind loads**

The importance of wind loads varies from site to site, but wind loads can never be ignored. Some areas are liable to hurricanes, cyclones or tornadoes. The higher up a site is, the greater the wind speed. Rough
ground slows the wind by friction. The buildings of towns and cities form a kind of rough ground, so the individual buildings are less affected by the wind. Conversely, wind speed is higher over water or open plains.

The way in which the wind produces a horizontal load on buildings may be intuitively obvious. Some of its other effects are not so obvious. Since the physical behaviour of the wind affects many aspects of building performance, it will be reviewed in some detail.

**Modelling wind behaviour**

In explaining wind behaviour, it is usual to start by assuming ‘laminar’ flow, that is, a perfectly smooth, even flow of air of constant velocity. In reality, even approximating this is quite difficult; in wind tunnels it is achieved by elaborate smoothing devices. However, like many of the fantastic assumptions made in applied physics, this one turns out to be quite useful. Now assume that this perfect wind is blowing exactly at right angles to one wall of an equally bizarre ‘building’, a perfect cube with perfectly flat, smooth walls and roof. What happens?

**High- and low-pressure zones**

Where the wind encounters the building, it loses velocity and a zone of high pressure is created. This increase in pressure is greatest at the centre of the building near the bottom, where the deflection of the ‘streamlines’ is greatest. It is least at the edges, where it is easier for the wind to escape.

At the edges of the windward façade, then, we have the original wind trying to blow straight past the building and another stream of air being pushed sideways or straight up by the façade. The result of these two streams can be pictured as a stream that is deflected away from the sides and top of the building. This stream in turn draws air away from the roof, the sides and the leeward or downwind face of the building by friction. These areas therefore experience negative pressure or suction. In very violent winds the resulting forces may be sufficient to suck off the roof or walls (Fig. 3.1).
Now imagine the idealised building having a sloping roof instead of a flat one. It is obvious that at some angle between the horizontal and the vertical the force on the windward side of the roof will change from positive to negative pressure. In fact, this angle is 30 degrees. Of course, there is still suction on the leeward side of the roof.

As the shape of the building varies from the cubical, the size and shape of the downwind low-pressure zone change accordingly. The low-pressure zone increases as the windward face becomes taller or wider. Conversely, it decreases as the depth of the building, in the direction of the wind, increases in proportion to its height.

Very tall buildings can create very high pressure zones at ground level – enough to knock people over. Passages through large exposed buildings can similarly speed up the wind, especially if they open onto courtyards which may be zones of low pressure.

**Eddy currents and vortices**

At some point downstream the low-pressure zone produced by the interaction of wind and building fades out and the laminar flow of the wind resumes. In this zone the opposite motions of the windstream and the air within the low-pressure zone produce a rotary movement, or eddy currents.

Somewhat similarly, in the high-pressure zone at the base of the building on the windward side, there is a pocket of air which is at the same time flowing towards the nearest side of the building, where the pressure is lower, and being ‘rolled’ by the upward flow that takes place simultaneously. This creates a vortex.

Since real buildings are seldom smooth, but have projections of various kinds such as chimneys, balconies, sun hoods and the like, numerous local zones of high and low pressure, with accompanying vortices and eddy currents, are created. The resulting forces can be quite large. Open doors or casement windows may be violently shaken or even snapped off. This is one reason why tall buildings, which extend into zones of high wind speed, are usually mechanically ventilated or air-conditioned.
rather than provided with windows that open. Recently, alternative solutions involving a double-skin external wall have been built (see 3.3.47). So far, however, such buildings have not been very tall.

**Supporting vertical loads**

Thus far, loads have been classified as vertical and horizontal, and the behaviour of the most common horizontal load, the wind, has been looked at. How can loads be related to supports? Taking vertical loads first, the elements to be supported can be simply divided into the roof, the lowest floor, and any floors above the lowest floor.

**Supporting roofs**

These days, supporting a normal roof presents few difficulties. Problems of spanning space, which preoccupied architects for centuries, have largely been solved. Speculative builders in Australia no longer even bother to provide internal supports for roof structures. Lightweight trusses spanning from external wall to external wall are cheaper and easier to erect. This is generally true for spans of up to about 16 metres (50 ft). For comparison, this is about the span of the nave of a typical Gothic cathedral.

**The roof and the building**

There are cases in which the roof structure is a significant constraint on the form of the building. For buildings in which a very long column-free span is demanded, such as sports arenas and exhibition centres, roof structure may still be a primary constraint. However, with these and a few other exceptions, the roof structure is usually constrained by planning and other considerations, rather than constraining them. The geometry of the plan, aesthetic considerations, the selection of roofing material, and the requirements of rainwater drainage will mostly be found to be more important than the technical problem of spanning space. If, for any of these reasons, the distance from the ridge, or the roof surface in the case of a flat roof, to the ceiling has to be less than about one-tenth of the span, internal supports to reduce the effective span should be considered.
Supporting the lowest floor

The term ‘lowest floor’ is used here rather than ‘ground floor’ because sometimes there are floors below ground, as on sloping sites or where there are basements. Supporting the lowest floor is usually very simple, unless the building spans a ravine or projects over a cliff. There are two basic methods. One is to rest the floor directly on the ground, or, if the ground is not level, compacted filling of some kind. The other is to ‘suspend’ the floor above ground on piers and beams of some kind.

Suspended floors are easier to keep waterproof, give better access to drains and other services, and, where termites are a problem, allow more effective inspection and control. Where the lowest floor is also the ground floor, the use of a suspended floor with a sensible-sized crawl space under it will result in a lowest floor level about 1 metre (3 ft 4 in) above the surrounding ground and this obviously affects the proportions of the building.

Suspended floors are usually of timber or concrete construction. Suspended floors of reinforced concrete are similar to upper floors. Methods of construction of suspended timber floors vary considerably in different parts of the world. In Australia, such a floor will consist of the floor proper, of 25 mm (1 in) thick boards, which is supported on 100 mm deep × 50 mm (4 in × 2 in) wide joists at 450 mm (1 ft 6 in) centres. These joists in turn are supported on 100 mm deep × 75 mm (4 in × 3 in) wide bearers at 1800 mm (6 ft) centres. The total thickness of this type of construction from the surface of the floor to the underside of the bearers is thus about 225 mm (9 in).

Floors supported directly on the ground are usually cost-effective but must be of concrete. In order to prevent water from the ground being drawn up through cracks in the concrete by capillary action, the slab is usually laid over a membrane on a bed of crushed rock or sand. At the edges of the slab is a downturned beam which stiffens the slab edge and retains the supporting bed. The resulting floor level is about 250–300 mm (10–12 in) above ground. This kind of slab on ground construction is not suited to clay soils for the reasons given in 3.2.4 and 3.2.5.
Supporting upper floors

There are two main kinds of supporting member, walls and columns. Very few buildings are solely supported on columns or solely supported on walls. Most, however, are mainly supported on one or the other. The choice is constrained by the nature of the plan. Walls can be used for support only where permanent walls are demanded by the layout. Columns can sometimes be introduced within rooms, depending on the size of the column, the activities housed and the aesthetic effect.

The arrangement of supports can be regular or irregular. A regular arrangement is called a ‘column grid’. Again the selection of arrangement is constrained by the plan. A useful first step in developing a structural system is therefore to consider the relationship between plan types and the types and arrangement of supports.

Walls as supports

There are three plan types for which walls are likely to be suitable supporting elements. The first is the multi-storey repetitive plan (2.5.27). The second is the multi-storey serviced space building with a central service core (2.5.26–37). The third is the two- to three-storey timber-framed house. Houses are also often built with masonry walls supporting the upper floors. In such cases, either the plan must be treated as repetitive or some or all of the walls on the upper floors must be lightweight.

Multi-storey repetitive plan structures

Buildings such as motels, hotels and shopping centres often consist of essentially equal chunks of space separated by permanent walls. Such plans are well suited to a structural system of regularly spaced walls. This kind of system is called cross-wall construction, because the walls run from side to side of the plan. Cross-wall construction is also often used for row houses; the upper floors span the whole distance between the cross-walls that divide the houses. In this case, the upstairs partition walls are lightweight. Multi-storey blocks of flats more often show irregular arrangements of supporting walls within flats, supplemented by repetitive cross-walls between flats.
Supporting walls in repetitive plan structures may be of masonry such as brick or concrete block or of reinforced concrete. Masonry walls can be used for buildings up to fourteen storeys high, but this is well past the limit at which the form of the structure becomes critical in resisting buckling, and imposes severe constraints on layout. It is not usual to use masonry for supporting walls in buildings of more than two or three storeys, mainly for reasons of buildability.

**Service core structures**

A service core by definition is surrounded by walls which, so long as they extend to the ground, can be load bearing. If, for energy conservation reasons, the windows in the external wall are treated not as continuous bands but as spaced openings, it too can be a load-bearing wall. Then it makes sense simply to span directly from the core to the outside wall, so long as the distance does not exceed about 11 metres (36 ft). In structures of this kind, the walls will be of reinforced concrete (see Fig. 2.24).

**Timber-framed buildings**

It sounds like a contradiction to say that the walls are the source of support in a framed building. However, traditional timber-framing tasks are shared by the constituent elements rather than divided between them. Structurally, it is the assembly of the studs, with their bracing and also often the sheeting, plus the mutual stiffening of the different walls where they join, that do the work. Much of this integrated character has been retained in modern framing systems that substitute light pressed steel or composite steel and timber members for timber.

Timber-framed supporting wall structures of four and even more storeys have been built, but today it is usual to limit them to two storeys, for reasons of fire safety. This form of construction is mainly used for houses.

**Openings in walls**

If a wall is being used as a support, this limits the number, size and location of the openings that can be made in it. Openings should not
be placed near the ends of supporting walls. This is particularly true for masonry walls. As a rough rule of thumb, try to keep them half the floor to ceiling height away from the ends. Within these limits, any opening that fits within an equilateral triangle drawn with its apex at the ceiling and its base on the floor can be ignored for preliminary design purposes. Openings that do not meet these criteria should be regarded as dividing the wall into two structurally separate sections. For reasons that will be discussed later, it is also wise to treat the section of wall over such openings as visually distinct from the surrounding wall.

**Columns as supports**

The distinction between walls and columns as supporting members is not an absolute one. There is a conceptual difference between a wall, which carries load along a line, and a column, which carries it at a point, but the practical distinction is not so sharp. A steel pipe column supporting the roof of a single-storey building approximates to most people’s ‘ideal’ column from the structural point of view. However, a reinforced concrete column at the bottom of a multi-storey building is a much more substantial object, and some of the columns that support the roof of the Sydney Opera House below the podium level are several metres square. Sometimes columns are flattened to fit within walls, for planning or aesthetic reasons.

Thus, any structure that can be conceived as being supported on load-bearing walls can be redesigned so that it is supported by columns. Similarly, any member conceived of as solid can for structural purposes be replaced by a truss. The arguments for and against substituting columns for supporting walls need to be considered.

Columns are the preferred means of support for multi-storey buildings for which the position of the internal walls is not known or is likely to be changed in the future. This applies to serviced space buildings in general, with the exception described in 3.2.18. For similar reasons, columns are used as internal supports in many industrial buildings where the span is too great to rely on support by the external walls only.
Columns or walls?

Columns are often used for support where walls could be used for reasons of buildability. Where the floors are to be of reinforced concrete and the supporting walls are of masonry, the concreters may have to leave the site for other work between pours and it may not always be possible to bring them back at the moment the walls are finished. Such delays are expensive. Even if concrete is used for the supporting walls, concrete walls are more difficult to form, cast and cure than concrete columns, mainly because they are thinner (see 3.5.6).

Against these economic arguments based on the labour element of technology, it can be said that massive walls often improve the comfort and safety of buildings. Walls can also be useful in resisting lateral loads.

Columns have also been substituted for walls for ideological reasons. During the first fifty years or so of the twentieth century architects and engineers tended to regard framed structures, primarily supported by columns, as progressive and structures supported by walls as old-fashioned. For the same reason, Le Corbusier in some of his early works made a point of displaying freestanding columns in rooms.

Regular or irregular grids?

If it is decided to use columns as the main supports for upper floors, it is an advantage from the point of view of structural economy to arrange them in a regular grid. This helps the structural engineer to take maximum advantage of the reduction of bending moments through continuity.

Continuity can be beneficial where columns support concrete, timber or steel beams, or reinforced concrete slabs. In the case of reinforced concrete slabs, whether supported on beams or not, it is also desirable that the grid be square. Under typical design codes, a square slab of a given thickness supported on all four sides can span nearly half as far again as one that is supported on two parallel sides only. Of course, a square grid imposes constraints on layout. Either the layout will have to be adapted to the grid or there will be columns in the middle of some rooms. Irregular grids are more practical in reinforced concrete
structures than in steel or timber frames. Usually a very thick slab, about 225 mm (9 in) or more, is supported directly on the columns and the complex pattern of stresses is resisted by suitable reinforcement. No simple rules can be given for such structures; they should not be attempted, even in the studio, without the advice of a structural engineer.

**What sized grid?**

The grid size is constrained by several factors. In multi-storey serviced space buildings it is a critical decision, affecting everything else, and much time and a good deal of trial and error are devoted to finding a satisficing solution. In smaller buildings it is still important but not critical. There are four main objectives or constraints that affect the selection of grid dimensions. As usual, they are not independent.

**Site considerations**

If the size and shape of the upper floors is fixed by the site constraints, the grid must be a whole number fraction of the floor dimension, or the distances from the core to the external walls.

**Planning considerations**

It is usually desirable to keep the number of columns to a minimum, because they limit the freedom of planning. It also helps subdivision if the grid size bears some kind of whole number relationship to the typical dimensions of the spaces into which the building is likely to be subdivided, offices for example. This in turn needs to be related to the divisions of the windows, so that partitions do not abut glass, and to the divisions of the false ceilings (see 3.4.43). Often all these things are related by locating them in relation to a modular grid. Grid sizes vary but usually lie between 1 metre square and 1.5 metres square; rectangular grids within this range of dimensions are also often used.

**Economy**

Reducing the number of columns somewhat reduces the difficulty of pouring a concrete frame. However, in all types of framing systems,
increasing spans more than proportionately increases the cost of the structure. The depth, weight and cost of horizontal members increase approximately as the square of the span. The increased depth of the floor structure may lead to an increase in the space between each floor and the ceiling below, and thus in the overall height of the building. At best this adds to the overall cost; if the overall building height is limited by regulation and the result is the loss of a usable floor, it may be an economic disaster.

**Aesthetics**

The structural grid of columns and beams is often visible on the façade; in such cases it is the main element in façade articulation and its proportions must be carefully considered from that point of view. (See 4.6.40–77.)

**Deciding on grids in the studio**

It will seldom, if ever, be possible to consider and reconcile all these factors in a studio problem. Therefore, a rule of thumb is suggested, fundamentally unsound from the theoretical point of view but useful. The acceptable range of column grid sizes under ordinary conditions is from 7.5 metres (25 ft) square maximum to about 4.5 metres (15 ft) square minimum. The top half of the range is slightly to be preferred.

**Developing a structural system: the vertical loads**

Let us summarise the steps towards developing a structural system for the support of upper floors and matching it to a layout plan. The first step is to decide whether walls or columns will be the main supporting elements. The number and arrangement of the fixed walls in the preliminary layout are the main guides in this decision. If walls are chosen, their locations will be determined by the plan, with perhaps minor adjustments to reduce spans. If columns are chosen, it is necessary to decide on the grid. After this step, the next thing to do is to check on the continuity of load and support and to resolve any anomalies. In order to carry out this step in a systematic way, it is necessary to give some more thought to what is supported, that is, the
floors. There is an enormous variety of floor structures, but they can be divided conceptually into two main types, lattices and slabs.

**Lattices**

Traditional timber floor construction, as described in 3.2.14, exemplifies the principles of lattice floor structures. The floorboards form a continuous thin layer which is supported on joists, spaced 450 mm (1 ft 6 in) apart and of a depth determined by the span. The joists are supported directly on walls or on beams which in turn are supported on walls or columns. Such a lattice system spans in one direction only, the direction of the lowest members. If it is to be supported on walls, they must be continuous on two opposite sides. If it is supported on columns, there must be a column at each corner of each room or bay of the structure.

**Slabs**

Slab structures are exemplified by the reinforced concrete slab. A slab may be supported directly on walls or columns, or on beams which in turn are supported by walls or columns. For the reasons given previously (3.2.26), they usually span in two directions. Thus, if they are supported on walls then walls are required on all four sides of each room or bay. If they are supported on columns, there must be a column at each corner of each bay.

**Checking vertical continuity**

If the structural system is based on walls and the plan is the same on every floor, checking is unnecessary. If the structural system is based on columns arranged in a regular grid, mark the grid on every floor. Starting from the top floor, overlay each floor in succession, making sure that for each intersection of the grid there is a column or a wall in which a column can be concealed.

**Structural anomalies**

Structural anomalies occur where the plan changes on successive floors. Large houses are the commonest example, but commercial buildings
built for a mixture of uses and some public buildings also show wide differences in plan on different floors. In the case of hotels, large column-free spaces are often wanted on the lower floors, while the upper floors show repetitive arrangements of more closely spaced columns or walls. There is a descending load, transmitted by all the walls and columns above, and nothing to support it on the lower floor. In such cases the load must be transferred to supports in some acceptable way.

**Overhanging upper floors**

In some ways the simplest kind of anomaly is the case in which the upper floors overhang the lower. If the projecting portion is one or two or even three storeys above ground, the simplest thing may be to support it on columns of its own, standing clear of the building. If the columns are more than three storeys high, conventionally they will need to be braced by connecting them to the building at intermediate points.

Small projections of less than 3 metres (10 ft) may be cantilevered in concrete or steel-framed buildings. Timber will not cantilever as far unless special laminated beams or trusses are used: about 1.8 metres (6 ft) is a sensible limit. The main problem with cantilevers is ensuring that the rotary action of the cantilever at its fixed end is resisted. This requires either a column that is very deep in the direction of the cantilever, or continuity between the beams or slabs that form the cantilever and others inside. Cantilevered slabs are prone to deflect and such deflection is very noticeable, so it is best to stiffen them with beams or keep them down to about 1.5 metres (5 ft). Cantilevers at corners are particularly prone to deflect because the maximum span is increased and its direction is changed; either the corner should be splayed off or it should be propped in some way.

**Transfer beams**

Now consider the case in which a ground-floor column in a building with three upper floors has to be omitted. The span is doubled, so the bending moment from the floor above goes up four times. In addition, the loads from two bays of each of the two floors above are delivered as
a point load by the column in the middle of the new, increased span, which generates twelve times the original moment. Overall, the new maximum bending moment increases sixteen times. Then the supporting beam will have to be roughly four times as deep, since the section modulus is proportional to the square of the depth. The shear forces will also increase alarmingly, but that will not be discussed here.

Now assume that the original span was in the order of 6.5 metres (21 ft) and that the beam was a reinforced concrete one of a reasonable depth for this span, say 600 mm (2 ft). Conventionally this implies that the new beam is going to be 2.4 metres (8 ft) deep. At this rate, the transfer beam is going to obstruct the space far more than the column that has been removed. The best solution, and the point of this example, is to select a layout that does not require this sort of thing in the first place. However, site and other constraints sometimes prevent this.

**Accommodating transfer beams**

The simplest way of accommodating a transfer beam is to put it above the floor instead of below it. This solution is, however, limited to cases in which the layout of the floor above requires a permanent wall without openings in that position. The bedroom floors of hotels are sometimes carried over the public spaces below by using the walls between rooms in this way. In service core structures (see 3.2.18) the ground floor can be opened up by treating the whole façade as a huge beam and supporting it on a few, necessarily rather big, columns. For this to work, the proportion of wall to window must be fairly high.

However, permanent walls without openings are often inconvenient. A solution that has been adopted in many multi-storey buildings is to interpose some kind of service space, usually a plant room (see section 3.4) between the upper floors whose columns have to be supported and the lower ones in which columns are to be omitted. By making the transfer beams into floor-to-ceiling trusses within the service space, the loads can be supported and pipes and ducts can still be passed through them, even though access for maintenance is sometimes rather awkward.
An extension of this approach is to move the transfer beam to the top of the building, where plant rooms are normally located. Instead of propping the unsupported columns from below, they are converted into tension members and hung from the top. This technique has problems of buildability, but it has been used, notably in Foster’s Hong Kong & Shanghai Bank (Fig. 3.2).

Finally, the problem can be diffused by eliminating the supports in question on the upper floors as well. This means that there will be deeper beams on every floor. They will, however, only be twice as deep and they may clear the door heads or even be able to be concealed in ceiling spaces.

**Resisting lateral loads**

A system that is capable of supporting the vertical loads on a building is not necessarily capable of resisting lateral loads. Earthquakes and cyclones regularly provide dramatic evidence of this. Under lateral loads, the whole building acts as a cantilever with a uniformly distributed load. It may then fail in one of three ways. First, it may simply overturn. One of the most dramatic photographs taken after the Kobe earthquake shows a multi-storey building that has fallen across an eight-lane highway; the building appears otherwise intact. Second, the building may distort so much that the vertical members start to act as cantilever beams rather than as columns, and collapse. Third, individual members may be damaged or displaced, increasing the stresses on other members so that the whole building collapses like a house of cards. This is what happened to a block of flats, Ronan’s Point, in England when a gas explosion blew out a wall panel. A discussion follows of ways of avoiding such failures, with special reference to preliminary design and the action of wind.

**Overturning**

Most buildings resist overturning by sheer mass. The tendency of a building to rotate about its leeward edge produced by the wind acting horizontally is more than balanced by the weight of the building acting vertically. This is not, however, true for all buildings. Timber buildings
in cyclone areas need to be bolted down to deep concrete foundations. Buildings that are tall, slender and exposed, such as skyscrapers and lighthouses, may also need to be fixed down using rock anchors or other techniques. These are not problems that are likely to be encountered in the studio. However, if one of your designs includes a tower, you should give thought to the problem of overturning, particularly if the tower is of lightweight construction.

**Distortion**

Overturning is easy to visualise. The effects of distortion are more complex. Many structures courses use models or animated cartoons to help students to visualise the distortion of buildings under lateral loads. If your school is not so well equipped or you have forgotten the demonstration, it may help to build your own rough model, along the lines of Le Corbusier’s ‘Maison Domino’ and observe what happens when you hold the base still and push the top floor sideways in different directions.

You will see that, as the floors move sideways, imitating the effect of wind load on the external walls, the columns move out of plumb and either the joint between the column and the floor breaks or, if you have used plenty of good glue, the joints rotate, bending the floors. If your columns are slender, they may also bend. If you put a heavy load, such as a book, on top of the model while it is in this condition, it will collapse.

**Resisting distortion: rigid frames**

The modes of failure of even such a simple model immediately suggest one way of resisting distortion. If the joints between the columns and the floors are made stiffer, and the columns themselves are also stiffened, the structure will be able to resist much larger lateral forces. In a structure in which the floors are supported by beams, this can be done by making the beams deeper, either overall or by ‘haunching’ them at the columns. Where slabs are supported directly on columns, the slab can likewise be thickened around the column head. In either case, the columns may need to be made bigger than the minimum size necessary
to support the vertical loads alone. In long narrow buildings the cumulative stiffness of all the column-to-slab joints may be sufficient and additional stiffness, in the form of larger column dimensions and deeper floor structure, may be needed only in the direction of the short dimension.

The larger the columns and the deeper the beams, and the more rigid their connections, the stiffer the structure. The Hong Kong & Shanghai Bank building by Foster takes this to its logical conclusion. There are just two columns, the service cores at each end, and they are connected by gigantic trusses from which the floors are hung. The structural logic of such a solution is good; its buildability is more questionable (Williams 1989).

**Resisting distortion: shear walls**

Deep beams may obstruct service distribution. Large columns interfere with planning. Thick slabs are expensive. It is therefore advantageous to stiffen some elements only and use these elements to brace the rest against distortion. Instead of the whole building acting as a cantilever, these selected parts do the work.

A shear wall is a very literal interpretation of this idea. In its simplest form it is a reinforced concrete wall running in the direction of the lateral force. Since the wind and other lateral forces do not always act in the same direction, at least two shear walls at right angles to each other are needed to brace a building against all likely lateral forces (Fig. 3.3).

For a shear wall to be effective, it needs a long dimension in plan of about one-seventh the height of the building. It must not have many large openings, nor openings near its edges. It must extend from the ground to the roof, though like any cantilever it may taper as the load decreases. It must be solidly and continuously connected to the neighbouring floors, both to ensure that it receives the lateral loads from the rest of the building and to prevent it from buckling.

**Placing shear walls**

Since walls of this kind are a great nuisance in planning, locating them
is a difficulty. One common solution is to combine them with the service core, where there is one, or in smaller buildings with other fixed vertical elements such as escape stairs. Another possibility is to treat part or the whole of the external walls as shear walls. This strictly limits the size and placing of windows and ground-floor openings. However, in climates where preventing heat gain or loss is important and only small external openings are wanted, it may be an attractive solution.

**Shear walls in framed buildings**

Exactly the same principles can be applied in timber- or steel-framed buildings. Here, however, the shear wall that is the equivalent of a solid beam is usually replaced by a truss. This is the effect of the diagonal bracing in traditional timber framing. Famous large-scale examples include the Beaubourg Centre in Paris, which has external steel trusses to provide lateral stiffness, and the Hancock Tower in Chicago, where the entire façade is a gigantic steel truss (Fig. 3.4).

**Failure of elements under wind load**

Even if the whole structure does not fail, elements of a building may fail under wind load, usually by breaking away from the rest of the building fabric. The loss of support or protection that the failed element provided may then cause other elements to fail. There are two issues here. One is the fixing of elements, which will be discussed in section 3.5. The other is the structural design of the elements themselves. In many instances, failures of elements occur because the designer has not understood the size of the forces or their direction, or has used heuristic design procedures outside their proper sphere, usually as a result of some attempt at innovation.

**The size of the forces**

A wind of say 20 metres/second (45 mph) generates a dynamic pressure of about 250 pascals (5.3 lbf/ft²) on a vertical surface at right angles to it. Even more moderate winds may generate enough pressure to make it difficult to open a door at the base of a tall building on an exposed site. This has implications even for preliminary design; doorways may have to be screened or automatic sliding doors or revolving doors
provided. It is important to realise that in naturally ventilated structures if doors and windows on the windward side are left open, elements on the leeward side may be exposed to both pressure and suction.

**The direction of the forces**

Failures often occurred in the past because suction had been ignored. Lightweight roofing or wall cladding was torn off because the fixings were not strong enough. Today most manufacturers of such materials are careful to recommend adequate fixings.

The movement of wind across façades, both vertically and horizontally, has also sometimes been disregarded. The forces may be violent enough to tear off lightly fixed projections such as open casement windows, window hoods or outward opening doors. The taller the building, the greater the forces.

Under some conditions, vortices of tornado strength can be created. A building of medium height in Sydney had a large semicircular recess in its façade which extended from two or three storeys above street level to the top. At the bottom of this recess was a terrace, intended for open-air dining. Under certain wind conditions a vortex was created in this recess that was powerful enough to lift the tables and chairs. The terrace is no longer used.

**Design**

Earlier it was pointed out that all quantitative design procedures are heuristic. That is, they are rules of thumb that work only if certain, often unstated, conditions apply. The handy tables and nomograms that are used in structural steel design, or their equivalents embodied in computer programs, for example, do not apply if the temperature is 1000 degrees Centigrade.

Even minor infringements of the underlying assumptions of design procedures can have bad consequences. The Hancock Building in Boston, which is both tall and very exposed, was clad in very large glass panels, nearly 2 metres (6 ft) wide and extending from floor to ceiling on each floor. Under certain wind conditions, these panels deflected so
much that they popped out of their frames and fell to the street below. Miraculously no-one was hurt. Here the designers understood the loads and their direction perfectly and designed in accordance with the best current practice. However, because the sheets of glass were much larger than usual, the standard algorithm for frame design no longer applied.

3.2.49

**When to worry about wind loads**

You need to worry about wind loads if:
- the site is exposed
- violent winds are common
- your building is tall in relation to its plan dimensions
- your building is tall in relation to its neighbours
- your building has deep recesses in its façades which extend to the top
- your building is of lightweight construction
- any wall or roof element is unusually large, especially if it is also thin and lightweight.

3.2.50

**The size of the members**

So far, this chapter has dealt with ways of developing a structural system that matches a preliminary layout. In order to convert a diagrammatic layout into a three-dimensional design, it is also necessary to know the sizes of the members, at least approximately. Even where a grid of columns and beams is not exposed on the façade, the thickness of the walls, the dimensions of the columns, the location and size of shear walls and the minimum distance from the ceiling of one set of spaces to the floor of those above impose constraints on the form of the building and the arrangement of openings.

3.2.51

**Using structures courses to advantage**

The most useful contribution that the teaching of structural theory can make to the design studio, and ultimately to practice, is to give an understanding of structural behaviour, or structural systems. The second most useful contribution is to give students a sense of the reasonable sizes of structural members in common forms of construction. A very good way to do this is to set students the task of developing their own
tables, or preferably graphs or nomograms, to be used in making quick, rough estimates of structural sizes when designing. Even if your course is not organised in such a way that this is possible, it is a good exercise and not as much work as it sounds. If, for example, you design reinforced concrete columns for a building with a 6 metre (20 ft) bay size and heights of two, ten and twenty storeys, you will be able to interpolate reasonable sizes for other dimensions and heights.

**The thickness of floors**

Failing the ideal suggested earlier, the following are some theoretically sound rules of thumb.

Timber-framed floor
- Allow 1/24 of the span plus 50 mm (2 in) up to 3 metres (10 ft) and 1/24 span plus 75 mm (3 in) between 3 metres (10 ft) and 6 metres (20 ft). Remember that structural timbers are usually sold with nominal dimensions that are multiples of 25 mm (1 in). An absolute limit for conventional timber-floor framing is 6 metres (20 ft) and 4.5 metres (15 ft) is wiser. For longer spans, it will be necessary to introduce steel beams or trusses to reduce the span of the timbers, or use special laminated beams. Add a further 65 mm (2.5 in) to the structural timber size for floor and ceiling finishes.

Concrete floor
- One-way slab with continuity: allow 1/28 of the span.
- Two-way slab supported on beams: allow 1/40 of the span.
- Flat plate: allow 3/100 of the span.
- Beams: allow about 1/10 of the span from the top of the slab to the bottom of the beam. To allow for easy placing, reinforcing beams should be at least half as wide as they are deep.
- Finishes: add 25 mm (1 in) to these dimensions for floor finishes.

The floor to ceiling height in reinforced concrete structures is usually considerably greater than the structural minimum to allow for services to be installed between the structure and the finished ceiling (see 3.4.45).
Steel beams
- Allow 1/15 of the span. Where steel beams are used to support timber framing, the timber members can be fixed between, rather than on top of, the steel, so that the overall depth is reduced.

Steel trusses
- Allow 1/10 of the span; the structural efficiency of a truss depends largely on its depth.

The dimensions of columns
If columns worked only in compression, estimating their sizes would be very simple. However, they are also subject to bending, partly because they are never perfectly straight and partly because of lateral forces. The taller and thinner a column is, the greater the danger that it will buckle due to bending.

Giving general rules of thumb for column sizes is therefore very difficult. If you can, go and measure the columns in a building similar in size to the one you are designing.

For domestic floor loadings, the following applies.

Steel column
- Sizes can be obtained from manufacturers’ tables. If you cannot get a set of tables, allow 100 mm × 100 mm (4 in × 4 in) for a single-storey building. Add 75 mm (3 in) to each dimension for lightweight fireproofing for a two-storey building.

Timber column
- Allow 100 mm × 100 mm (4 in × 4 in) for single-storey heights up to 2.7 metres (9 ft) and 150 × 150 mm (6 in × 6 in) for heights over 2.7 metres and the lower floors of two-storey buildings.

Reinforced concrete column
- Allow 225 mm × 225 mm (9 in × 9 in) as an absolute minimum. This apparently large size is necessary to allow reinforcement to be placed in the formwork with sufficient concrete cover to prevent it from rusting. For external columns, allow 300 mm × 300 mm (12 in × 12 in) minimum.
**The thickness of walls**

The thickness of walls is more influenced by considerations of materials, assembly and system performance than by structural requirements. These issues are discussed in sections 3.3 and 3.5. Load-bearing walls are usually more than capable of supporting the loads in compression. The main problem is buckling.

The stiffness necessary to resist buckling can be provided by junctions with other walls. However, if the floor-to-floor height of a load-bearing wall is more than twenty times its thickness, and the length unsupported by cross-walls is more than thirty times its thickness, you should provide intermediate stiffening members. As a rough guide, the projection of these members from the wall should be one-tenth of the wall height and their width should not be less than the thickness of the wall.

**Movement**

Buildings move. If you live in a timber house, this is easy enough to accept. You hear and feel its movements all the time. It is less obvious in masonry- or steel- or concrete-framed buildings. Nevertheless, they all move and some predictable movements are large enough to be considered even in preliminary design.

**Why movement is important**

Movement cannot be eliminated, but it is an objective of most designs to control it. There are three reasons for this. The first is that people often find visible sagging, leaning or cracking alarming. They see these things as warnings of possible collapse. The second is that uncontrolled movement can produce unsightly cracking in finishes. The third is that cracking in external finishes or elements may lead to water penetration and decay.

**Kinds of movement**

Movements can be divided into three broad classes according to their causes. Dead and live loads produce movements, usually called ‘deflections’. Changes in the chemical composition of materials also
cause movement. Building materials also move with changes in the physical environment, particularly changes in temperature and humidity.

These three kinds of movement interact. For example, thermal movement can produce structural forces. It is also the case that most of the precautions that can be taken to reduce the ill effects of movement concern the assembly and fixing of cladding and finishing materials, which are discussed in section 3.5. Therefore, this section deals only briefly with the kinds of structural movement and their effects.

**Movement of the whole building**

The potential deflections at the tops of very tall buildings under wind loads can be of the order of metres (or yards). Elaborate precautions are taken to keep such deflection within limits that will at least avoid seasickness in the occupants. Such special cases are beyond the scope of this book. However, even small and low buildings may be exposed to bending or shear forces that act on the building as a whole, as a result of foundation movements.

Foundations move differentially under building loads for one of two reasons. Either the load is not spread evenly over the foundation, or the foundation material is not uniformly resistant. The former situation may arise if, for example, different parts of a building are of very different heights, or are built of different materials, or have different floor loads. A proper site investigation will reveal differences in the bearing capacity of the ground. In either case, the problem can be overcome by recognising that movements are likely to occur and providing suitable joints that will allow them to take place without being noticed (see 3.5.61–64).

Finally, if the strength of the building, considered as a beam, differs very much from point to point, cracking is likely to occur at the weak points. Large openings in the façades of masonry buildings create such weaknesses. Once again, a partial solution is to pre-crack the façade (see 3.5.61–64).
Movements of elements

Deflections of horizontal members are the most significant structural movements affecting building elements. They include elastic deflections which will recover when the load is removed, and plastic or creep deflections which result in a permanent change in the shape of the element.

Elastic deflections

Structures are usually designed to limit elastic deflection to between 1/240 and 1/360 of the span. This avoids visible sagging and visible cracking of rigid finishes such as plaster. 1/360 of the span does not sound much, but in a span of 6 metres (20 ft) it amounts to about 16 mm (5/8 in). This can be ignored at the scales usually used in studio drawings, but not in detailing. However, if much larger spans – of, say, 9 metres (30 ft) – are proposed, some consideration will have to be given to the effects of elastic deflection even in small-scale drawings. In the case of reinforced concrete construction, the effects of creep deflection have also to be taken into account.

Creep deflection

Members subjected to bending are partly in tension and partly in compression. Compression gradually squeezes the water out of concrete, as if it were a sponge. As it loses water, the concrete shrinks. This shrinkage is in addition to the overall drying shrinkage discussed in 3.5.45. It takes place slowly over a year or more; hence the name ‘creep’ deflection. Because the shrinkage takes place on the compression side of the member only, it causes the member to sag.

The amount of this deflection can be twice the elastic deflection, and must be added to it. Thus, the total deflection of a concrete beam with an elastic deflection of 1/360 of the span may be as much as 1/120 of the span, or 50 mm (2 in) in a 6 metre (20 ft) span. While this can be reduced in a variety of ways, such movements clearly have visible effects even at the small scale. For example, where there is a long run of windows directly under a concrete beam, a movement joint of 50 mm
(2 in) or more will be needed between the window and the beam, in addition to the normal frame.

**Advanced structures**

In concluding this section, a word should be said about advanced structures, which include tent structures, reinforced concrete shells, and space frame structures. The word is don’t. Such structures seem attractive because they appear to make possible a free, plastic, creative approach to building form. Exactly the opposite is true. In all such structures, great economy of material is achieved by ensuring that the load is distributed as equally as possible to every part. Their forms are therefore rigidly determined by structural considerations and little or no departure from the ideal structural form is possible. Without expert technical knowledge, either personally possessed or immediately available, the chances that a shape that a student dreams up will be able to be built using such techniques are very low indeed.

The Sydney Opera House provides a paradigmatic example. The forms initially imagined by Utzon proved structurally unsound and practically unbuildable and had to be completely revised in the final design (Fig. 3.5). This is worth mentioning because some disastrous failures have resulted from architects carrying from school into practice the notion that they could freely invent structures of these kinds.

![Figure 3.5](a.png)

‘Final form in arching vaults, not shells’, Sydney Opera House (1957–73) Jørn Utzon

Despite this, advanced structures are very attractive to students and if the necessary expertise is available to the school a special course or elective, with accompanying studio work, may be valuable, if only to disillusion the participants.
**Energy and building**

**Introduction**

Control of energy is important; that is, it is a value that is growing in strength. A great deal of energy is used in buildings. The exact proportion varies with the climate, but the total is always significant. According to some estimates, buildings in the northern hemisphere account for 40% of total energy consumption. The twin threats of global warming and energy resource depletion can therefore be reduced if energy consumption for heating and lighting is reduced.

Other forms of energy control are also necessary for safety or comfort. As previously noted, fear of fire in buildings is universal and strong. The control of sound is important for health and comfort. People often complain of disturbance to sleep or concentration caused by external noise and of anxiety caused by a lack of acoustic privacy.

**Regulation**

Because control of energy is regarded as important, it is increasingly subject to regulation. In this, as in other matters, regulations may vary from place to place, though there is a growing international consensus. Fire regulations in particular have existed in many countries for a very long time; there are well-established paths of international communication on fire issues, and consensus is correspondingly strong. Consensus on regulation of other aspects of energy control is likely to develop in a similar way.

**Constraints on building form**

Energy control is a goal of design which can constrain building form at the most basic level. It has therefore to be taken into account at the earliest stages of design. This suggests that it should be considered in the design studio. The degree of constraint depends on which of two approaches is adopted to each kind of energy control: passive or active. Passive control generally makes more, and more-specific, demands on building form.
3.3.4  Passive and active control

Passive control of energy is achieved by the form and materials of the building itself. Active control involves some application of energy through controlling devices and systems, such as air-conditioning plant. There is no sharp distinction between the two and they are almost always combined to some extent. However, this section on energy will deal mainly with passive control. Active control will be discussed in the next section, on building services.

3.3.5  The human factor

Whether passive or active control is adopted, there is a human factor in every aspect of energy control. An obvious example is clothing. The more people rely on changing their clothes to keep them warm or cool, the less energy is consumed. This is not true, however, where a badly designed active system of air-conditioning cools the air too much in summer and heats it too much in winter, forcing people to adapt their clothes to compensate.

More generally, both passive and active systems rely on human intervention for their continued success. Passive systems of thermal control, for example, may require that vents and shutters be opened and closed at the right times. Active systems require maintenance, even if they are so-called intelligent systems in which many routine aspects of operation are monitored by computer.

3.3.6  Scope and limits of this section

Even within the limits of passive systems, this section does not attempt to do the job of a basic text on the thermal or acoustic behaviour of buildings, or on natural lighting or ventilation. It concentrates on qualitative decisions that directly affect preliminary design. Quantitative aspects are introduced only in the form of rules of thumb that can help the designer to avoid taking a direction that would certainly be invalidated by a quantitative analysis.

3.3.7  In praise of mass

In most climates and circumstances, the simplest and most reliable
method of energy control is an informed use of heavy materials – mass. What ‘informed use’ means is explained in more detail later. Right at the start, though, it must be said that the admiration expressed here for massive construction is controversial. If one looks at the production and consumption of buildings as a total system, the embodied energy cost of construction of massive buildings (that is, the energy consumed in the transportation and erection of the heavy materials) may be more significant than the energy savings generated over the lifetime of the building (Pawley 1990, ch. 4). However, this depends in part on the average life of buildings, and there are signs that, after having got shorter from about 1930 to 1980, this is now getting longer. The issue is unlikely to be settled while the price of energy is so much affected by politics and subsidies.

**Mass and heat**

Massive materials such as stone, brick and concrete have a high thermal capacity. They can act as stores or sinks for heat energy. In cold climates and in winter in temperate climates, heat absorbed by massive walls or floors exposed to sunshine during the day is slowly released at night, slowing the cooling of the building as a whole. In hot dry climates and in some temperate climates, massive elements can be cooled down at night by exposure to cooler night air or to the nightsky, which when there is little cloud is an almost perfect absorber of radiant heat. To control the rate of heat loss and gain, and to match it to the seasons, a system of filters, screens and insulation is needed. The general principles of such systems will be discussed later. In hot humid climates, mass is of limited help with thermal control. An impressive use of mass for thermal control can be seen in a large building in the capital of Zimbabwe, Harare. This building, designed by Pearce Partnership, illustrates both the possibilities of passive control and the constraints that it imposes (Slessor 1996).

**Mass and fire**

Fire is, of course, a form of heat. Massive materials generally do not burn well, and insofar as the surfaces exposed to fire are made of such
materials, this will help to prevent fire breaking out in the first place, or spreading. If a fire breaks out, massive materials will absorb some of the heat and thus help to reduce the rate of spread of the fire.

**Passive fire protection in multi-storey buildings**

In multi-storey buildings, reduction of mass is usually an objective for structural reasons. For a long time, this was in conflict with fire protection. Steel beams and columns are easily weakened by fire, and encasing them in concrete or other forms of masonry was the only effective way of protecting them. In order to ensure that people could escape safely if a fire broke out, large floor areas were divided into fire compartments by fire-resistant partitions, and these too had to be of masonry.

Besides increasing structural loads, concrete casings around columns and firewalls of the necessary thickness took up valuable space, so other approaches were sought. Most of the successful solutions depend on materials that either change chemically when heated so as to absorb a great deal of heat or give off water vapour, which is notoriously good at absorbing heat. These materials are applied to steelwork as a coating or made into sheets that can be used to enclose steel members or to construct fire-resisting partitions. Concrete-covered steel columns are about 100 mm (4 in) larger than the steel in each direction; lightweight casings can reduce this to 50 mm (2 in). The reduction in thickness of fire partitions is proportionally less; they remain about 150 mm thick but their mass is reduced very considerably.

**Mass and acoustics**

Thick, heavy building elements are difficult to set vibrating. Since sound is a vibration, mass contributes to keeping noise out, or in. The exception is impact noise, because the denser and heavier a material is, the better conductor of sound it is, once it is actually set vibrating. So messages can be transmitted for long distances by tapping pipes, and the noise of jackhammers smashing rock on a site next door can run all through a concrete-framed building. In the preliminary design phase, however, it is mostly air-borne sound that we have to consider.
Lightweight forms of construction that give reasonable acoustic isolation have also been developed. The principle is to separate the two sides of the wall acoustically. In fact, two framed walls are built, without structural connections, and each is faced on the outside with two layers of a dense material such as plasterboard. Since sound energy is lost each time it has to pass from dense material to air, this works quite well. However, such walls are necessarily fairly thick; you need to allow about 225 mm (9 in).

**A note on theatres and concert halls**

In theatres and concert halls, keeping unwanted sound out is a major objective. Where lecture theatres or conference rooms, in which loudspeakers may be installed, are set among other, quieter spaces, it can be equally important to keep sound in. In such cases, massive construction and double-skin construction are often combined, giving walls from 300 mm (14 in) up to 450 mm (1 ft 6 in) thick. Windows must be eliminated as far as possible (or double- or even triple-glazed) and doors specially designed and/or protected by airlocks. The complexities of acoustic design for theatres are beyond the scope of this book. Lectures on theatre acoustics are often combined with a special studio on theatre design.

**The informed use of mass**

In summary, walls and floors of massive materials such as brickwork, concrete and stone can be useful in controlling energy flows in the following ways:

- Internally, for the control of heat flow. Massive solid materials are good conductors of heat, so heavy solid walls do not make good heat barriers between inside and outside. If such materials are used externally for the reasons discussed below or for reasons of durability or symbolism (see 3.5.9), then some form of filtering system will be desirable to control the heat flow. Filtering systems are the next topic in this section.
- Internally and externally for fire resistance.
- Internally and externally for acoustic isolation.
Many buildings today use a mixture of heavyweight and lightweight construction. In designing houses for hot dry climates, for example, it may make sense to build the spaces used in the daytime of massive materials which will warm up slowly and the spaces used at night of lightweight materials which will cool down quickly. Whether such technically rational arrangements will be acceptable to the final users, however, depends on their values (in the case of housing, in particular, but to a greater or lesser degree in every kind of building). In Australia, in temperate, hot and hot humid climates ‘brick veneer’ houses are built with a single skin of brickwork only on the outside of the external walls; the brick here serves a symbolic, not a practical, purpose.

In multi-storey buildings, the problems of supporting massive walls have to be considered. It is easiest to take advantage of the benefits of mass in buildings with repetitive plans (see 2.5.27).

**Filters**

The term filters is used here to describe techniques which either passively or with a minimum of manual adjustment contribute to controlling flows of energy in buildings. Unlike mass, they do not simply absorb energy: they slow or control its transmission. Insulation is the first kind of filter to be considered. It will be followed by a discussion of fixed or adjustable barriers and screens. Insulation has relatively little influence on preliminary design, but barriers and screens are important both for planning and their effect on appearance.

**Insulation**

Thermal insulation is of two kinds, radiant and conductive. Radiant insulation, as its name implies, slows the transmission of heat between surfaces by radiation. It consists of a thin layer of metal foil or of plastic with a thin metal coating, which reflects the radiated heat back to its source. Radiant insulation must have an air gap next to its reflective face (or faces, if it is double-sided); otherwise, the heat will be transmitted by conduction. To reduce transmission by convection, or heat-induced circulation of air, the air gap should ideally be no more than about
50 mm (2 in). Radiant insulation is often used in framed roofs and walls, particularly in climates where heat gain is the major problem.

**Conductive insulation**

Conductive heat insulation is usually made from light materials that are poor conductors of heat. (Glass-fibre insulation is an exception.) The effectiveness of the materials is usually increased, and their weight reduced, by making them into foams, open-textured boards of glued fibres, loosely woven textiles, or quilts of loose or lightly bonded fibres covered in tough but flexible sheet materials. The principle in all these cases is the same: air, which is a very poor conductor indeed, is mixed with a solid that is a poor conductor. The result is that the heat has either to pass repeatedly from solid to air or to follow a maze-like path through the solid parts, a path much longer than the direct distance from face to face of the insulating material. The cavity in a cavity-brick wall acts, among other things, as a conductive insulator.

Conductive insulation slows heat transmission; it does not prevent it. Such insulation is more effective against heat loss than heat gain; it is more useful in cold climates or in the cold seasons of temperate climates than in hot climates. In cold climates, insulating roofs is more effective than insulating walls. In hot climates and seasons, insulated buildings warm up more slowly, but they also cool down more slowly at night. The ‘lag’ in heating up provided by insulation is seldom more than about two hours, which is not sufficient by itself to keep interiors comfortable during the whole day.

**Insulation and wall thickness**

Radiant insulation takes effectively no space in frame construction, where it is mainly used. Conductive insulation is subject to the law of diminishing returns; for each additional unit of thickness, the heat transmitted is reduced by the same fraction. As a consequence, for all but the very coldest climates, 50 mm (2 in) of insulation is the economic maximum and 25 mm (1 in) is a common rule of thumb.
Sound insulation

Sound insulation is somewhat of a misnomer. Mostly what is referred to as sound insulation is sound absorption. It reduces the sound level in the treated space, but offers little if any barrier to sound transmission. The complex systems of absorbers used in concert halls are beyond the scope of this book. However, simple porous absorbers are used in all kinds of buildings to reduce sound reflection from ceilings in public spaces and from walls, particularly back walls of lecture theatres and larger conference rooms.

The principle is simple. The surface to be protected is covered with some kind of perforated or gridded material. Behind this is an air space, in which, supported by and often fixed to the perforated surface finish, are blankets or pads of some porous material – which often looks very like thermal insulation, thus contributing to the confusion. To put the matter crudely, the sound wave has to force its way through the porosities of the material, and in the process some of its energy is converted into heat. The remainder of the sound wave is reflected by the wall or ceiling beyond the absorbent material, and passes through the absorbent again with still more loss of sound energy.

Spaces that need sound absorbent treatment usually have false ceilings for other reasons, so the absorbent treatment adds little or nothing to their overall dimensions. Sound absorbent treatment of walls, however, may add 75 mm (3 in) to 100 mm (4 in) to the wall thickness, which is not trivial.

Doors, windows, verandahs and awnings

Added to the list in the heading can be shutters, blinds, curtains, screens, brise-soleils and so on and on. Human ingenuity has provided innumerable devices, fixed or movable, for the control of radiant heat and light from the sun and of air movement. Many of them also have important weatherproofing functions (to be discussed in the next section). Very often these purposes are combined with the control of privacy by the definition of territory and by permitting occupants of the building to see without being seen. In a traditional Japanese house, one
could enter the walled courtyard without impoliteness, but at the
verandah edge one stopped and called out to announce one’s presence.
Curtains in suburban houses in Europe, America and Australia and
mihrab screens in many houses in the Islamic tradition control both
energy and privacy. Because they combine a range of functions,
including symbolic ones, such devices have great cultural significance.
They are often given decorative elaboration, as with the cast-iron
verandah railings of New Orleans and the east coast cities of Australia.
Last, but not least, for many buildings the devices form the major means
of façade articulation and expression.

To bring some order into the complexities of this topic, the control of
radiant heating will be considered first, followed by daylighting and
ventilation. No attempt will be made to describe or evaluate all, or even
a significant fraction, of the available devices. The application of
principles will, however, be illustrated by some cross-cultural examples.

**The heat of the sun**

The sun heats buildings by direct radiation, indirectly by reflected
radiation from the ground and surrounding buildings, and still more
indirectly by heating the air. Here, we are concerned with direct radiant
heating. The control of this radiation has different objectives in different
climates. In climates that are mostly cold, the warmth of the sun is
embraced as far as is possible without losing more heat by conduction
and convection than is gained by radiation. In climates that are mostly
hotter than is comfortable, solar radiation is reduced. In temperate or
mixed climates, it may be necessary to make a choice between a good
design for the warm weather or a good design for the colder weather.
Alternatively, it is possible to design different spaces or even different
buildings for different seasons, a principle carried out to a remarkable
degree in the aristocratic villas of ancient Rome (MacDonald and
Pinto 1995).

**Radiation and the exterior**

In a freestanding building the roof in general receives the most solar
radiation, followed by the south-facing walls (northern hemisphere) or
the north-facing walls (southern hemisphere), the west walls and the
east walls. Since few buildings are perfectly oriented to the compass
points, this gives only a rough indication of the importance of shading.
More accurate estimates can be made by using a heliodon or an
appropriate computer program.

3.3.22 Shading the whole building

A whole building may sometimes be effectively shaded by a natural
feature, such as a mountain. One- and even two-storey buildings may be
shaded by trees. If solar heat is desired in winter, deciduous trees (which
shed their leaves) may be used. In hot dry climates, it is technically
possible and might in some cases be efficient to shade an entire building
with a tent (but see 3.2.62).

3.3.23 Shading the roof

Shaded roofs are less common than one might expect. Temporary or
permanent roof awnings have been used in hot dry climates since at
least the New Kingdom of ancient Egypt (McDowell 1996). They are
generally associated with flat roofs used as auxiliary living or working
spaces. In wet and windy climates, the expense and difficulty of
constructing and maintaining such secondary roofs, not to mention the
problems of weatherproofing the flat roof (see 3.5.77), seem to have
inhibited their use. The problem has more often been addressed by
planning. Since the space immediately under the roof is exposed to
extremes of heat loss and gain, it is often used for storage, as an attic, or
for service spaces such as plant rooms. Where these options are not
available, as in many single-storey buildings, insulation, as previously
discussed, or more rarely ventilation of the roof space may be used to
reduce the heat gain (or loss).

3.3.24 Shading the walls

Walls of low buildings can also be shaded by trees or shrubs. In very hot
and dry climates, the streets are kept narrow and buildings are built up
against each other, which protects walls from the heat of the sun. In
principle, walls can be shaded by permanent light screens mounted on
the outside of the wall or by systems of adjustable panels or louvres that can be manipulated either manually or by some automatic mechanism so as to allow the wall to heat up in winter and remain cooler in summer. The space between wall and screen must be ventilated to allow the air to escape; otherwise it will heat up to a higher temperature than the outside air and much of the benefit will be lost.

It is difficult to think of an example, probably because the costs exceed the benefits. However, there are many examples of walls shaded by roof extensions or secondary roofs; the verandah is the commonest form. While such overhangs cannot completely protect walls from eastern and western sun, since the angle of the morning and setting sun is too low, they are very effective in shading the walls most exposed to the sun. They can be supplemented with partial vertical screens, as with the lattice screens often found at the perimeter of verandahs in traditional houses in Queensland, Australia (Fig. 3.6).

Verandahs and related spaces can also provide additional usable space, a transitional zone between inside and outside, benefits in the control of daylight, and valuable weather protection. This accounts for their popularity, at least in low-rise buildings.
Windows

In considering the shading of openings for heat control, we can for practical purposes disregard doors, unless they are glazed doors that double as windows or form part of a large window.

Windows have evolved into very complex devices which combine, not altogether happily or effectively, a number of different objectives. They admit light. They allow people to look out. They usually have opening sections for ventilation. Finally, they may form part of a system of thermal control, which is the current topic.

Glass and heat transmission

Modern windows are always glazed, and their thermal behaviour depends largely on the thermal behaviour of glass. Glass is a poor insulator. Touch the glass of an ordinary window on a hot day and you will find it hot, and on a cold day it will be cold. On a cold day, windows cool the room mainly by convection and radiation; the cold convection currents they create are felt as ‘drafts’. On a hot day, convection and radiation still operate, but less obviously. These effects may be somewhat controlled by curtains, but the air space created by the curtains and the curtains themselves soon cool down or heat up. For this reason, in extreme climates double glazing is used; the best forms of double glazing consist of two layers of glass spaced about 25 mm apart, sealed around the edges and with the space between them partly evacuated. The increase in the number of boundary layers and the low conductivity of the evacuated space make double or even triple glazing an effective insulation. Double glazing also has acoustic advantages, and this, combined with the energy savings it can produce, has led to it being used in large buildings even in temperate climates.

Glass and the transmission of radiation

When solar radiation strikes an ordinary pane of glass in a window, some is reflected, and some is absorbed by the glass, heating it up. However, most of the radiation passes through the glass and strikes surfaces inside the room, where again some of it is absorbed and some
of it is reflected (Fig. 3.7). This produces a change in the wavelength of the radiation, and the glass is much less transparent to those altered wavelengths, so that a good deal of the energy of radiation is trapped in the room. This is the source of the heating obtained in glasshouses. The amount of heat transmitted in this way is quite substantial: 300 mm × 300 mm (1 ft × 1 ft) of glass exposed to the sun on a winter’s day in a temperate climate is equivalent to a two-bar electric radiator burning in the room. This is highly desirable during cold weather but disastrous during hot weather. Control of sun penetration is therefore essential to controlling the balance of heat energy in buildings.

**Absorbent glasses**

One way to control the penetration of sunlight is to modify the properties of the glass so that it transmits less. Heat-absorbent glasses transmit less infrared (heat) radiation. The disadvantage of this approach is that the glass itself heats up much more than normal glass. The resulting expansion and contraction may crack the glass if the frame is not carefully designed; internal stresses produced where the glass is partly in the sun and partly in shadow can also produce cracks. Furthermore, some of the ‘absorbed’ heat is still transmitted to the inside by radiation and convection from the inner surface. Finally, the transmission of visible light is reduced.

**Reflective glass**

Heat-reflective glass is produced by coating the glass with a thin film of metal. Because the film is delicate, it is usually located inside a panel of double glazing. This is therefore an expensive solution seldom used in domestic, small-scale or lower cost buildings, but highly effective in reducing heat loads in larger and higher quality ones.

Reflective glass also has disadvantages. The amount of light transmitted is noticeably reduced and its colour is changed. Further, the reflection of the sun off a large building that has been made into a gigantic mirror can be a nuisance to pedestrians or the occupants of other buildings and a danger to drivers; for these reasons, some cities have banned the use of highly reflective glass.
External sunshades

The first thing to grasp about sunshades is that they must be external. Internal curtains, venetian blinds, roller blinds, shutters or screens are virtually useless in preventing heating by solar radiation through windows. Once through the glass the heat is in and most of it will stay in. The only exception is a further refinement of the double-glazed window: in some examples, both reflective and otherwise, tiny controllable venetian blinds are installed between the panes of glass. In this case, the blind is still outside the innermost layer of glass.

All sunshading devices also exclude a considerable amount of visible light. They are on the outside of the building and so require cleaning and maintenance, which may be difficult to carry out. On restricted sites, some types of sunshade may reduce the effective building area unacceptably. Despite these disadvantages, such devices give other major benefits in controlling the quality of internal light and improving weatherproofing (see 3.5.92), which combine to make them the method of choice for controlling solar heat gain.

Fixed sunshades

There are innumerable types of external sunshading devices. They can, however, be roughly divided into those that are fixed and those that are adjustable. Fixed screens are designed geometrically to take advantage of the changing angles of the sun’s apparent path in winter and summer, so that the rays are largely excluded in the hottest months and largely admitted in the colder ones. For a window facing the sun’s path (that is, due south in the northern hemisphere and due north in the southern), a rectangular hood designed so that its outside edge is at the level of the window head, and projecting outwards to a distance equal to half the window height, will provide satisfactory conditions in temperate climates. The hood must extend somewhat beyond the window opening on either side.

As the façade turns away from this ‘ideal’ condition, either towards the east or the west, sun angles become lower and it is necessary to introduce vertical projections in increasing numbers until the screen
becomes a sort of honeycomb, the scale of which can vary from quite small, as in Costa, Niemeyer and Wiener’s Brazilian pavilion at the New York World Fair of 1939, to the heroic, as in some of Le Corbusier’s late work in India. At this point, both daylighting and outlook are severely affected and adjustable devices may be preferable. Since the appropriate form of fixed sunshading devices with orientations other than due south or north varies with latitude, no rule of thumb can be given.

Most schools of architecture include in their courses some study of sunshading devices, using computer programs or models or both.

**Adjustable sunshades**

Adjustable sunshades also come in many varieties. Most fall into one of two categories: those whose axis of movement is horizontal and those whose axis of movement is vertical. Vertical axis devices include traditional shutters and vertical louvres. Horizontal axis devices include awnings of various kinds, from the striped canvas affairs popular around the Mediterranean to the pivoting panels of fixed louvres found in many south-east Asian countries. Other horizontal pivoting devices include adjustable louvres and venetian blinds.

![Figure 3.8](image)

*Automated flexible sunshade system with light-deflection components in an office building, Wiesbaden, Germany (2001)*

Herzog & Partners
Besides these two main types, there are façade-fitted sliding screens and shutters, the external roller shutters widely used in Italy, and various exotic, mechanically controlled devices on the principle of the camera iris, such as those at the Institute of Arab Studies in Paris by Jean Nouvel and the intelligent façade of an office building in Weisbaden, Germany by Herzog & Partners (Figs 3.8 and 3.9).

Adjustable sunshades can effectively exclude solar radiation at any angle, but often at the cost of completely obstructing light and view. Since they mostly depend on human agency for their adjustment, they are frequently not used correctly.

**Daylighting**

The topic of daylighting is well calculated to cause a rational person to give way to despair. Daylight is good light. It gives the best colour rendering. It is free. It is plentiful. Many people prefer its natural variability to the uniformity of artificial lighting. It has disadvantages: it is turned off at night and at some times and seasons there may not be enough of it. These disadvantages are easily overcome by artificial lighting.
Despite all this, the effective use of daylighting is beset with difficulties and contradictions. Some of the difficulties have already been brought out in discussing heat control. Others arise from the properties of the human eye and of daylight itself.

The eye and daylighting

The human eye adapts to the brightness of the visual field and especially to its brightest points. It does this, as everyone knows, by expanding or contracting the pupil, so that more or less light is admitted, an involuntary process. If there is too much light altogether so that the eye cannot adapt, as may be the case on a sunny day in the tropics, for example, and people have to walk around squinting or wearing dark glasses, this is one kind of discomfort glare. Another kind is produced by too much contrast between small bright areas and larger darker ones in the visual field; the eye cannot adapt to both at once. The darker ones appear gloomy. In extreme cases, for example where a sunlit window is placed at the far end of an otherwise unlighted corridor, the darker areas may become effectively invisible; this is known as disability glare.

Discomfort glare and daylighting

Discomfort glare is a major problem for daylighting. If sunlight comes into a room, the sunlit patches will be much brighter than the rest of the surroundings. If we look out of the window at a sunny scene, the sunlit areas will, once again, be mostly much brighter than the interior if it is relying on daylight alone. Even if there are no sunlit areas in view, the sky itself is very bright. Tiresomely, too, the sky changes its brightness characteristics; on overcast days the luminance at the horizon is roughly one-third that at the zenith; on clear days the sky is brightest near the sun, but significantly brighter near the horizon away from the sun than higher up. Finally, if sufficient windows are provided to give good light under the worst conditions, it is probable that the interior will be too bright for visual comfort when the daylight is brighter. Sunshades can effectively cut off the view of the zenith, thus reducing discomfort glare, but they also reduce the amount of daylight received. These problems are compounded by considerations of the distribution of light in the interior.
Light distribution in interiors

The problems of daylighting mainly concern workplaces. In dwellings things are much easier. Spaces are smaller. Lighting levels can generally be lower. Areas that need brighter lighting, such as kitchen bench tops or desks, can be placed near windows. The distribution of light in domestic interiors is thus mainly an aesthetic issue, and from this point of view it will be discussed further in Chapter 4. From the quantitative point of view, the rules of thumb for window sizes given in 2.2.7 will serve for domestic daylighting.

In office and industrial settings, the theory and the calculation of lighting levels are based on the idea of the ‘working plane’. The ‘working plane’ is an imaginary horizontal plane extending throughout the work area, and the aim is to get an even and sufficient level of lighting throughout the working plane. What constitutes sufficient lighting for various tasks is defined internationally; needless to say, it is considerably more than the minimum in which such tasks can actually be carried out. The quantitative aspects will not be considered here.

Roof lights and skylights

Satisfactory lighting conditions for work can be obtained in single-storey buildings or on the top floors of multi-storey buildings by means of roof lights or skylights. Roof lights set in the plane of flat or sloping roofs should not be used in any climate where heat gain is a problem, for the reasons given in 3.3.26; they will be constantly exposed to the sun and excessive heating will result. For most climates, therefore, the most efficient form of roof lighting is one of the many variants on the ‘saw tooth’ roof, in which vertical or steeply sloping glazing, continuous across the space, is placed at regular intervals and connected by roofs sloping from the top of one range of glazing to the bottom of the next. The glazing is arranged to face away from the sun’s path, north in the northern hemisphere or south in the southern, so that there is no problem with sun protection. Internal blinds can be used to control glare (Fig. 3.10).

An advantage of this system is that trusses can be placed in the roof
plane and the plane of the glazing so that the system will span long distances without columns. A disadvantage is that large continuous gutters have to be placed at the junctions of the roof and glazing area to remove the water, and such ‘box’ gutters are always potential sources of leaks and flooding (see 3.5.88).

Figure 3.10
’Saw tooth’ roof, Renault’s Communication Centre, Boulogne-Billancourt, France (2005)
Jakob & MacFarlane

**Side windows**

Even in single-storey buildings, side windows (that is, windows set in the vertical plane of the wall) are usually wanted for outlook and ventilation. In multi-storey buildings, side windows are the only option. Unfortunately, it is difficult to provide good daylighting for work spaces from side windows. The higher up the top of the window, the more deeply the light penetrates the room; Le Corbusier made a mistake about this when he argued that horizontal strip windows give the best light distribution. However, for reasons of economy, ceiling heights in multi-storey workplaces such as offices are usually limited to less than 3 metres (10 ft). A rule of thumb is that effective daylighting from side windows can be obtained so long as the distance from the window to the back of the room is no greater than three times the height of the window (Phillips 1980). This is reduced if the light is obstructed by other buildings, or if there are external sunshades the projection of which must be added to the depth of the room. Similarly, heat-absorbing or reflective glass reduces the amount of light entering and thus the depth of the room that can be lit.

It is worth noting that American skyscrapers built before the Second World War, which had to rely mainly on natural lighting because the
incandescent lamps then available generated too much heat, and air-
conditioning had not yet come into common use, generally have a
distance from the external wall to the rear of the office of no more than
6 metres (20 ft) and sometimes less. This may therefore be taken as a
rough working rule for daylighting work spaces from side windows.

The distribution of daylight from side windows can be improved by the
use of glass or plastic lenses for glazing. However, they tend to distort the
view and can only be used in the upper sections of windows.

**Daylighting in modern office buildings**

The use of low-voltage fluorescent lights and air-conditioning allows
modern office buildings to be deeper than the figure given in 3.3.38.
Deeper plans are more economical in terms of materials, since there is
less outside wall and less overall heat loss and gain. Daylighting can thus
at best be seen as a supplementary form of lighting in such buildings.
Windows, sunlight and outlook have been demonstrated by researchers
to have a mitigating effect on occupational stress for occupants.

**Natural ventilation**

Natural ventilation of buildings is demanded for a number of reasons.
First of all, we need air to breathe. Second, breathable air that contains
too much carbon dioxide, from human lungs or open flames, is
experienced as ‘stuffy’ or unpleasant. Third, and particularly in modern
buildings, other gases given off by synthetic materials may accumulate
and cause discomfort or even health problems. We should bear in mind,
however, that this kind of thing is not really new: in the nineteenth
century people were occasionally poisoned by arsenic fumes given off by
the dyes in wallpaper. Fourth, there may be perceptible smells, such as
body odour or cooking smells, and our age is particularly sensitive to
smells. Finally, air movement may be desired for cooling, particularly in
hot, moist climates. The first four of the requirements can be met
comparatively easily in low-rise buildings; the last is more difficult and
imposes much more stringent planning constraints.
Changing the air

It is almost impossible to suffocate in modern buildings, even those inaccurately described as ‘hermetically sealed’. It is no longer the case that ‘In well built modern residences the construction is often so good that it will hold water’ (Banham 1969, p. 41, quoting Baldwin 1899). Indeed, schemes to reduce energy consumption in modern houses by such measures as insulation and draft seals in doors and windows have been much less successful than expected, because the basic construction leaks so much air. If people are conscious of stuffiness or smells and they can open windows they will do so and the accumulated gases will dissipate by diffusion or convection. The rough rule of thumb for window sizes given in 2.2.7 is adequate for this purpose, provided that the room is not too large and deep. Improving ventilation will not solve the problem of toxic gases that are odourless; these must be eliminated at the source. Compulsory fixed ventilation, as has often been demonstrated, produces marvels of ingenuity in blocking the ventilators, which are a source of drafts in cold weather and do nothing useful in hot.

Natural ventilation and cooling

A flow of air can cool you if it is cooler than your own temperature, or by the evaporation of sweat. If the air is too much colder than the skin, it will be experienced as a draft, but this is rarely a problem where cooling is wanted. One view of human thermal comfort is that it is limited to the zone of ‘vasomotor control’, that is, situations in which the increase or decrease of blood flow to the skin is sufficient to keep our internal temperature within its proper limits. On this view, someone who is sweating is already uncomfortable, as is someone who is shivering, because these responses occur when the conditions are too hot or too cold for vasomotor control to be sufficient. Nevertheless, air movement is much desired in hot and humid climates. However, it should be noted that when the humidity is very high the ability of air to absorb moisture is correspondingly reduced. This means that sweat may not evaporate sufficiently and air movement will then not be very effective in cooling.
Wind

Wind and breezes are produced by convection currents in the atmosphere. As previously noted (see 3.2.7–10), wind blowing on a building produces a high-pressure zone on one side and a low-pressure zone on the other. By making controllable openings in the appropriate places on each side of a building, it is possible to direct streams of air through the building in a more or less controlled way. The constraints on the building form and orientation that this imposes will be discussed shortly. An interesting adaptation of building form to wind behaviour is found in Queensland, where the climate is often hot and humid. Traditional Queensland houses have verandahs and these verandahs are often elaborated at the building corners into quite large pavilions intended for summer living. If you think about it, you will see that an open pavilion in this corner position must always experience some air movement if there is any breeze at all.

Wind speed

Again as previously noted (3.2.7), wind speed increases with distance from the ground. Partly for this reason, buildings in hot humid climates are often raised off the ground on stilts or piers. An interesting reversal of this approach is found in some North African houses. Here the houses huddle together to shade the walls, but poke up tall wind-catchers, or chimneys in reverse, into the air stream above the town. Combined with openings lower down and on the downstream side of the building, these devices produce a flow of air through the building, which may also be cooled by convection (see 3.3.47).

The increase in wind speed with height is not always an advantage, however. At the heights reached by many of today’s tall buildings, wind speeds are such as to make reliance on natural ventilation difficult and even dangerous. Pressure difference between the windward and the leeward side can be sufficient to prevent doors being opened, or to fling them open violently. Windows on the leeward side can even be ripped out. At the level of nuisance, papers and curtains are blown around. Similar effects can be seen in buildings of
no more than five or six storeys that are exposed, for example on a cliff edge or facing a large body of water. Recently, buildings have been designed that seek to overcome these difficulties by the use of convective ventilation.

**Natural ventilation: windows**

Air will not flow through a room with openings on one side only. The internal pressure will increase to match the external pressure. The ideal arrangement is to have windows of approximately equal sizes in the opposite walls, so that one will be in the high-pressure zone and the other in the low-pressure zone. The direction of the air flow can be controlled by louvres. In hot humid climates, whole walls can be made of louvres. However, comfort in these climates also requires the exclusion, or at any rate partial exclusion, of insects by insect screens which slow the air flow.

If there is to be natural air flow between two adjacent rooms, there must be quite large permanent openings connecting them. This effectively does away with acoustic privacy, which is one of the main goals in dividing buildings into rooms. This tends to limit effective ventilation and cooling by means of side windows to buildings no more than one room thick. However, this limitation, like that on the height of naturally ventilated buildings, may be overcome if recent experiments with convective ventilation prove successful.

**Convection in buildings**

The tendency of warm air to rise and cooler air to sink, combined with the thermal inertia of massive construction, accounts for the chill often felt on entering the Gothic cathedrals of Europe and similar tall, massive interiors. In hot climates, this can be turned to advantage, particularly if the hot air is allowed to escape at the top of the building and air can be drawn in at the bottom from some cool source, such as a permanently shaded courtyard exposed to the night sky. Traditional houses of North Africa made much use of this principle. Conversely, in cold climates, solar heat trapped in massive floors and walls at ground level during the day can heat upper floors by convection at night.
Advanced convective systems

Thanks to advances in engineering, it has recently become possible to apply the principles of convection to ‘natural’ ventilation and thermal control in larger buildings. Three main methods of doing this have appeared so far. One is to make use of chimneys, which work in the same general way as the chimneys of fireplaces. The second is to use an atrium, or multi-storey central courtyard, as a giant chimney. The third is to construct a double-skin outer wall.

A system of centrally placed chimneys and ducts can draw air out of rooms on either side of a corridor without greatly affecting acoustic privacy. The natural convection of the chimneys may need to be assisted at times by fans. Fresh air is admitted through openings in the external walls. A system of this kind was included in a building at the University of New South Wales, Sydney, which housed, among other things, the School of Architecture. The building was designed by Mitchell, Giurgola, Thorpe, Architects (Cantrill 1997).

Offices for Daimler Benz in Berlin by Richard Rogers Partnership (Fig. 3.11) illustrate the use of an atrium for thermal control and ventilation (Russell 1995a). The atrium is glazed over at the roof. In the winter, the atrium is heated to what is described as an ‘acceptable’ level

Figure 3.11
Atrium acts as thermal buffer,
Daimler-Benz project, Berlin, Germany (1995)
Richard Rogers Partnership
by solar heat gain. In the summer, hot air rising in the atrium is allowed to escape through slats in the glazed roof. Cooler fresh air is drawn in through a ground-level plenum. All the offices are naturally ventilated by means of opening windows on both the atrium and the external faces.

Cavity walls can be constructed with an external skin of glass (Figs 3.12 and 3.14) or movable ventilation louvres (Fig. 3.13). Quite often this is done as much for aesthetic reasons as for climate control. The external skin covers up an awkward and badly articulated façade. However, an external glass skin can contribute to climate control in two ways. If the cavity between the outer and the inner skins is sealed, the cavity performs the same insulating function as in a cavity-brick wall (3.3.16). It will, however, be much less efficient in hot climates. Here we are more concerned with ventilated façades that depend for their working on convection, or the ‘stack effect’. In such cases, the glass external skin protects the inner skin from wind and weather, permitting opening windows in the inner skin even in quite tall buildings. In summer, cooler air is drawn up between the skins by convection. In winter, closing or reducing the ventilation of the cavity allows air in the cavity to heat up, reducing heat loss from the building.
Some problems of advanced convective systems

There are several things to note about all these systems. First, like all passive climate control systems, they work best where humidity is low and the daily temperature variation is relatively large. Second, few of them can provide comfort for all seasons of the year without the support of conventional air-conditioning and heating. Third, the engineering involved is extremely sophisticated and requires close and continuous collaboration between architects and engineers from the earliest stages of design. Such systems are therefore unsuitable for incorporation into undergraduate designs, unless as part of a special course or elective. Fourth, in the past when asked whether these techniques were proven in practice, an expert panel of engineers were notably cagy in their replies (Russell 1995b). Fifth, initial costs are significantly higher than for conventional mechanical systems and the energy savings are not sufficient to cover them under existing political and economic conditions in most countries. That is why a large proportion of such systems have been designed for or built in Germany, where ‘green’ regulations and subsidies make them more economically feasible (Russell 1995b).
**Internal convection: fireplaces**

Fireplaces are the commonest example of the use of convection in thermal control. The fire heats the air around it in the fireplace and if the size and shape of the opening, the shape of the upper part of the fireplace and the size of the flue are all correctly related on aerodynamic principles, the hot air will rise through the chimney. This stack effect will be helped if the top of the chimney is in a low-pressure zone but prevented if it is in a high-pressure zone; for this reason, chimney tops should be above the ridge line of pitched roofs. In the case of flat roofs, this does not matter since there is always a low-pressure zone over the whole of the roof area (3.2.9).

The convective flow of air through the fireplace maintains the combustion of the fire and gets rid of the smoke. It also drains cold air from the rest of the building, creating draughts; hence the popularity of inglenooks and high-backed chairs in really cold climates. A fireplace is an extremely inefficient heating device because most of the heat goes up the chimney. It is still worse if located on an outside wall, since much heat will be lost to the outside by convection and radiation. The best place for a fireplace is an inside wall, where the heat that does not go up the chimney will be distributed throughout the building by convection, conduction and radiation.

The details of fireplace design are too complex to be discussed here. If you are including a fireplace in one of your designs, allow about 1500 mm (5 ft) width by 750 mm (2 ft 6 in) depth for the fireplace itself. The flue, which must of course go through all floors from the fireplace to the roof, will be about 225 mm (9 in) square internally and 450 mm (1 ft 6 in) overall.

**Fire**

Any tall open space inside a building can act as a chimney if a fire breaks out. Smoke and flames will be drawn up and accumulate at the top. Death in a fire is mainly due to smoke inhalation. Staircases are particularly vulnerable to this effect, which is why escape stairs in tall buildings are usually required to be of fireproof construction sealed by
airtight doors, and mechanically ventilated so that the pressure inside is
greater than the pressure outside. This risk should be considered
wherever a space of more than one storey in height is incorporated into
a building.

**Evaporative cooling**

If hot dry air passes over water, it will absorb water vapour, and since the
evaporation of water requires energy, the air will be cooled. This
principle is much used in hot dry climates, where pools (both external
and internal) are popular features. Slightly porous jars filled with water
and placed in an air stream produced by any of the methods discussed
earlier are a somewhat more economical but related device. Evaporative
cooling uses a lot of water, and since water is often scarce in hot dry
climates, it is a luxury. Trees and plants cool the environment in part by
transpiration of water, a form of evaporative cooling. Evaporative
cooling will not work in hot humid climates because the air is already
full of water.

**Condensation**

Just as hot dry air takes up water, so warm moist air will give up moisture
if it encounters a surface that is cold enough; that is, at a temperature
below what is known as the ‘dew point’. In cold climates, porous
insulation has to be protected from water vapour coming from inside
the building, otherwise condensation will occur somewhere within the
insulation, and wet insulation does not work. Air inside buildings tends
to contain a great deal of water vapour, much of it breathed out by or
evaporated from people, but also from other activities such as cooking
and washing. Condensation on interior surfaces is generally regarded
as unacceptable and this discourages the use of ‘cold radiators’ on the
lines of the familiar, hot radiators. The issue has little direct effect on
preliminary design but is important for the understanding of air-
conditioning, which is discussed in the next section (3.4.5–18).
Summary

Issues of energy control directly affect preliminary design in several ways:

- If it is desired to make much use of solar heating or daylighting, particularly for work spaces, or of natural ventilation for cooling, the shape and orientation of the building will be quite strongly constrained.

- Decisions have to be made about the size and distribution of massive elements to assist in the control of temperature, noise and fire.

- A small allowance of space may need to be made for various forms of insulation.

- The size and placing of windows and of external screens and shades depends on decisions about the relative importance of solar heating, daylighting and discomfort glare. There are computer programs that can help with this, by calculating the various trade-offs, but no clear single criterion can be stated. From the viewpoint taken in this book, the decision should be made on the basis of the values of the users.

- Pools of water, trees and planting are among the most useful devices for improving building comfort in hot climates.

Designing for the maximum use of passive forms of energy control in a small to medium-sized building can form the basis for an interesting studio exercise, provided that the necessary science has been introduced much more fully than has been possible here. From this type of exercise, students can learn why such buildings are seldom built and often work poorly when they are.
Services

Introduction

Services of various kinds are essential to the working of most modern buildings. They also account for a significant portion of their cost. This section will discuss the spatial requirements of service systems. The technology itself will be described only insofar as it directly affects the spatial requirements. Books are available that give more detail, for example Cowan and Smith (1983).

The services to be considered are: heating, ventilating and air-conditioning; artificial lighting; transport services; supply services; and waste and cleaning services. Heating, ventilating and air-conditioning are discussed first because the issues relate to the previous section; otherwise the order is arbitrary. The section concludes with a discussion of service coordination in the service cores of large buildings and the sizing of plant rooms and other plant spaces.

Central heating

In central heating, fuel (usually oil) is burned in a ‘central’ furnace rather than in open fires in each room. It heats air or water which is then circulated throughout the building, in ducts or pipes, or in the case of air by convection. The hot air is released into the rooms through grilles near the floor. The hot water passes at intervals through what are still often called ‘radiators’ but are in fact mainly convective heaters. These take many forms, but they are always designed so as to have a large surface of conductive metal exposed to the air. Convective heaters are usually placed under windows to reduce draughts.

Space requirements for central heating

A central heating system for a small to medium-sized building imposes few design constraints. A furnace room is required but it need be no more than 2.7 metres (9 ft) square. A tank for fuel is also needed and there must be access to it for fuel deliveries. When the building does not cover the whole site, the fuel oil tank is usually buried in the ground near the boundary for ease of access.
Hot-water central heating can also be powered by solar panels. This requires a large area of pitched roof oriented towards the sun’s path. It therefore imposes more constraints on building form than the traditional systems.

Circulation ducts and pipes can be largely disregarded during preliminary design. However, central heating is less and less used in larger buildings, in which some form of mechanical ventilation is almost always wanted. The combination of heating and ventilation is most efficiently achieved by air-conditioning, even where cooling is not a major consideration.

**Mechanical ventilation**

Mechanical ventilation, as distinct from air-conditioning, is ineffective in those situations in which it is most necessary. Mechanical ventilation is here distinguished from the use of extract fans to remove cooking smells from kitchens or hot air from roof spaces, or of fixed or mobile fans to provide local cooling. A system of mechanical ventilation pumps outside air into the building to keep the air inside from becoming too polluted.

This is often perceived as being necessary in hot climates and in crowded spaces such as lecture theatres. In such circumstances, pumping hot air in from outside can frequently make the interior hotter, and since the space is already full of people generating heat, absolutely unbearable conditions can be generated in a very short time. In general, if air-conditioning cannot be afforded, the restrictions imposed by natural ventilation should be accepted. Mechanical ventilation is in general an ineffectual compromise.

There are, however, some exceptions. In the case of carparks and toilets, for example, it is desirable to pump polluted air *out* of the building. This is often required by regulation. Conversely, fire stairs are pressurised to prevent smoke entering them.

**Air-conditioning**

The following discussion begins by looking at relations between air-
conditioning and people. It then goes on to discuss air-conditioning systems and their impact on preliminary designs.

Air-conditioning gets a very bad press. In the fifty or so years since air-conditioning of public buildings and workplaces became commonplace, its advantages have come to be taken for granted, while the disadvantages and dangers are widely publicised. As a result, some negative ‘urban myths’ about air-conditioning have become established. Therefore, let us start by considering the real advantages and disadvantages.

At its best, air-conditioning can provide an environment that is comfortable as to temperature and humidity for most people, and extremely clean, and it can do this with better economy of energy than any other system. It is extremely difficult to provide a comfortable working environment in hot humid climates without air-conditioning.

However, all this depends on having a system that is well designed, well constructed and well maintained. Since such systems are expensive, necessary elements of a good system are often omitted. Even if all the right parts are there, they will not function as they are supposed to if maintenance is poor. In addition, there are real problems inherent in air-conditioning. The failings of air-conditioning systems can be divided into two classes: problems of temperature control, and problems of air quality and health.

**Temperature variation**

You cannot please all of the people all of the time, and this is especially true of temperature control. People’s preferred temperature varies according to the usual normal distribution; there are also differences according to age, sex, clothing habits and customs and so on. People with extreme temperature preferences will never be satisfied with temperatures within the median preference range. Therefore, there will always be some complaints. Complaints will be reduced if people are given some individual control, but this is only possible in the case of individual offices or rooms.
Contrary to widely held opinions, the best air-conditioning system is not necessarily one that maintains an absolutely constant temperature throughout the building at all times. Thorne and Purcell (1976) showed that people were most comfortable in air-conditioned buildings in which the temperature varied somewhat; constant environmental temperature upset their diurnal temperature rhythms.

However, in many cases temperatures in air-conditioned buildings exceed generally acceptable ranges. This happens first because external and internal conditions vary and the system is not ‘intelligent’ enough to adapt to this, and second as a result of deliberate policy.

**Variation in external conditions**

Air-conditioning systems can easily be designed to adapt to changes in external air temperature. The main problem is the movement of the sun, which produces changing heat loads on the building faces exposed to it. Spaces at building corners are especially vulnerable. This difficulty can be reduced or in some cases eliminated by the use of sun screens (see 3.3.30–32).

**Variation in internal conditions**

The interior of a deep plan building (see 2.5.43) is likely to need cooling whatever the season owing to heating from internal services. The areas near outside walls will need heating in winter and cooling in summer. The main sources of heat inside an air-conditioned building are people, lights and machinery. All these are somewhat variable, but people display the most variability. They crowd together in meeting rooms or go out to lunch in a body; as a result, machines may be less used and if there is ‘intelligent’ control of the lights they may be turned off. If the system is designed to cope with the extreme heating conditions and is not adaptable, spaces will be over-cooled. Most people have had the experience of going into an air-conditioned meeting room or lecture theatre that has been empty for some time and is so cold as to cause shivering. Conversely, a system designed for ‘average’ conditions will be unable to cope with a crowded space, which will become hot and stuffy.
3.4.9

**Wilful abuse**

Managers of some public spaces, such as large stores or shopping malls, sometimes raise or lower the internal temperature beyond what is needed for general comfort so that people entering from sweltering or freezing conditions will experience a ‘rush’ of relief: ‘Oh, it’s so warm (or cool, as the case may be)!’ Later the users find themselves sweating or shivering.

3.4.10

**Air quality and infection**

For reasons of economy of energy, much of the air in an air-conditioned building is recycled. Enough external air is added to avoid stuffiness. The recycled air inevitably contains bacteria and viruses exhaled by some of the building population. How many of these hostile agents are eliminated depends on the efficiency of the filtration system. However, even the most expensive, efficient and well-maintained filters, such as those used in hospitals, do not get rid of all of them. As a result, people who move into an air-conditioned building often suffer from a short outbreak of minor respiratory infections. Much more serious outbreaks of disease can occur if elements of the system such as filters, cooling towers and ducts are not properly cleaned and maintained; so-called ‘legionnaire’s disease’ is the best known.

3.4.11

**Pollutant gases**

Pollutant gases originating in the building are also recycled. The widespread ban on smoking in public buildings or air-conditioned workplaces has eliminated one major source of air pollution. However, there are still problems with other gases, mostly volatile solvents used in synthetic materials or adhesives. This is not a direct consequence of air-conditioning, and it is probably no more serious in air-conditioned buildings than in buildings that are not air-conditioned. The solution is not to do away with air-conditioning but to change the chemistry of these materials.

3.4.12

**Coping with variability**

Air-conditioning systems cope with the variability of conditions in a
variety of ways. Only a sketchy review is possible here. In the crudest systems, variability is ignored. Air at some preset temperature is pumped in, through a ‘plenum’ space above a false ceiling or through a single large duct over a corridor or exposed in the space being served. The air then filters back through grilles to a ‘return air’ duct. Little or nothing in the way of sensors or controls is needed. More flexible systems are more complex and more expensive. Four will be described: the zoning system, dual duct and reheating systems, and fan-coil systems.

**Zoning systems**

A zoning system divides the building into three or four zones, each served by a separate air supply which can be at different temperatures. This system can respond to the differences between the core and the periphery and also to differences between different parts of the periphery. Sensors are required to control the temperature of the air delivered to each zone.

**Dual duct and reheating systems**

These systems are still more flexible. The temperature of the air supplied can be varied either by mixing hot and cold air supplied through two separate systems of ducts or by reheating cold air with electric heaters in the ducts serving a particular zone. A large number of zones can be created using these systems. They can also cope with areas of greatly varying load, such as conference rooms. Both are expensive: the dual duct system wastes ductwork, the reheating system wastes energy. The number of sensors needed and the complexity of the controlling system increase with the number of zones.

**Fan-coil systems**

Some of the most flexible systems so far devised separate the tasks of fresh air supply and temperature control. An example is the fan-coil system. In this system, only the fresh air required is provided by the central plant. The main supply and return air ducts are therefore much smaller. The heating and cooling of the air is done locally by small fans that draw air from the room and blow it over metal coils cooled by cold
water circulated from a central plant or heated by electric heaters. This system gives almost complete local control. In isolated rooms such as hotel rooms it is even possible to turn off the system and open the windows.

This system is most useful around the periphery of buildings, where control is most needed and it is easy to run the water pipes. The units can be fitted under a window sill about 150 mm wide. Despite its great advantages, this system is expensive to maintain, because it has many small local motors and air filters rather than a few large central ones.

**Mechanical principles of air-conditioning**

Before discussing the size and arrangement of ducts and plant rooms, a brief explanation of the mechanical principles of air-conditioning is in order. Air-conditioning depends on the heat pump. The principle is the same as that of a domestic refrigerator. Under normal conditions, heat flows from hot to cold, but a heat pump can reverse the flow. In a domestic refrigerator, heat is absorbed at the internal cooling coils. The extracted heat is disposed of by convection through another set of coils, usually at the back of the unit. Similarly, although on a larger scale and usually with a smaller heat differential, heat is taken out of the air by an air-conditioning system and is discharged, at least in the case of large buildings, through a cooling tower, usually at the top of the building.

It was remarked earlier that air-conditioning systems may use less energy on a yearly basis than a pure heating system. This is because even in winter it is possible for the heat pump to extract heat from the fresh air taken in, provided it is not below 0°C. Such a system is known as ‘reverse cycle’. In hot weather, when cooling is the main objective, surplus heat need not be wasted; it can be used to help heat the hot water supply.

**Elements and arrangement of a system**

An air-conditioning plant consists of the heat pump or pumps, which feed heating and cooling coils, a fan to move the air through the system, filters to clean the air, and water sprays for humidity control. The order of arrangement of these elements varies. Besides, there are the air
intakes, with a mixing chamber for return air, and the outlets to one or more ducts depending on the number of zones and the kind of system. All of these elements are connected by control systems.

**Size of air-conditioning plant**

Because the volumes of air that have to be handled by central systems are very large, the elements of the system are large too, and the enclosure that surrounds them may range from the size of a small mobile home up. Air-conditioning plant in large buildings is usually installed in a general plant room with other equipment (see 3.4.51).

**Horizontal ducts**

The sizes of the ducts are a matter of calculation. The calculations are not difficult but will not be discussed here, because in most cases it is unnecessary at the stage of preliminary design to know the exact duct sizes. The system of air distribution in a central system is roughly as follows. Air diffusers, usually mounted in a false ceiling, are connected by relatively small, round, flexible pipes to the main supply ducts, which are of rigid metal and wrapped in insulation.

These ducts are stepped in cross-section, getting bigger as they near the main supply riser. At the point of joining the main supply riser, the cross-sectional area of a supply duct may be 1 square metre (10 sq ft) or even larger. The ideal cross-section for an air duct is round or square. These shapes have minimum frictional resistance because they have minimum perimeter for their area. However, duct shapes often have to be adapted to the space available in a false ceiling and to the requirements of other services. Because of the limitations on false ceiling space, the art of duct layout consists in ensuring that the ducts reach all the required outlets without one duct having to cross over another. False ceilings as service distribution spaces are further discussed in 3.4.45.

**Vertical ducts in multi-storey buildings**

Air-conditioning systems other than fan-coil systems require at least two large vertical ducts, a supply duct and a return air duct. Two or even
more supply ducts may be used depending on the number of zones. More supply risers can also make the layout of horizontal ducting easier. The total area of the ducts depends on such factors as the size and the number of floors to be air-conditioned, the type of system used, the perimeter/area ratio of the building, and the presence or absence of sunshades. If no expert advice is available, assume internal duct dimensions of 1 metre × 1 metre (3 ft 4 in × 3 ft 4 in) to 1200 mm × 1200 mm (4 ft × 4 ft). See also 3.4.49 for the location of ducts in service cores.

Artificial lighting

Artificial lighting now imposes few technical constraints on preliminary design. The space required for light fittings in false ceilings will be discussed in 3.4.44–45. In buildings for entertainment, shops and buildings that are much used at night, the design of artificial lighting is a primary element in the aesthetic effect. However, the technology is advanced and rapidly changing. Despite its importance, therefore, artificial lighting is seldom considered in the studio in detail and is also beyond the scope of this book.

Transport services

Under this heading will be considered moving walkways or beltways, escalators and lifts. The first two can be dealt with very briefly. Lifts require more attention and are discussed in 3.4.46–48.

Moving walkways

Moving walkways are used where very large numbers of people have to travel long distances horizontally and/or short distances vertically. They are most commonly used in transport terminals. They are typically about 1 metre (3 ft 4 in) wide between handrails. They are installed in pairs, one to go and one to come. Their rise is limited to about 7°.

Escalators

Escalators can also move large numbers of people. The approximate maximum capacity of an escalator 1200 mm (4 ft) between the handrails is 130 persons per minute. An escalator of this size is about
1700 mm (5 ft 8 in) wide overall. Smaller escalators are made but this is the usual size. The length of the sloping portion of an escalator will be approximately $1.75 \times$ (floor to floor height) to which should be added 1600 mm (5 ft 4 in) at each end for the horizontal sections. Landings must be added to these dimensions.

**Supply services**

The common supply services in buildings are hot and cold water supply, gas for cooking and heating, fire sprinkler services, electricity, and information services. Hospitals, laboratories and factories require piped supplies of more exotic and dangerous gases, but these systems will not be discussed here. In general, supply services do not take up much space. However, they all require access for maintenance.

In single-storey buildings with suspended floors, supply services can be run under the floor. In multi-storey buildings they can run in false ceilings, provided that the ceiling is removable or has access hatches for maintenance. Vertical risers can be exposed in low-status spaces such as closets, or concealed in shallow ducts with doors for access (see also 3.4.49).

It is rash to assume that supply services can be buried in concrete or masonry walls or in concrete floors. If a failure occurs, the service will be interrupted for some time and the necessary demolition work will cause nuisance and disruption. Similarly, it is overly optimistic to provide service riser ducts that are deep but too narrow for a maintenance technician to walk into. There is a desperate shortage of technicians with arms over two metres long and eyes in their fingertips.

**Cold-water supply**

Where there is a public supply of piped water, cold-water supply for houses and other small buildings does not constrain initial design. However, the water pressure at the tap depends on the pressure that the public system provides, which in turn depends on the relative height of the local reservoir. In the case of tall buildings, this may not be enough for the upper floors. One commonly adopted solution is to install a water tank near the roof and pump water up to it. The tank acts as a
buffer supply in case the pump breaks down. Such tanks can be quite large; however, they are usually installed in plant rooms with other bulky equipment (see 3.4.52). Where there is no plant room, which may be the case in multi-storey flats or apartments in temperate climates, water tanks are often placed on top of lift towers, adding a storey to their height.

**Fire control**

Public buildings in general and tall buildings in particular are usually protected by sprinkler systems, which automatically release sprays of water in the event of a fire. Water is needed to supply sprinkler systems and fire hoses. Since there is a danger that the pump will break down during a fire, in tall buildings sufficient water is stored in the same tank as the domestic supply; the domestic supply is drawn from higher up in the tank and the fire supply from the bottom, so that the fire supply is always available.

Some fire-fighting organisations prefer to maintain complete control over the water supply for fire-fighting. They pump water from their own street hydrants into a dedicated system of pipes that supplies the fire hoses. This requires a clearly visible and readily accessible access point.

Whatever system of supply is used, cupboards for hydrants and hose reels are required on every floor of all public and commercial buildings, in the same position on each floor. Such cupboards need to be about 1050 mm (3 ft 6 in) high, 1m (3 ft 4 in) wide and 250 mm (10 in) deep. Spacing regulations vary. However, it is usually required that all parts of each floor should be able to be reached from a hose point by a hose not exceeding a certain length, often about 30 m (100 ft), after allowing for obstructions such as partitions.

Sprinklers have to be located in a regular grid to ensure that they cover the whole floor area. The layout of sprinklers and the cold-water pipes that supply them is one factor in the design of false ceilings in public and commercial buildings (3.4.45). Where upper floors
open onto multi-storey spaces in public buildings, a ‘water curtain’ of closely spaced sprinklers is often provided to prevent the spread of fire and smoke.

Modern fire-fighting also makes use of systems of smoke detectors and thermal alarms to locate fires.

**Hot-water supply**

In large buildings with central heating or air-conditioning, the hot-water system is often combined with other heating equipment and located in the same plant room (3.4.51). In houses, hot water is used in bathrooms, kitchens and laundries. If the house is planned so that these activities are close together, vertically or horizontally, a single ‘hot water system’ can easily be connected to all of them. If the points of use are far apart, it may be better to have two systems, one for the bathrooms and one for the kitchen and laundry. This reduces heat loss from the connecting pipes. Since the most frequent use of hot water is normally in the kitchen, and the kitchen and the laundry require water at a higher temperature than the bathrooms, a separate system located under the sink in the kitchen or exposed in a laundry nearby can be quite efficient.

For a single domestic system, or for a separate system servicing the bathrooms, a closet 1 metre square or less will be sufficient. Hot-water systems can also be placed in pitched roofs. Wherever the hot-water system is put, remember that it will eventually wear out and have to be replaced, so there should be clear, though not necessarily direct, access from the outside.

Most hot-water systems are heated by electricity, but if gas or oil is used the space containing the heater must be ventilated and should be of fire-resisting material. Solar hot-water systems are becoming increasingly popular. As with heating by solar panels, such systems require correctly oriented roof space. The storage tank for a solar system is also often mounted above the roof, where it is quite conspicuous; manufacturers will provide dimensions and details.
Gas for heating and cooking

There is a tendency to regard gas as a nineteenth-century anachronism. However, gas and particularly natural gas is a cheap fuel. Many cooks, including professional chefs, prefer gas ‘cooking tops’ to electric ones. Against this, gas, whether obtained from coal as in the old town gas systems or piped from natural wells, is a non-renewable resource. The supply of gas places few constraints on initial design. As usual, there must be a place to run the pipes and access for maintenance.

Electricity

The distribution of electricity in houses does not constrain the initial design. However, there must be provision for a switchboard, which is usually mounted outside so that it can be reached by meter readers and maintenance men without entering the house. Since the householder may have to replace fuses or adjust circuit breakers at night or in bad weather, it is also desirable that the switchboard be accessible from inside, under cover. A porch or carport provides a suitable location. A domestic switchboard will fit into a cabinet about 900 mm × 900 mm × 150 mm deep (3 ft × 3 ft × 6 in). This is quite large enough to be visible even on a small-scale elevation.

In major buildings, the main switchboard is a much larger affair, but since it is usually put in the plant room it need not be considered further here. Most such buildings also have emergency generators, also in the plant room, to maintain essential services if the power supply fails. Exit signs and emergency lights are supplied by batteries. Electrical distribution in multi-storey buildings requires a shallow, fully accessible vertical duct housing the main ‘busbars’ (large-diameter conductors) and distribution switchboards, of about domestic size or a little larger, in accessible positions on each floor, near to or combined with the riser duct. Horizontal distribution is by ‘cable trays’ in the false ceilings.

Information services

Information services in buildings are of four types. There are those that bring information into the building from outside: telephones,
television and satellite broadcasts for example. There are internal communications, such as connections between computers. There are services that assist users to find their way about the building or to operate it properly. Finally, there are the systems that monitor and control the workings of the building itself. These last systems are increasingly ‘intelligent’ (that is, automated and integrated), but they still have to report faults that require maintenance to a supervisor.

**Distribution**

All of these information services require cabling of various kinds which must be distributed vertically in ducts and horizontally through false ceilings in such a way that the different services are clearly identifiable and accessible in the event of a failure.

**Aerials and antennae**

The external appearance of large buildings, and even of some houses, may be affected by the demand for antennae and aerials of various kinds to receive external information. Architects now treat these technical features as part of the overall design rather than unfortunate blemishes. As in all cases in which technical constraints are strong, the forms of such accessories cannot simply be treated as abstract sculpture. The technical constraints must be understood and exploited.

**Displays**

User advisory displays may be external or internal. External displays include the building name, company symbols and advertising, usually illuminated and sometimes moving. External displays are often aesthetically important features of urban settings, such as the Ginza in Tokyo, Times Square in New York and of course Las Vegas. Despite many efforts, however, architects have had difficulty in coming to terms with them and they are often disregarded or viewed with alarm.

Internal displays include all the innumerable pieces of explanatory and way-finding signage. Most are fixed signs. Some, such as exit signs, may be required to be illuminated. Building directories now often take the form of interactive computer displays. In public buildings, such
information displays are among the most visually important features of
lobbies and corridors, and therefore need to be given proportionate
attention even in the preliminary design of interiors.

Building control systems in large buildings also have displays, which
are usually concentrated in a building control centre. This is yet
another function that is often included in the plant room space.
An exception is the display of the fire detector system (3.4.27), which
must be near an entrance so that fire-fighters can reach it and use it to
locate a fire.

Waste services

Waste services include systems for the disposal of solid wastes, and
sewerage and drainage services. Wastes of both kinds are a major and
continuing source of environmental pollution. In addition, water-borne
waste disposal wastes a great deal of water, which is an increasingly
scarce resource. Because the cost of solid waste disposal to local
governments is high, the problem is being addressed internationally.
Water-borne waste disposal is a much greater problem because of its
direct public health implications, and it seems that traditional systems,
perhaps with improved processing at sewerage farms, will be with us for
some time.

Solid-waste disposal

Recycling appears to be the method of choice for improving solid-waste
disposal and this has implications for the design of buildings. Efficient
and economic recycling requires the separation of waste into types at
the source, with from three to five basic types. Instead of one or at the
most two traditional waste bins, a home may have to have space for up
to five. For convenience, such bins should be stored outdoors and under
cover, with easy access to the street boundary.

The implications for major buildings are even greater. In the future, a
waste storage room, with its row of recycling bins, may be required on
every floor, with easy access to a goods lift. This will be yet another
element to be crammed into the service core (3.4.46–49). Similarly,
instead of one waste skip located near a loading dock with street access, there will have to be several.

**Liquid waste**

The consideration of liquid-waste disposal is inseparable from the location and arrangement of the fittings that form the use points of the system: sinks, showers, baths, water closets and urinals. These fittings form part of the system in a much more intimate and inflexible way than the outlets of most other services. In single-storey buildings, the associated problems are much simpler than in multi-storey buildings. Single-storey buildings will thus be discussed first.

**Plumbing and drainage in single-storey buildings**

A typical domestic drainage system consists of a drainage line, about 100 mm (4 in) in diameter, buried in the ground and connected at the site boundary to a branch of the main sewer, which usually runs under the street. At the far end of the line from the street connection there is a vent, extending above the roof line. This prevents gases building up in the line and, even more importantly, stops suction being created at the fittings if the line is running full.

From this main drainage line, branches extend to individual fittings or groups of fittings. The fittings are separated from these branches by a water seal, a crude but effective device that consists of a U-shaped bend in the connecting pipe. This bend is filled with water, which prevents odours from the line from entering the building. The reason for avoiding suction in the line is that these seals must be maintained.

For economy, the drainage line should be as short and straight as possible. This implies that all the plumbing fittings should be grouped and aligned along one outer wall of the building. This is particularly desirable in the case of buildings of slab-on-ground construction. A blockage in a drain buried under a concrete floor inside a building can be a disaster. This special case aside, the economies of limiting drainage runs are not very large, and other planning values often override them.
Plumbing and sewerage in multi-storey buildings

As previously noted, liquid wastes in buildings of more than one storey are carried from the upper floors to the ground in vertical pipes or stacks. These stacks can be regarded as extensions of the drains laid in the ground, and like them they are vented to the open air at the top of the building. A stack is thus a vertical drain extending from above the roof to the ground. It cannot be interrupted and regulations usually prevent it from being diverted very much from the vertical.

Further, regulations often require that any fitting that has to be connected to a stack be no more than a certain maximum distance away from it, usually about 2 m (6 ft 8 in). For this reason, and to avoid the nuisance and expense of additional stacks and the ducts to contain them, plumbing fittings in multi-storey buildings are usually grouped together in plan and placed above each other in section as far as possible.

Toilets in public buildings

Toilets are the subject of strong taboos, and values vary considerably between cultural groups with respect to such matters as segregation of the sexes, privacy and even orientation. However, under the influence of international airports and hotel chains, practice is becoming increasingly standardised. What follows is a rough guide to this international practice.

You should consult your local building regulations. Handbooks are available that give more detailed dimensions than is possible here. It is a good idea to form a collection of manufacturers’ pamphlets which give exact sizes of fittings and installation details. It is also worthwhile to spend some time working out a variety of possible toilet layouts, which you can quickly adapt to individual projects.

Dimensions and numbers

An individual WC compartment can be taken to be about 1500 mm (5 ft) front to back by 900 mm (3 ft) wide, from centre to centre of partitions. Toilets for wheelchair users are larger, about 1900 mm (6 ft
3 in) wide and 2600 mm (8 ft 6 in) deep. They are preferably entered from the side. At least one should be provided in each group of toilets. The total number of WC compartments per floor can be estimated on the basis of one for each twenty men and one for each fifteen women. In addition, urinals should be provided for men on the basis of one for every twenty-five men. Allow approximately 700 mm (2 ft 4 in) of wall space for each urinal.

In order to minimise the number of stacks, WC compartments are usually grouped in rows backing onto a continuous duct about 600 mm (2 ft) wide internally. In this wide, vertically continuous space, it is possible to make steeply sloping connections and thus increase the minimum distance of the furthest fitting from the stack previously specified. In order to conserve stacks and duct space, the men’s and women’s toilets are often arranged so that their respective WC compartments are either back to back or in a row.

**Handbasins in toilets**

Handbasins should be provided in toilets on the basis of one for every thirty people. The most common arrangement is to line them up on the wall opposite to the compartments. Sometimes, however, the toilet space is divided into two and the basins are placed in the outer lobby section. Allow about 450 mm (1 ft 6 in) for basins alone or 600 mm (2 ft) if they are to be set in a benchtop. Clearance between basins and the wall or WC compartment opposite should be 1200 mm (4 ft) minimum.

**Coordination of services**

In multi-storey serviced space buildings such as office buildings, and still more in highly serviced buildings such as hospitals and laboratories, the coordination of services is a critical issue that cannot be ignored in the initial design. Coordination of services is polite jargon for the process of making sure that it does not become necessary to run a sewer pipe through the middle of an air-conditioning duct, and that ceilings are not deformed by unsightly bumps and bulges because it is otherwise impossible to cram the required services into them. Coordination of
services affects the size of false ceiling spaces, and thus the height of the building. It also affects the size and the arrangement of service cores and the size and position of plant rooms.

**False ceilings and floors**
False ceilings in serviced space buildings are essentially large horizontal ducts, faced with a thin layer of acoustically absorbent material which is supported by a grid of metal sections hung from the concrete slab above. The grid is usually about 600 mm × 600 mm (2 ft × 2 ft) or 1200 mm × 600 mm (4 ft × 2 ft) and the acoustic panels or ‘tiles’ are removable for access to the services. Lights replace some tiles or rows of tiles, and air-conditioning outlets or ‘diffusers’ are also fitted into the grid. Fire sprinkler heads and smoke detectors may be mounted on the surface of the tiles.

For both aesthetic and technical reasons, the grid of ceiling tiles is usually related to the structural grid, the subdivisions of the windows, and the partitioning grid. Coordinating all these elements is a complex technical task and it is not usually undertaken in studio projects. Here it is the function of the false ceiling space as a duct which is of interest.

False or raised floors are becoming more common in some kinds of serviced space buildings, particularly office buildings. The main reason for this is that it is easier to connect computer cabling down to the floor rather than up to the ceiling. Where false floors are used for cabling alone, they can be relatively small. About 300 mm (1 ft) from slab to floor surface is a minimum and 450 mm (1 ft 6 in) is generous. If other services are to be installed in the underfloor space, the problems of coordination discussed in the next subsection apply.

**Coordination of services in false ceilings**
Problems arise in the coordination of services in false ceilings because the various services have to cross over each other. Where a large air-conditioning duct, sprinkler pipes, a couple of cable trays and the reflector of a recessed light fitting all have to pass through the same
vertical space, things can get crowded. In principle, this could be overcome by making the space large and zoning the services strictly. In practice, ceiling spaces are kept as small as possible: an extra 300 mm (1 ft) a floor over twenty storeys amounts to two floors of building, in terms of volume. Where regulations impose height limits, such height increases can also result in the loss of usable floor space.

Therefore, a generous floor-to-ceiling space is 1200 mm (4 ft) and buildings designed with strict economy may have floor-to-ceiling spaces of 900 mm (3 ft) or even less. These dimensions, of course, include the floor slab and the false ceiling itself. The restrictions on floor-to-ceiling space make it likely that at some points the relationship of services will be critical. The greatest difficulties are likely to occur at the junction of the ceiling with the service core, where the air-conditioning ducts are largest. Thus, the coordination of services in false ceilings depends to some considerable extent on service core planning.

**Principles of service core planning**

A typical service core for a medium-rise multi-storey serviced space building will contain a lift lobby, lifts, two toilets, two fire stairs and a number of ducts. Buildings over thirty storeys usually have more than one lift lobby. Methods of estimating the size of these elements have already been given. The best way to get a feeling for the arrangement of service core elements is to review as many examples as you can. However, some discussion of principles may make the reasons for the arrangements you observe somewhat clearer.

**Lift lobbies**

The largest and the most symbolically important element of a service core is the lift lobby and its associated lifts. It is also usually a main structural element. Therefore, it should be considered first. If the core is central, the lobby is usually arranged so as to run through the core, opening onto corridors on each side. This cuts down walking distances to the lifts. If the core is at one side, the lobby usually abuts one side wall and opens at the other end on a central corridor.
If there are four or fewer lifts, they may be arranged in a single run. Larger numbers are usually arranged in two facing rows. It is undesirable to have more than six lifts in a row, as the time taken for people to notice the lift indicator and get to the lift can be too long. This is one reason why very tall buildings, which may require dozens of lifts, have multiple lift lobbies, with different lobbies servicing different zones of the building. If lifts are arranged in a convex curve, people may have to pace up and down to keep an eye on all the indicators, a very irritating arrangement.

A lift lobby may be from 1800 mm (6 ft) wide for a small lobby with two or three lifts to 3000 mm (10 ft) wide for a lobby with six or more lifts. It does not pay to make lobbies too wide, as this increases the distance that an intending passenger may have to travel to reach a lift.

**Lift cars and shafts**

The calculation of the number of lifts required depends on the number of people who can be expected to travel during the peak five minutes, which in turn depends on the use or uses of the building. The number of lifts also depends on the waiting time, which should not exceed thirty seconds. There is a trade-off between the number of lifts and the size of the cars and shafts. The calculation is thus a fairly complex one, usually done by a computer program. If such a program is available to you, you should of course use it. If not, a rough approximation of the number of lifts can be got by dividing the total floor area of the floors served in square metres by 2800, or the floor area in square feet by 28,000. Flats or apartments and hotels can make do with fewer lifts, since the up and down peaks are not so marked. For the clear internal dimensions of lift shafts, allow 2500 mm (8 ft 4 in) depth and 2800 mm (9 ft 4 in) width for each lift.

**Locating the other elements**

Once the size and arrangement of the lifts and the lift lobby have been roughly settled, the other elements of the service core can be arranged according to the following principles:
The fire stairs should be located as far apart as possible.

The men’s and women’s toilets should be next to one another, but their entrances should be separated. They are often placed back to back, facing corridors on opposite sides of the core, or side by side, facing a secondary corridor that runs through the core.

The main supply air duct should be on the outside of the core, as near to the centre of the building as possible.

A shallow duct space, 600 mm (2 ft) deep and approximately 3 m (10 ft) wide, should be provided on a corridor wall on the outside of the core, as far from the main supply air duct as possible. This duct can be subdivided to contain electrical, fire and information services.

The return air duct should be located on a corridor wall. Its location is not usually critical.

Besides these elements, cores may include cleaners’ rooms and kitchenettes. Cleaners’ rooms will need space for the storage of waste and of cleaning equipment, and a sink. A minimum size for a cleaners’ room is about 1200 mm (4 ft) × 1800 mm (6 ft), though more room may be needed if recycling bins are to be provided. Kitchenettes can be about 1 m (3 ft 4 in) × 2 m (6 ft 8 in) and must have a sink, a boiling water unit, and possibly a refrigerator. Both cleaners’ rooms and kitchenettes, if provided, are best located next to the toilets because of the waste connections.

Finally, an objective in planning a core is to keep it a compact, usually rectangular, shape, without odd projections that will disrupt the flow of traffic in the corridors around it.

**Lift machine rooms**

Plant rooms can be divided into lift machine rooms and general plant rooms. Lift machine rooms include the lift overrun, an extension of the lift shafts to about two storeys above the ceiling of the topmost floor served by the lifts, and the surrounding space for machinery and maintenance, usually including the whole of the area occupied on lower
floors by the lift lobbies plus approximately 2100 mm (7 ft) on either side at the back of the shafts.

In buildings of more than thirty storeys, the lifts are usually divided into two zones, one of which goes only halfway up the building. A lift machine room is then required at the top of this zone. Usually it will be combined with an intermediate-level general plant room.

It is important to note that lift shafts also go down two or even three storeys below the lowest floor served. This can be a considerable obstruction to basements, particularly basement car parks.

For buildings of lesser height (up to about twenty-three storeys), with the emergence of the machine roomless lift system a separate machine room is not required.

**General plant rooms**

In buildings that are not air-conditioned, plant rooms are often located in a basement. Air-conditioning plant is usually placed as high up as possible in the building so that the intake air is cleaner and the discharged air causes as little nuisance as possible. Therefore, if there is just one plant room it will usually be on the roof. Since many parts of the plant room must connect to riser ducts, the plant room usually surrounds the service core. This has the advantage of concealing, or largely concealing, the lift overruns and the lift machinery room, which otherwise project from the roof and, with their cantilevered ‘ears’, tend to attract much more visual attention than their symbolic status deserves.

In buildings of over thirty storeys, two plant rooms, one on the roof and one about halfway up, are often provided in order to reduce duct sizes. As previously noted, in such cases the lower plant room will also surround the lower lift machine room and overrun.

**Size of general plant rooms**

Besides enclosing the lift machine room, the service core and perhaps the central control room for the building, the plant room of a large
building has to house the air-conditioning plant and much other equipment, some of which has already been mentioned. As with any other collection of equipment, there has to be space for maintenance and access for replacement when necessary. Plant does not last as long as the building structure and will have to be replaced two or three times during the building’s life.

For high-rise office buildings, the plant room space will vary between 6% and 10% of the total floor area, depending on the quality of the installation. It is usual for plant rooms to occupy at least one full floor of the building, and they are often taller than normal floors: about 1.5 times the regular floor-to-floor height. ‘High tech’ buildings such as hospitals, laboratories or computer centres may have plant room spaces up to 15% of the total floor area. Despite this, being inside such a room is often rather like being inside the engine space in a compact car. They give the impression of being crammed full of ducts, motors, pipes and cable trays.

Engineers would always like to have larger plant rooms, but since plant room space costs money and produces no direct return, convenience of maintenance is usually sacrificed.

**The nature of materials**

**Introduction**

This section has two main parts. The first part outlines some of the ways in which the properties of materials, their appearance, fabrication, transport, erection, fixing and finishing can affect the approach to the initial stages of design. The second part deals with the weatherproofing of roofs, walls, doors and windows. The two parts are connected by a single technical problem, the problem of jointing. Taken together, they deal with the connection between the studio and what is usually taught as building construction.

Once again the reader is reminded that this is not a book on technology. The concern here is the connection between technical knowledge and patterns of decision making in preliminary design. This section cannot
take the place of a text such as Cowan and Smith’s (1988) admirable The Science and Technology of Building Materials or whatever similar text your course suggests.

**Do materials matter?**

It is certainly possible to work out a preliminary design for a building without fixing on the specific materials to be used. The practice, common in many studios, of presenting designs in the form of models of cardboard or wood, with no differentiation of colour or texture, encourages what may be called an immaterial view of architecture. In favour of this, it may be argued that students have enough to do in arriving at a workable plan and structure that also meet the aesthetic goals of design, without worrying about the choice of materials.

Against this, it can be said that architects have often found an important part of their inspiration in this aspect of technology. This is obviously true of the architects directly influenced by nineteenth-century Arts and Crafts theory, such as Frank Lloyd Wright and many architects of the Scandinavian countries. It is also true, however, of Mies van der Rohe, Louis Kahn and others who cannot be assigned to that tradition at all. So there can be positive advantages in thinking of buildings from the start as material objects, made in particular ways that give them various characteristics, visual, tactile and so on. Some of the disadvantages of neglecting to look at things in this way have been suggested previously (3.1.17), and other peculiarly aesthetic disadvantages will be discussed in Chapter 4.

**General properties of materials**

If there were a perfect building material, the problems of technology would disappear. Unfortunately, the demands made on building materials, like many of the demands made on buildings, are contradictory. As a result, building construction usually employs combinations of materials to achieve an overall performance that is acceptable. However, the need to combine materials and get them to work together creates further difficulties.
Significant properties of materials for the present purpose include appearance, density, strength, dimensional stability, and durability. Thermal conductivity and inertia were discussed in 3.3.8. Economy is not strictly a property of the material itself but has to be considered in the choice of material.

**Is concrete the perfect material?**

It was suggested above that there is no perfect building material. From time to time during the twentieth century reinforced concrete was put forward for this position, or treated as if it had already achieved it. Suitably reinforced concrete does have many desirable properties. Its structural performance is good and it is fire resistant. It is massive enough to give good acoustic protection and thermal inertia. Finally, the ingredients are fairly cheap. However, it also has important failings. Concrete is far too good a thermal conductor, so walls and roofs of concrete need insulation and/or shading. It can be made waterproof, but only with first-class control of materials and placing and very careful attention to pouring and movement joints. The making of cement consumes an immense amount of energy. Finally, its natural appearance is unacceptable to many people. The problems of giving concrete an acceptable appearance form a useful introduction to the general issue of the appearance of materials, and also illustrates why it is that materials are used in combination.

**The appearance of concrete: formwork**

Concrete is cast into moulds or forms. Since it is a plastic material, it reproduces the surface detail of the formwork, including joints between sections, dents, bulges and bumps, the ties used to hold vertical surfaces of the formwork together and so on. The cost of the concrete depends largely on the cost of building the formwork; formwork that is put together quickly and carelessly and reused often is the cheapest. Such formwork will produce concrete with all kinds of small projections and dents. For comparison, the basic formwork for the visible internal concrete work in the Sydney Opera House was lined with a second set of formwork made to joinery standards.
3.5.6

**The appearance of concrete: placing**

Even if the formwork is of the best quality, good concrete when it is poured is only just liquid, and as a result it is difficult to avoid bubbles of air being trapped between it and the forms. This is particularly likely to happen in relatively thin vertical elements such as walls. Partly to prevent this, the concrete is vibrated as it is placed. However, even with good and careful workmanship, the bubbles often remain and appear as little pockmarks on the surface. To get around this, and also to conceal other defects, forms have been lined with strongly textured material such as sand-blasted pine, or made with projecting and recessed boards. These ‘solutions’ cost money and attract dirt, so that in city settings they quickly become shabby.

3.5.7

**The appearance of concrete: colour**

Standard concrete is a cold, pale grey colour which many people find unattractive, and it is often disfigured by darker blotches. The colour can be changed by using coloured cement and selected coloured sand.

3.5.8

**The appearance of concrete: exposing the aggregate**

One technique for overcoming the problems of both texture and colour is to remove the surface of the concrete as cast to expose the stone aggregate that is the third main ingredient of concrete. This has to be done mechanically, with pneumatic tools. It is a great deal of work; and the work has to be done carefully or the texture will be uneven. The effect obtained depends on the colour and size of the aggregate, which has to be carefully selected, and the colour of the matrix (that is, the sand and cement), as discussed above. Because concrete is cut away, extra concrete has to be cast in the first place. All in all, it is a laborious and expensive technique, and it is still highly risky.

At this point the astute reader will be asking why, if producing an acceptable concrete surface is so difficult and expensive, anyone bothers. Why not cover it with some other, more suitable material? This brings us back to the properties of materials in general, starting with appearance and durability, properties that have a major influence on the selection of materials.
The appearance of materials: decorative materials

Richly coloured and inherently patterned building materials have been valued by almost every culture. Marbles imported from Egypt and Tunisia are found in Hadrian’s Villa at Tivoli. Today, marble from Italy is imported to Australia. Serious flaws may be tolerated in a beautiful material; some heavily veined marbles are very fragile because the veins are intrusions of another, weaker material, but they are still used. Similarly, woods with rich colours and growth patterns are sought after for decoration.

Decorative materials are usually expensive. They are in demand, and they often have to be transported for long distances. Therefore, they are usually used as thin facings in the case of stones or as veneers in the case of decorative woods. Gold is used in the form of ‘gold leaf’ – a very thin veneer indeed. For the same reason, the materials are often imitated, either in ‘faux’ finish applied coatings or by other materials; for example, many plastic veneers are given a wood-grain finish.

Decorative materials that are used as applied finishes must be applied to something: an underlying structure that supports them and performs the other functions of the building element concerned. The facing material adds to the thickness of the element. The jointing and fixing of the material are also a part of the overall visible effect.

Durability

The appearance of materials in use is affected by their durability. Deterioration or decay of materials can also affect the local and overall structural safety of the building and its waterproofness. Materials can be roughly divided into ceramics, metals and organic materials, natural and synthetic. The durability of materials depends on their resistance to various kinds of physical and chemical attack. Each group of materials has its own characteristic strengths and weaknesses. These qualities of materials constrain their use in building.

Durability of ceramics

Ceramics include natural stones, brick, concrete, and for the present
purpose glass, since the igneous rocks like granite and ‘fully vitrified’ clay tiles are, in effect, glasses. All these materials are hard and brittle. In thin sheets they are vulnerable to mechanical damage. Their hardness makes them resistant to abrasion; generally the glassier the material, the harder it is. Most of the ceramics are resistant to chemical attack. Limestone and marble, however, are easily attacked by acids; the acidity of modern city air is such that marbles can no longer be used as external finishing materials. The softer ceramics, such as sandstone and terracotta, are porous and liable to be damaged by frost and disfigured by mosses and lichens. Frost damage occurs because water enters the pores of the material, freezes and expands.

3.5.12 Durability of metals

The main metals used in building today are steel, aluminium and copper. Lead is no longer used because it is poisonous and pollutes the surroundings. Bronze (an alloy of copper and tin) and even gold and silver are still sometimes used but in very small quantities because of their cost. All the main metals used in building are alloyed to give them properties that the pure metal does not possess. They are all fairly hard, though not as hard as ceramics, and elastic (springy, not stretchy). The main problem with building metals is resistance to chemical attack.

3.5.13 Acids and electrolytic corrosion

All the main building metals are liable to be damaged by acids in urban rainwater, especially if the water lies on the metal and evaporates (see 3.5.22). Combinations of metals can produce ‘electric batteries’ that very quickly corrode the ‘baser’ metal. The further apart in the electrolytic table the metals are, the worse the effect, but, in general, combinations of metals are to be avoided.

3.5.14 Copper and aluminium

Copper and aluminium form natural oxide coatings that stick to the base metal and resist further corrosion. In the case of copper, the resulting colouring is attractive, but natural aluminium oxide is an ugly blotchy grey, so that aluminium used for building facings is usually
anodised, that is, given an artificial oxide coating in one of a fairly limited range of colours. Anodic coatings are hard but thin and liable to damage in transport and handling. For this reason, powdered coats of fluorocarbon materials are now often used; again the range of colours is somewhat limited.

**Steel**

Steel is, of course, an alloy of iron. Unfortunately, it is much more easily attacked by rust than iron itself. Because the oxide has a much larger volume than the original steel, it flakes off, leaving the underlying surface exposed to further oxidation. There are three main methods of protecting steel from corrosion: alloying, plating and painting.

Alloying produces stainless steel which does not rust and steels in which the rust layer does not flake off but adheres. These materials are durable but expensive.

Plating consists of the electrolytic deposition of other, corrosion-resistant metals onto the steel. Chromium plating is used for plumbing fittings and some decorative metalwork. Galvanising, which involves depositing a layer of zinc or a compound of zinc and aluminium on the steel, is used for general waterproofing, for example utilitarian railings and ‘corrugated iron’ roof sheeting. Since the pieces have to be got into and out of the plating bath, true plating is generally used only for small elements. Most galvanising is now ‘cold’ galvanising, which consists of the spray application of zinc or a zinc–aluminium compound in a bonding agent: a highly superior paint.

Painting can be used as a decorative finish over galvanising or as a protective and finishing system. If paint is to be an effective protective system by itself, particularly in corrosive atmospheres such as sea air or air polluted by industry, a large number of coats and constant repainting are required. No paint coat is ever perfectly free from flaws at which rust can begin. On the whole, it is wise to avoid as far as possible the use of externally exposed steelwork in corrosive atmospheres. Problems of maintenance, as well as initial cost, explain the general use of reinforced concrete rather than steel for structural framing.
Organic materials

Wood is the organic material most commonly used in building; the synthetic organic materials are usually known as plastics. The distinction is no longer hard and fast, since wood is now largely used as plywood, chipboard, and other combinations of natural and synthetic materials.

Organic materials vary greatly in their properties. They are generally softer and more easily abraded than ceramics or metals. Most of them are flammable, some dangerously so. Most are also liable to photochemical degradation when exposed to the sun. This is the process that turns unpainted wood grey; since it is a photochemical process, no transparent finish will prevent it; it is useless to use decorative woods externally. Wood and many plastics are attacked by termites. Untreated wood is also attacked by a variety of other forms of insect and plant life. Wood is both eroded by water and liable to rot if it is constantly wet. Most of the plastics used in building are resistant to water and common chemicals, though ‘foamed’ plastics are an exception.

Weathering

Weathering is the action of external forces – sun, wind and water – on the materials that make up the surface of a building. Traditional building construction often aimed both to limit the bad effects of weathering and to exploit its harmless effects. Modern construction either ignores weathering, with predictably bad effects, or attempts to prevent it altogether, with limited success. The main effects of weathering are erosion or decay of materials, and discolouration or staining.

The sun

Sunshine also destroys materials and, as discussed in 3.5.16, particularly organic materials, by breaking up the chemical bonds between their constituent elements. Sunshine contributes largely to the destructive effects of thermal movement. A particularly annoying aspect of the sun’s chemical action is its tendency to fade coloured materials, including paints. Fading is in its nature uneven; shaded parts fade less than exposed parts. Most of the enormous range of colours in use today are organic materials, and they all fade badly; the darker the colour, the
more it fades. Durable colours are mostly produced by metallic oxides and the range is quite limited. Therefore, a building that relies on strong, bright colours for its effect will have to be constantly refinished. At such times, the original colour scheme is very likely to be changed, to reduce the maintenance costs.

The wind

Wind contributes to water penetration (see 3.5.68). Wind-borne sand can produce serious erosion of soft materials and even, in time, of hard stones. This is particularly apparent in desert areas. Corners and fine detail tend to be eroded first. Often the response is to use easily renewed facing materials rather than try to resist the erosion with more expensive material.

The wind also stirs up dust and deposits it on building surfaces. This in itself can discolour rough surfaces, to which the dust can stick, and horizontal or sloping surfaces that are not rough. Deposits of wind-blown material may contain aggressive chemicals and can also provide a foothold for plants and moulds which then attack the fabric.

Water and weathering

Rainwater flows over the external surfaces of buildings under the influence of gravity, wind and its own capacity for ‘wetting’ – its surface tension. Since building surfaces are not perfectly smooth, the flow is never perfectly even. Vertical projections and recesses collect and channel flows downwards. Horizontal or sloping projections interrupt the flow and may throw it clear of the building (Fig. 3.15). They also collect more water than vertical surfaces under most wind conditions. Horizontal projections can also be designed as gutters, to collect and concentrate the flow and discharge it in a controlled way (Fig. 3.16).

The flow of water attacks the building both mechanically and chemically. It also washes and wets the surface. All of these actions affect the appearance of the building. Controlling and directing the flow of water is therefore a significant, though often neglected, part of façade design. Here only the large-scale effects will be considered. Detail design is beyond the scope of this book.
3.5.21

Physical action of water

Water erodes surfaces over which it flows or onto which it drips. The dripping of water wears away the stone. How quickly it does so depends on the material and the rate of flow. Smooth, hard, impervious materials produce higher flow rates but are more resistant to erosion. Rough, porous surfaces, such as that of a brick wall, may absorb and break up the flow so that it does little damage. Observation and experience are the best guides to the behaviour of different materials.

In areas subject to freezing, water may penetrate porous materials and then freeze. If this happens, the expansion of the water as it undergoes the phase change into ice may crack the material. The crack then allows more water to penetrate next time and eventually some kind of failure will occur.

3.5.22

Chemical action of water

Pure water is a powerful solvent in its own right. That is why we use it for washing. Its solvent action increases its tendency to erode materials with which it comes in contact. Also, as is now well known, industrial gases released into the atmosphere can be dissolved in rainwater to produce weak acids that will particularly attack metals and limestone or marbles, and other materials more or less. Water that is allowed to lie in puddles on building surfaces will gradually evaporate and if it is acid the acid will become more concentrated; this is a particular danger to sheet metal roofs.

3.5.23

Washing and staining

As water flows over the building surface, it picks up dirt. Water that penetrates porous materials and flows through them may also take up soluble salts. If all this happened perfectly evenly, it would not matter much. However, the effects tend to be very uneven. More dirt accumulates on horizontal or sloping surfaces. Water flows vary. Thus, washing is uneven and some flows of water pick up more dirt than others. If the flow stops before the façade is completely clean, for example after a light shower following a dry spell, the drying water will deposit ‘curtains’ of dirt like a river depositing silt.
The modern response to this is to try to make buildings perfectly smooth and impervious, for example by sheeting them with glass. This does make them easier to clean, but it does not stop them from getting dirty and unevenly dirty. Such buildings require constant cleaning and maintenance. The traditional approach was to throw water clear of the building before it had the opportunity to do much harm. This is one function of ‘string courses’ or horizontal mouldings at each floor level or more frequently, and of strongly projecting window sills. To do their work, such projections must extend at least 75 mm (3 in) beyond the wall face and have a recess at least 25 mm (1 in) wide and 13 mm deep as near the front edge as the material will allow; if the shape is smooth or the underside flat, water will simply flow around the projection (Fig. 3.17).

**Wetting**

Porous materials absorb water and the wet material usually looks different from the dry. As with washing, wetting occurs unevenly because of variations in the material itself and in the amount of water flowing over it. Thus, such materials can appear blotchy, particularly while drying out, which may take some time. The larger the unsubdivided area of material, the more obvious the effect. It is particularly noticeable on large panels of precast concrete. Wetting can be reduced by applying sealants or paints, but they do not last forever.

Wetting and drying can also carry soluble salts to the surface, where they appear as staining or ‘bloom’. Nothing can be done about this except to try and avoid using materials that contain soluble salts in the first place.

**Fabrication**

The fabrication of materials is a huge subject. However, the direct constraints on preliminary design imposed by methods of production can be treated quite simply. They can be considered under two main headings: forming and assembly. In each, the long-term trend has been towards the reduction of skilled labour and an increase in the amount of work done away from the building site.
Until the nineteenth century the visual effect of buildings depended largely on the use of carving. Carving is skilled and labour-intensive, and it has therefore virtually disappeared. This is a loss, because carving is the only process that can produce **undercutting**, by which parts of the surface are made to appear to stand free of the rest, as, for example, in the leaves of Corinthian capitals (Fig. 3.18). Undercutting produces dark, rich shadows, visible at a great distance.

**Forming: moulding, casting and extrusion**

All of these processes depend on shaping a more or less plastic material, such as clay, wet concrete or liquid metal or glass, by means of a mould of some kind. In the case of extrusion, the mould is a nozzle and the material is forced through it like toothpaste from a tube.

The shapes that can be obtained by moulding are limited by the need to get the finished article out of the mould. Moulding can be used to produce complex three-dimensional decorative shapes such as the cast-iron decorations of Guimard’s Metropolitan Stations (Fig. 3.19) or Sullivan’s Carson Pirie Scott store, but it cannot produce undercut shapes because such shapes cannot be removed from the mould. Casting a three-dimensional object, like a bronze statue, is much more difficult than casting a panel that is decorated in relief, such as the cast-iron balcony railings widely used in Australia and parts of America (Fig. 3.20). The simpler the mould and the more often it can be reused, the cheaper the process. Coarse material, such as normal concrete, cannot be moulded into finely detailed shapes. Casting is used in the production of many cheap or bulk materials, such as concrete block, plasterboard and ‘precast’ concrete floor and wall elements.

**Forming: extrusion**

Like moulding and casting, extrusion can produce complex shapes, but they can vary only in cross-section. It is the nature of extrusion to produce long, straight pieces such as aluminium window frames (Fig. 3.21). The design of nozzles for extrusion is more complex than the...
design of moulds for casting, and the designer’s control over such forms is therefore limited: it is a matter of selecting from catalogues. Bricks, terracotta blocks and plaster mouldings are among the materials sometimes formed by extrusion. Structural steel members are also produced by a sort of extrusion through rollers, which is even less adaptable to the designer’s wishes.

**Forming: pressing and spinning**

Thin sheets of metal and plastic can be formed and shaped by a variety of processes involving pressure: pressing in an hydraulic press, spinning, rolling and vacuum moulding. Spinning is used mainly to shape aluminium and vacuum moulding only for plastics. All of these processes have precise technical limitations. For example, the thicker and stiffer the sheet, the less complex the forms that can be produced.

**Forming: cutting and drilling**

By far the most common method of shaping materials is cutting them, using a variety of tools including saws, lathes, routers, drills and lasers. All kinds of material – ceramic, metallic and organic – can be worked by cutting. The harder the material, the slower and more expensive it is to cut: some ceramics, for example, can only be cut with diamond saws or lasers. Drilling, with either solid drills or lasers and routers, can produce recessed or openwork patterns in sheet materials; computer control has made this more economical. The other methods of cutting produce either long, straight pieces of uniform cross-section or, in the case of lathes, round pieces of uniform profile. Whatever the form of cutting, the more complex the profile or pattern the more it will cost.

**Factory production of building elements**

The tendency in modern building has been to transfer more and more work to the factory, where conditions are cleaner and safer, more control is possible and there is a better chance of providing a continuous flow of work for highly skilled labour. Doors and door frames, windows, cupboards and fittings, and many kinds of decorative elements are delivered to the site finished and ready to install. Other elements, such as partitions, false ceilings and ‘curtain walls’, are supplied in kit form,
ready to erect with reduced on-site labour. Large structural and cladding elements of precast concrete are also commonly made in the factory and delivered ready to erect. This process has not, however, been carried to the point at which all elements are factory produced, or ‘industrialised’. Some reasons for this are given in 3.1.12–14. Here, some of the technical reasons are outlined in more detail.

**Kits of parts**

The ‘kit of parts’ approach has often been applied to whole buildings. Although the Crystal Palace remains the paradigmatic example, the commonest type of kit building is the timber house. Kit houses of timber were being shipped all over Queensland in the early years of the twentieth century, well before the European Modern Movement experiments of the 1920s. The Queensland situation well illustrates the circumstances in which mass-produced kit buildings are likely to be successful. There was a growing demand, widely dispersed geographically; there were local shortages of skilled labour and materials; and there was good transport by sea and rail for at least primary distribution.

However, once kit buildings have to compete with other local forms of production they usually fail. This is partly due to transport costs, partly due to the inflexibility of design, which reduces market acceptance, and partly due to the difficulty of maintaining a large enough market in the face of demographic fluctuations (Russell 1981). The mechanisation of building has indeed taken place but largely by way of the production of components that can be used in many designs (Habraken 1983) and the use of power tools on-site. There are additional technical factors to do with transport and erection that tend to limit the size of factory-produced parts, despite some much-publicised experiments with room- or even apartment-sized elements.

**Transport and erection of large building elements**

There is nothing new about building elements being shaped, finished and even assembled off-site, nor about transporting and erecting large, heavy and fragile elements. Egyptian obelisks were transported to
imperial Rome. Before the nineteenth century, however, such exercises were enormously costly and difficult. Modern machinery has made moving large, heavy objects much cheaper and easier, but it is still expensive and still involves risk.

**Costs in transporting large elements**

It is expensive to transport large objects because shipping costs are based on volume. Over a certain size, special arrangements may have to be made to close streets and control traffic, as is done when whole timber houses are moved. Thus, delivery times may be restricted or delivery delayed. Moving the element through or around the building may be difficult; if, for example, the element has to be hoisted by crane, hoisting times may be restricted by windy weather. Finally, the larger the element, the more precise the tolerances to which it must be built in order to ensure successful installation (see 3.5.37–40).

Large elements also tend to be heavy. Expensive machinery in the form of large and powerful lorries, hoists and cranes may be needed to transport and position such elements. Further, while less on-site labour is needed overall, manoeuvring and locating large elements may require the concerted effort of a considerable number of people. If the machinery and the labour are kept waiting by unpredictable delivery schedules, little money may be saved by factory production of large elements.

**Risks of transporting large elements**

Besides, these processes are not without risks. One of the advantages of factory production of building elements is that finishes can be applied under controlled conditions. However, the advantage is lost if the element is damaged in transit. Because of the difficulty of wrapping large elements effectively, their lack of manoeuvrability and their weight, the risk of damage to them is much greater than the risk to small elements.

There is also an increased risk of injury and even death to workers or bystanders. This is partly once again because large elements are not manoeuvrable but also because the hoisting machinery is working near its limits. Under these conditions, it requires only careless maintenance
of working slings, a crane with an inadequate foundation, or momentary inattention on the part of a crane driver or worker and a disastrous accident will result.

Assembly and fixing on site

Designing for successful assembly and fixing requires an understanding of tolerances: that is, the degree of precision with which different building elements can economically be produced and the amount of control that can be exercised in assembling them. Allowance also has to be made for the movement of the various elements. Consideration of tolerances and movement constrains the choice of element sizes, the design of joints and the type of fixing used.

Tolerances in traditional building

Traditional on-site building methods were not very precise. Walls are built 'out of plumb', not vertical. Rooms and openings are not square; that is, corners that are intended to be right angles are not and surfaces that are supposed to be flat or level billow or slope. Errors of 1 part in 120 are quite common. In traditional buildings this did not matter much. The errors did not affect the stability of the building. Though easily detected by measurement, they were not easily detected by eye. Last, but not least, elements were shaped on-site to fit each other: the individual window, for example, was built to fit the slightly-out-of-square opening.

Tolerances on the modern building site

Thanks to the use of precise surveying methods in setting out, large modern buildings are more accurately built. Standards in houses and smaller buildings have changed less. Precision on-site is expensive: it requires careful setting out, careful supervision and careful workmanship. Therefore, no more precision is aimed at than is actually required. Even with the best site management, some departures from the straight, the flat and the square have to be accepted: the design limits of elastic and creep deflection, for example (see 3.2.60–61).
**Tolerances in the factory**

In factory-made elements, tolerances can be much narrower. Equipment for precise setting out, such as plane tables and jigs, can be kept permanently set up, and precisely controlled tools can be used. This, of course, is part of the argument for transferring more and more of building production to the factory. However, we have seen that there are limits to this. Therefore, a major problem of contemporary building is likely to continue: the placing and fixing of factory-produced elements that are straight, square and precise into a building carcase that is considerably less so. The traditional process of ‘offering up’ or shaping the element to the carcase no longer works because the elements are prefinished and any attempt to alter them is likely to damage them. The problem then becomes one of jointing and fixing.

**Tolerances and size**

The larger the building element, the more precise the tolerances to which it must be made if it is to be fitted successfully into the building fabric. This can be understood by comparing a traditional brick with a large precast concrete panel. Bricks vary in size, but a typical size for the exposed face of a brick is 225 mm (9 in) × 75 mm (3 in). Such bricks are laid with mortar joints about 10 mm (3/8 in) thick. Even with hand-made bricks, which are often very far from being true in any dimension, it is possible to build a wall that appears even in texture without much difficulty.

Now consider a precast concrete wall panel 6 m (20 ft) by 1800 mm (6 ft). The tolerance given by a 10 mm joint for a 225 mm brick is 4%. To have an equivalent tolerance for the 6 m panel, the joint would have to be 240 mm (9.6 in) wide. Since this is not practical, the panel must be made to much tighter tolerances than the brick.

This gives some idea of the scale of the problem but understates its complexity. A large panel such as that described can be distorted in a number of different ways. It may be twisted; sides that are supposed to be parallel may not be. It may be bowed; the sides may be parallel but not straight. The sides may be straight and parallel but the surface may
be concave or convex. When a wall built of such panels is exposed to oblique lighting – particularly sunlight – any such defects will be pitilessly revealed.

**Movement**

All building elements move somewhat. This movement aggravates the problems of tolerance, fixing and jointing. Movement of the structure, and in the form and elastic and creep deflection, has been previously discussed (see 3.2.56–62). Two other important forms of movement are thermal movement and moisture movement. The amount of movement varies with the material and the size of the element.

**Thermal movement: coefficients of expansion**

Almost all materials expand somewhat when heated and contract when cooled. (Materials undergoing phase changes, like water changing into ice, or reversible chemical changes, provide some exceptions.) How much they change per unit of initial length per degree of temperature change is given by the coefficient of thermal expansion. Steel and ceramic materials generally have expansion coefficients in the region of $10^{-5}$ metres per metre per degree centigrade. (This and subsequent figures can be converted to feet per foot per degree Fahrenheit by dividing by 1.8.) Copper and aluminium move more than twice as much. Plastics and, surprisingly, wood across the grain move eight times as much. (Wood moves much less with the grain.) The record for common building materials is held by polyethylene, which can move eighteen times as much as metals or ceramics.

**Thermal movement: How much?**

These figures may not sound very large. However, the actual movement is a function of the temperature range and the maximum dimension of the element. The temperature range to be taken into account is not just the difference between the air temperatures on the hottest day and the coldest night. For external elements the heating effect of the sun must also be taken into account. Elements exposed to the clear night sky may also cool well below the surrounding air temperature. Temperature
ranges of 100°C are thus by no means uncommon. At this rate, a 1 metre (3 ft 4 in) slab of granite can be expected to expand and contract 1 millimetre. However, a 6 metre reinforced concrete panel will move about 6 millimetres (1/4 in) and a 20 metre (100 ft) brick wall will move 30 millimetres (1.2 in).

Thermal movement can cause cracking or damage to fixings if it is restrained or resisted. Sudden thermal movement, or thermal shock, which can occur, for example, when the rays of the rising sun strike a building surface that has been exposed to a clear night sky or freezing conditions or both, can produce damaging stresses within the material itself or on fixings. The effects of thermal movement are compounded by moisture movement.

**Moisture movement**

Moisture movement occurs in wood and some ceramic materials, notably brick and concrete, as they absorb or lose moisture. It does not occur in metals, glasses or plastics. Green wood and fresh concrete start off wet and lose moisture and shrink until their moisture content is more or less in balance with the surrounding atmosphere. Clay bricks start off very dry since they are baked at high temperatures, and they then absorb moisture and grow until they too are in equilibrium with the atmosphere. After the initial decrease or increase in moisture content, these materials expand or contract as the humidity of the atmosphere increases or decreases.

**Moisture movement: How much?**

Wood can shrink as much as 10% of its initial dimension across the grain during its initial drying out. For this reason, wood is usually seasoned or kiln-dried to about the average moisture content of the atmosphere in which it is to be used.

Even after seasoning, the across-grain movements of wood with changes in humidity are quite large and fairly rapid. This presents a special problem in air-conditioned buildings. The air in such buildings is usually below normal atmospheric humidity, so if the air-conditioning
is switched off for any reason, for instance at weekends to economise on power, there will be a dramatic change in humidity and a corresponding growth in wooden elements. This does not matter much in the case of ordinary joinery, but large timber floors can grow enough to tear themselves loose unless special precautions are taken.

Concrete poured on-site also shrinks, though not nearly as much as wood. Shrinkage can be of the order of 1 in 2000, which, as with thermal movements, does not sound much, but in a 60 metre (200 ft) long building it amounts to 30 millimetres (1.2 in).

If clay bricks are used hot from the kiln they can expand quite strongly: as much as 1 in 500. This is obviously bad practice, and the expansion of bricks that have been allowed to humidify in the yard is much less.

All these movements must be considered in conjunction with thermal movement and structural movement. Together they influence the sensible size of external building elements and the size and spacing of joints, and thus the appearance of the building.

**Sensible dimensions**

The ‘sensible’ dimensions of a prefabricated building element are those that produce a satisfactory appearance and performance at a reasonable cost. This depends on the material itself, the method of fabrication, transport and handling, the control of movement, and in the case of external elements, particularly the desired visual scale and texture. A rule of thumb is that anything that cannot be handled by two men or manoeuvred through a standard doorway in a 1.5 metre corridor is too big. For sheet materials, including glass, a dimension of about 2 m × 1.5 m is a ‘sensible’ maximum. Much larger sheets can be used where access is good and the material is relatively light, for example in metal rib roofing.

**Methods of fixing**

The methods used to fix materials have a major influence on the appearance of buildings. Fixing methods can be divided into three types. There are methods that depend mainly on gravity and friction. Second,
there are mechanical fixings, which may be visible or concealed. Third, there are adhesive fixings.

Welding may be regarded as a fourth type of fixing but it will not be discussed here; an understanding of welding is essential in metalwork detailing but not for early design.

**Gravity and friction**

Ancient masonry was and often still is held together by gravity and friction. The individual stones were large and carefully fitted to each other. Even though the fit was not perfect, the resulting joint was much stronger than the then available mortars. The weight of the wall overall and of the individual stones was such that friction between the stones kept them from moving. This continued to be true of much mediaeval masonry: mortar was used but primarily as a lubricant to slide fitted stones into place. The shape, colour and texture of the stones give traditional masonry its character.

By contrast, brickwork has always relied on mortar joints. Until the nineteenth century, bricks were usually not much stronger than the mortar, and most often not very precisely shaped. The mortar, made with lime, produced some adhesion between the bricks but acted mainly to ensure that loads were transmitted to the whole surface of the bricks in each course, since the wet mortar fitted itself to their shapes. This changed with the introduction of cement mortars, which are in many cases stronger than the bricks and adhere strongly to them.

Unlike traditional stonework, the character of brickwork depends on the size, colour and form of the joints almost as much as on the appearance of the bricks themselves. Recessed joints, for example, give a strong contrast of shadow; flush joints emphasise the colour of the mortar.

**Mechanical fixings**

The curtain wall façades of modern buildings rely largely on mechanical fixings. So do the outer walls of buildings of timber- or steel-frame
construction. The basic forms of mechanical fixing are bolts and rivets, screws and nails, cramps and dowels which have themselves to be fixed to the structure in some way, and frames which also have to be fixed to the structure. There are innumerable variants of each form. In initial design it is only the most visible forms of fixing, namely bolts and frames, which need be considered.

**Bolts**

Exposed bolts and related fixings have the great advantage that they are easy to get at if maintenance is needed. Bolts can be used to fix stiff heavy materials, including stone, and also frames containing sheet materials. Bolt heads can be designed as decorative elements and arranged in ornamental patterns, as at Wagner’s famous Church Am Steinhof in Vienna (Fig. 3.22), where the marble facings are bolted on and the bolts have screw-on copper covers. This methodology is now commonly adopted for installation of glass or stone veneer panels.

The disadvantage of such fixings is that great care and precision are required in locating the sockets for the bolts in the structure and the holes for the bolts in the material to be fixed so that they match up. The holes have to be large enough to allow for tolerance and movement, and the bolt heads have to be large enough to cover the holes.

**Frames**

Frames are mainly used to hold glass, clear or coloured, but they can also be used to hold thin panels of other materials, including stone and metal. Timber frames are still widely used in domestic construction, but even there they are being replaced by aluminium. The reintroduction of steel frames in smaller buildings is only a recent phenomenon. In major buildings, aluminium and stainless steel have almost entirely replaced steel and bronze for frames.

It is important to realise that frames are not fine lines on paper but substantial objects, whose dimensions are determined both by the framing function and the need to resist lateral loads and to support the material framed. Bronze and steel are strong, stiff materials and can therefore be used to make delicate-looking frames, as in the beautifully
precise stainless steel curtain wall of Arne Jacobsen’s Town Hall at Rodovre, Denmark. Aluminium is much less stiff and proportionately much bigger cross-sections are needed.

**Sizes of frames: timber**

The minimum width of a timber frame to hold fixed glass or other fixed panels is determined by the depth of the rebates or recesses that hold the panel plus the thickness of the timber that forms the edge of the frame. The minimum rebate is about 12 mm (0.5 in) and a reasonable minimum thickness for the timber is 18 mm (0.75 in), so the overall frame thickness will be about 30 mm (1.25 in). Vertical and horizontal divisions within frames, known as mullions and transoms respectively, must be thicker as they have two rebates; allow 43 mm (1.75 in) overall. The depth of frames front to back should be at least 100 mm or 1/24 of their length, whichever is the greater. Opening sections must have their own frames within the main frame. Such frames will be about 78 mm (2.75 in) wide, all round the opening. Joinery practice differs in different countries, but these are reasonable approximations. Larger sizes can be used for decorative effect.

**Sizes of frames: aluminium**

Aluminium frames vary much more in size than timber frames. Small, cheap windows made for domestic use with opening sections that slide may show a frame no more than 25 mm (1 in) wide. For most commercial and major buildings, a width of 50 mm (2 in) will give a reasonably correct impression. Depths are similar.

**Mortars**

Mortars (mixtures of sand with lime, cement and possibly other materials in various proportions) are used in several different ways. They are used for bedding or levelling of masonry or paving, and backing for wall facings, particularly stone facings that may actually be supported by cramps, a function very similar to bedding. Mortar may also be used simply to fill joints in such facings. Finally, mortar may be used, in effect, as an adhesive to fix thin sheets or tiles.
Mortar as an adhesive

Mortars do not make very good adhesives. Mortars, like concrete, shrink on drying and then move somewhat with changes in humidity. The more cement a mortar contains, the more adhesive it is and the more it shrinks. Shrinkage of mortar, combined with the greater thermal movement of the facing tiles or panels, often causes adhesion to break down, even where adequate movement joints have been provided. This is particularly likely to happen in the case of exposed external surfaces where the range of temperature and humidity is greatest. The effect is always unsightly, and if the finishes concerned are high up in a building it can be dangerous.

It may very reasonably be objected that mosaic tiles bedded in mortar have stayed in place on some ancient buildings for thousands of years. However, ancient mosaics were made of very small pieces of stone, quite rough on the back, which were individually pressed by hand into a thick, soft mortar with a high proportion of lime. Their fixing was as much mechanical as adhesive.

Modern adhesives

Modern adhesives are mostly organic compounds. Used in the factory, under well-controlled conditions, adhesive fixing of wood and even metals and plastics can produce joints that are as strong as or stronger than the surrounding material and very durable.

The attempt to produce adhesives that can be substituted for mortars for fixing ceramic materials in tile or sheet form on the site has not been wholly successful. Materials are available that are strongly adhesive, durable and sufficiently elastic to cope with the various forms of movement and retain their grip, but they all have deficiencies that limit their use.

Limitations of adhesive fixing

Organic adhesives contain solvents that make them workable enough to apply. The evaporation of these solvents into the air inside buildings has been blamed for various health problems.
Some adhesives lose their properties if they become too hot or too cold. Some also suffer slow chemical degradation as a result of repeated heating and cooling or prolonged exposure to water and atmospheric chemicals.

Finally, successful adhesive fixing requires excellent workmanship. Adhesives are expensive and are therefore mostly used in ‘thin beds’ of 1–2 mm. Therefore the surfaces to be stuck together must be flat: there is little tolerance. As discussed earlier, the larger the element, the more precise the tolerance must be. The surfaces to be stuck together must also be very clean, which is particularly difficult to achieve on a building site.

In summary, adhesives should be used with caution for fixing ceramic or metal elements on-site, particularly externally, and particularly where the risk of failure is high. Either mechanical fixings should be used or some other fixing material substituted. If adhesives are used under these conditions, the facing material should not be in the form of large panels or sheets.

**Cracking**

Cracking is a form of failure particularly characteristic of the ceramic materials that form the bulk of the structure, cladding and finishes of so many buildings. Timber and metals also crack, but more rarely.

Ceramic materials have poor tensile strength and little capacity for deformation. Therefore, if their natural movement is restrained or if they are exposed to tensile stresses by the movement of other building elements, they very easily crack.

Cracks are unsightly. They can admit water and provide a foothold for various destructive organisms. They cause alarm because people regard them as a prelude to structural failure, and even though most cracks are the result of either structurally harmless irreversible or reversible movements such as thermal or moisture movement, there is an element of truth in this. Accustomed to the standard of finish of factory-produced goods such as refrigerators and cars, people are less willing to
accept cracks today than they were in the past. Because movement is inherent in building materials, cracks cannot be eliminated. They can, however, be controlled.

**Controlling cracking**

Cracking can be controlled by camouflage. If a brick wall built in lime mortar with recessed joints cracks, the cracks will not be noticeable unless the movement causing them is very large. This is because the mortar is weaker than the bricks, so the cracks will run through the joints where they are in shadow; lime also tends to ‘heal’ cracks. Somewhat similarly, the classical articulation of walls with pilasters and attached columns, string course and so on tended to concentrate cracking at or near the articulating elements where, once again, it was concealed in shadow. Materials used for decorative finishes with strong small-scale variations in tone can serve the same purpose.

Modern buildings, however, often have large flat areas of wall of homogenous colour. Taken together with the modern phobia about cracks, this favours the other main method of crack control, by ‘pre-cracking’ through the design of joints to allow for movement.

**Control joints**

Control joints, if they are big enough and numerous enough to be effective, will be visible both inside and outside the building. It is therefore necessary to consider the spacing, size and visual effect of joints (Fig. 3.23). External joints must be weatherproof, and since the principles of weatherproofing are the same for all kinds of joints, this aspect will be considered along with weatherproofing in general.

**Spacing of joints**

The size of the joints depends on the amount of movement, which in turn depends on the spacing of the joints. The amount and kind of movement, as we have seen, depends on the material.

In the case of reinforced concrete, some authorities consider that joints can be avoided altogether by suitable reinforcing. However, the more
general opinion is that it is wise to provide joints. Proposed spacings vary over a wide range, but about 40 metres (120 ft) is an average figure. In a concrete-frame building, joints must pass through walls, floors and roofs.

Concrete block or brick has been unkindly described as a sensitive hygrometer. It moves a lot with changes in moisture. Thermal movements are also significant. For this reason, control joints should be spaced at about 12 metres (36 ft). In the case of clay bricks, the usual spacing of control joints is about 24 metres (72 ft).

**Size of control joints**

The size of control joints can be estimated from the figures already given. With joints at 40 metres (120 ft) a concrete element may shrink as much as 20 millimetres (a little more than 0.75 in) and this is the major movement. Clay brick used hot from the kiln with joints at 24 metres (72 ft) may expand initially by 48 millimetres (nearly 2 in). Obviously it is wise to ensure that the brick rehumidifies before using it in building. However, even in bricks that have been properly treated, a thermal movement of up to 24 millimetres (1 in) is possible in a 24 metre (72 ft) run.

What this implies for buildings faced with ceramic material is that at fairly regular intervals on the building face there are going to be continuous vertical joints about 25 millimetres (1 in) wide. Thought clearly needs to be given to their appearance.

**Visual effect of control joints**

The visual effect of control joints depends on the detailed treatment of the joints and on their relationship to the general articulation of the façade. The latter issue will be taken up in the next chapter. It should be borne in mind that in flat-roofed concrete-frame buildings the joints in the roof will, for reasons of waterproofing, be raised above the general roof surface, which will affect both the appearance and the use of any proposed roof terraces.
As to the detailed treatment of the joints, there are two main approaches. The traditional approach was to cover the joint with a moulding or decorative element, either formed in the material or made of some other material such as wood or metal. The modern approach has been to treat the joint as a recess. The two have different implications for the general character of the building and also specifically for waterproofing. Before turning to the topic of waterproofing, however, a brief concluding discussion of movement and joints is necessary.

**Differential movements generally**

While the provision for the movement of building materials constrains initial design only in relatively small ways, the understanding of differential movements is the most important aspect of detailed design.

So far, only jointing and movement within one material have been considered. However, as was pointed out earlier, buildings are assembled from many different materials, with the object of securing the advantages of each. Wherever two different materials are joined, whether in the same plane or overlaid on each other, there will be differential movements and joints have to be provided to prevent these movements from causing damage.

For example, large areas of ceramic floor tiles must have movement joints to prevent them from tearing themselves loose from their backing. Metal and plastic elements have much larger thermal movements than other materials; elements such as railings or gutters that are made of these materials must be free to move at their ends or jointed to absorb movement or they will crush the restraining material or buckle themselves.

The designer may ignore the need for such joints, regarding it as a technical matter that can be delegated to others. In this case, the joints will either be omitted, with resulting failures, or they will appear as flaws in the intended effect. Alternatively, joints and their detailed treatment can be incorporated in the initial design and treated as ornamental features.
Weatherproofing

Not all buildings have to be proof against wind and rain, but the great majority must. How water enters buildings will be considered first, along with the main techniques that have been adopted for keeping the water out and the principles that underlie them. After that there will be a brief discussion of the application of these principles to roofs, walls and openings. Before reading the following section, it may be helpful to review the discussion of wind behaviour in section 3.2.

How water enters buildings

If rain was not wet and always fell straight down, there would be few difficulties in weatherproofing buildings. However, the surface tension of water is such that (unlike mercury, for example) it readily spreads over surfaces and wets them. Rain is also very often blown by the wind, so that it wets vertical surfaces, while at the same time pressure differentials are created between inside and outside. Capillary action, an aspect of wetting, and pressure differentials individually and together are the main causes of water penetration.

Capillary action

The wetting effect of water is increased inside a narrow tube, something that is demonstrated in most school science classes. Porous building materials and fine cracks between materials create capillary tubes that can draw water into buildings. Brickwork, some stones and mortar joints generally tend to admit water by capillary action. This can happen when a wall is wetted by driving rain. It is also the cause of ‘rising damp’; the ground may remain wet even between periods of rain and the water can be drawn up from it by this mechanism. If joints between different building elements are badly designed or built, once again water may penetrate by capillary action even though the elements themselves may be made of impervious materials such as metals, glasses, plastic or wood.

Pressure differentials

As discussed in section 3.2, the wind creates pressure differentials
between inside and outside. An ordinarily strong wind can generate enough pressure to raise a column of water by 10–12 millimetres (1/2 in). It will be recalled that the taller a building is the greater the wind speed, and at the upper floors of a very tall building the column of water that can be raised increases to as much as 100 millimetres (4 in). Contrary to general belief, then, water can flow uphill and this has important consequences for weatherproofing.

**Resisting water penetration**

Water penetration is resisted by absorption, by designing to avoid capillary action, by sealing, by gravity, and by creating pressure gradients to oppose external pressures.

**Absorption**

Before the nineteenth century the walls of most masonry buildings (or at least the walls of the majority built of sedimentary stones or bricks) kept water out largely by their thickness. The porous material absorbed moisture, but it took so long for it to pass through the wall that the rain had stopped before any significant amount had reached the inside. However, long periods of heavy rain can saturate the thickest walls. Therefore it is now usual to design walls to avoid capillary action.

**Cavity walls**

From the earliest times, efforts were made to reduce water absorption by capillary action, for example by providing overhanging eaves to reduce the amount of water reaching the wall surface, which works quite well for single-storey buildings. As far as walls are concerned, however, the most useful development was the invention of the cavity wall, which consists of two skins of masonry, today usually brickwork, separated by an air gap of about 50 millimetres (2 in) (Fig. 3.24). The air gap, as previously noted (3.3.16), also acts as an insulator. The two skins are tied together with metal ties for stability. Because it is thin, the outer skin may be running with water on the inside and the ties are designed so that water will drip off them and not cross to the inner skin. The water that enters the cavity is collected at the bottom by a flashing and
drained to the outside through ‘weep holes’ or open joints. The weep holes themselves need not be very noticeable, though like any such feature they can be treated decoratively; the water running from the joint contributes to weathering (see 3.5.20). Cavity walls thus make use of gravity as well as a capillary break to exclude water.

Hollow concrete block walls work on the same principle except that, since concrete is relatively impervious, the ‘ties’ are formed as part of the block itself.

**Wide joints**

Another method of preventing capillary action is to make the joint too wide for such action to occur. In order to prevent water blowing or running in directly, the joint is made narrower on the outside and wider on the inside, so this is another kind of capillary gap. In the case of horizontal joints (Fig. 3.25), the joint is widened upwards, so that gravity also works to prevent the water from crossing the gap; the movement of water across the lower surface is stopped by an upturn such as a ‘rebate’ or weather bar, again relying on gravity. In the case of vertical joints, a vertical groove or gap is required on each side of the joint and once again the water runs down the groove rather than bridging the gap. These techniques are used in the design of roofing elements, and also in the fitting of windows into walls and opening sections into window frames.

**Sealants: wall surfaces**

One method of reducing capillary action in walls, which has been used from the earliest times, is to seal the external face by the application of some fine-grained material such as plaster or whitewash. Properly maintained, such methods are effective. Sealing by means of plasters or paints is still used, but mainly to reduce or correct the effects of weathering.

**Sealants: joints**

Joints can also be sealed. One of the functions of mortar is as a sealant. The ideal sealant is one that sticks so firmly and tightly to the materials
on either side of the joint that it prevents capillary action, and one that is sufficiently flexible to put up with differential movements. Many such materials have been developed and they are constantly being improved. However, they are expensive and are therefore used only in small quantities. Also, like adhesives, they require clean surfaces on each side of the joint and careful application if they are to work as they should. Sealants are thus highly reliable for such tasks as setting glass into frames or even waterproofing vertical joints between glass sheets in long runs of fixed window. They are less reliable in sealing joints with porous materials. To use sealants, as has been done, to waterproof an entire façade of glass sheets without frames seems extremely optimistic.

Sealants can be used in joints either to exclude wind-blown rain only or as the sole barrier to water penetration. In the latter case, the sealant can be placed either at the front or the back of the joint; if it is at the back, the front is kept wide enough to prevent capillary action and the joint relies on pressure gradients as well as the adhesion of the seal. As noted, sealants are expensive and therefore joints that are to be sealed are seldom made more than about 10 millimetres (1/2 in) wide; if they are to provide for movement, they cannot be much less than this either.

Sealing roofs: the ‘flat’ roof

It is traditional to seal the joints between sheets of corrugated galvanised steel sheet roofing with paint to reduce capillary action, even though the waterproofing action relies largely on gravity. The same approach is also used with more modern sealants to waterproof the laps of ribbed metal roofing. In contrast, ‘flat roofs’ rely entirely on creating a continuous waterproof sheet or membrane, a gigantic ‘seal’. The waterproof ‘membrane’ is either literally a membrane, of heavy plastic sheet with welded or glued joints, or sheets of fabric impregnated and glued together with waterproof organic materials, or fabric-reinforced poured organic material. Whatever the nature of the membrane, it is exposed to great risks. Even though flat roofs are not in fact flat, but drain to outlets, in heavy rain the roof membrane will be subject to water pressure and the slightest flaw will result in a leak. Weaknesses can occur through manufacturing faults, through careless laying,
through the membrane being punctured during laying, through the movement of the building after laying, or through subsequent activity on the roof that tears or punctures the membrane. Because the membrane acts as a vapour barrier, vapour pressure from underneath may produce bubbles which are particularly likely to be punctured. Because it is an organic material, it can be damaged by sunlight and may become brittle in very cold weather. All these problems can be overcome by good detailing and workmanship, but the resulting roof is expensive. The question then is, why use flat roofs at all?

**Why use flat roofs?**

Flat roofs are popular with students and some practitioners because they can be used to cover a large area or a complex plan shape without having to worry about the appearance of the resulting roof (see 3.5.84–86). Flat roofs have also been used for ideological reasons, as a way of distinguishing ‘modern’ from traditional architecture. Where snow is common, a well-designed and well-executed flat roof has some advantages over a pitched roof (see 3.5.90). Finally, in tall buildings the advantages of other roofing systems are reduced by violent wind forces and uplifts. In some places there is a tradition of flat-roof building and reliable flat roofs can be easily obtained, even for small buildings. In general, however, a student should be prepared to advance good arguments for using a flat roof rather than other, less risky forms.

**The form of flat roofs**

The most likely place to use a flat roof is on a multi-storey building. A good-quality flat roof will consist, above the slab, at the lowest point, of about 50 mm (2 in) of insulation, the membrane itself, and a further 50 mm (2 in) of paving and topping, so that it will be at least 200 mm (8 in) thick overall. Downpipes must be provided (one is not enough – what if it gets blocked?) as equally spaced as possible and near the centre lines of the building. Remember that the downpipes must run down through all floors of the building and will require ducts; putting downpipes inside columns is clever lunacy; again, what if they get blocked? From the downpipes the roof slopes up to the edges of the building, with a minimum slope of 1 in 100. The slope is often formed
in the insulation. At the edges the roof is usually finished against a parapet both to conceal the edge of the roofing assembly and to enable it to be waterproofed. The parapet needs to rise at least 150 mm (6 in) above the topping so the minimum height of the parapet above the slab level will be 250 mm (10 in) + (1/200 × roof span).

**Gravity and water penetration: Weatherboarding**

Despite what has been said earlier, water has a strong tendency to run downhill. Some applications of this fact to weatherproofing have already been mentioned. Another common application is in the timber-sheeted or weatherboard wall. A framed wall is covered with horizontal timber boards that lap over one another. The lap must be sufficient to allow for the shrinkage of the board and to prevent water penetration due to wind or capillary action. The width of the boards is constrained on the one hand by the need to minimise movement, which argues for narrow boards, and on the other to minimise the number of fixings, which argues for wide boards. The resulting compromise usually lies between 200 mm (8 in) and 150 mm (6 in) nominal size, which will show about 175 mm (7 in) to 125 mm (5 in) on the face. The texture of the result is affected by the width of the boards and the detail design of the joints. It should be noted that vertical boarding, even with lapped joints, is not waterproof in itself; water will be driven through the joints by wind even if it is not drawn in by capillary action. Such boarding is largely decorative and must rely on a backing of waterproof sheet material or ‘sarking’.

**Roofs**

Perhaps the commonest and most important application of gravity to waterproofing is in the design of roofs. It seems obvious to say that most roofs are made sloping so that the water will run off, but it is the interaction between this intention and the technical properties of different roofing systems which gives roofs their characteristic shapes.

**Thatch, slates and shingles**

Thatch is an almost pure example of a gravitational system of weatherproofing. Thatch consists of tightly bundled dry plant material
such as straw or reeds. It is laid to a very steep pitch, not less than 50°, with huge overlaps between the rows of bundles so that it is very thick. Water penetrates the bundles but it runs down the slope faster than it can penetrate and therefore does not reach the inside before it arrives at the eaves. Absorption is also involved here: as the dry plant material becomes wet it expands and the joints between individual stems become tighter.

Slates and shingles operate on the same principle of steep slopes and multiple layers (Fig. 3.26). However, because the materials themselves are waterproof they can be used at lower pitches: 35–30°.

**Tiles**

Some traditional terracotta tiles also operate on the same principle as slates. Pan tiles and Spanish tiles improve the side joints by providing overlaps, but the vertical lap is still open to wind and capillary action, so the slope must still be fairly steep. ‘Marseilles’ tiles were the first to provide both horizontal and side laps with capillary breaks. However, their production tolerances were not very precise, and under violent wind and rain they still admitted water if the slope was less than 30°. Modern pressed concrete tiles are better in their design and precision of manufacture and can be laid to slopes as low as 15°. This, however, requires sarking.

**Sarking**

Sarking consists of waterproof sheet material, supplied in wide rolls, which often includes reflective insulation. It is laid under the roofing and greatly improves the waterproofness of slate, shingle and tile roofs.

**Corrugated and rib metal sheet roofing**

Metal sheet roofing is inherently waterproof and easily formed to give weatherproof joints. It can also be made in large pieces, which reduces the number of joints. Thus it can be laid to relatively low pitches. Traditional corrugated sheet roofing was and is limited to lengths of about 3600 mm (12 ft). In order to prevent water entering through the end laps, it had to be laid at about 15°, though lower pitches are often
to be seen in sheds. Modern rib metal roofing can be made in continuous sheets of any length. For reasons of transport and erection, however, sheet lengths are usually limited to 15 m (50 ft). Such sheets can be continuous from roof to eaves in most buildings and can be laid to slopes of 5°. If the slope is less than 5°, minor dents or buckles, which can be caused for example by walking on the roof, may hold water, with resulting chemical damage to the metal.

The disadvantages of metal sheet roofing are that it is vulnerable to chemical attack, it is practically transparent to noise, heat and cold, and it is subject to large thermal movements, particularly in the case of very long sheets.

**Roof forms**

The forms of pitched roofs are constrained by the pitch characteristic of the roofing material and the problems of ensuring that roof surfaces meet in the same plane at changes of direction.

This latter problem does not arise in the case of ‘lean-to’ or mono-pitch roofs, gable roofs that have two slopes meeting at a ridge, or roofs whose cross-section is an arc of a circle or similar curve. Such roofs are, however, only suited to simple rectangular plans. For more complex plans, a ‘hip’ roof is required.

‘Hips’ occur where two external walls meet with an internal angle between 0° and 180°; ‘valleys’ occur where the internal angle is between 180° and 360°. Of course, internal angles of 90° and 270° are by far the most common. If the two adjoining roof slopes are to meet in the same line at hips and valleys, the two slopes must be the same and the hip or valley line must bisect the internal angle.

**The appearance of pitched roofs**

The height of a pitched roof increases with the span. The steeper the pitch, the more rapidly the height increases. The visible area of a steeply pitched roof can thus be as great as or even greater than that of the walls, particularly in single-storey buildings. Some architects have accepted this dominance of the roof and enhanced it, as Asplund did at the
Woodland Chapel of 1918 (Figs 3.27 and 3.28). However, there are two related objections to this. First, if the area of the walls and the area of the roof are nearly equal, the effect is often awkward. Second, too much emphasis on the roof distracts attention from the walls, which may have more complex messages to convey. These are aesthetic issues but they have generated technical solutions. The most obvious solution is to use a roofing system that allows a lower pitch. Two other solutions will be considered here: the mansard roof and the box gutter.

**Mansard roofs**

Mansard roofs (Fig. 3.29) are named after François Mansard, who probably did not invent them but certainly made extensive use of them in his designs for chateaux, for example at Balleroy (1626) and Blois (1635). The principle is simple: the roof is made with a pitched section and a flat section. The pitched section extends from the eaves to whatever height gives, in the designer’s opinion, a satisfactory
proportion. Beyond that it is flat. The easiest way to imagine a mansard roof is to picture it as an ordinary hipped roof cut off part of the way up: the area of the cut is the flat roof. This kind of roof is easier to build today than it was in Mansard’s time. It works, but it does seem a rather contrived way of getting the appearance rather than the reality of a pitched roof.

**Box gutters**

Another much less satisfactory solution to the problem of reducing the roof height is to reduce the span by making not one but two pitched roofs which meet in the middle (Fig. 3.30). In the case of hipped roofs,
this produces a hollow in the shape of an inverted hipped roof. To prevent the water simply running down inside the building, it must be collected in a gutter. Such gutters are known as 'box gutters', as distinct from eaves gutters (see 3.5.90).

A box gutter is an extremely risky, not to say dangerous, contrivance. It receives half the water from the roof, and if it overflows the water ends up inside the building. Downpipes, even large and numerous downpipes, can become blocked by all sorts of things, from leaves to birds’ nests, and are particularly likely to do so when they are invisible and difficult to get to. Generally, to ‘solve’ a roofing problem by means of a box gutter is not to solve it at all.

Box gutters can be used successfully between gables or saw-tooth roofs if certain conditions are very strictly observed. The gutter should be large: at least 450 mm wide and 150 mm deep at its highest point, and with a fall of not less than 1 in 50, enough to wash it clean of most obstructions (Fig. 3.31). The end of the gutter should project beyond the outside of the building and be provided with generous overflows. The downpipe should be at least 150 mm in diameter and preferably bigger, and should also be outside the building.

**Eaves**

Since the best place for water is outside the building, and as far away from it as possible, most buildings with pitched roofs have projecting eaves. The projection of the eaves depends on the type of roofing and the construction of the roof. In traditional wooden roof framing supported on rafters and purlins, the eaves are formed by projecting the rafters, which are about 100 mm (4 in) × 50 mm (2 in) and will cantilever safely no more than about 600 mm (2 ft); wider eaves required the support of brackets or struts of some kind. In modern roof framing based on trusses, the trusses can be designed to project much further and the issue becomes purely one of economy and appearance. It is perfectly possible to cantilever concrete roof slabs a short distance to form eaves but this is seldom done; on tall buildings it would be pointless because of up-draughts.
Eaves in framed roofs can be boxed, that is, enclosed with a sort of ceiling, or lined on the underside of the rafters, which is often done in gable roofs, or unlined, which is usual only in utilitarian buildings. In roofs constructed with rafters, it is possible to line the eaves on top of the rafters, so that the rafters are exposed, but in this case the rafters must be carefully finished and set out, which is expensive.

**Eaves gutters**

The water running off eaves can erode the ground, damage plants and seriously inconvenience passers-by or people trying to enter a building; in windy weather it will greatly add to the amount of water reaching walls and openings. Therefore, it is usual to provide the eaves of pitched roofs with eaves gutters. Eaves gutters are usually of sheet metal or plastic, about 75 mm (3 in) deep. Their width depends on the required size of the downpipes: they should be at least 25 mm (1 in) wider than the downpipe. It was traditional to lay eaves gutters to a fall and this has the advantage of avoiding ponding in the gutter, the dangers of which have been discussed earlier. However, level gutters have been shown to be just as efficient in removing water, provided that there are enough downpipes; if the cross-section of the gutter is semicircular rather than rectangular, ponding is largely avoided. A rounded gutter gives the eaves a different effect in profile to a rectangular one. In the nineteenth century gutters were often pressed into complex shapes (Fig. 3.32) but this is expensive and is now done only in restoration work.

**Problems with snow**

In areas of heavy snowfall, special problems can arise with eaves and gutters. Snow accumulates on the roof. Heat from within the house melts the snow nearest the roof, which runs down the roof surface. Since the eaves and the gutter are outside the house, they are colder and the run-off water freezes there, eventually forming a dam of ice at the edge of the roof. The weight of this ice can be sufficient to break the eaves. Even if this does not happen, water can accumulate behind the ice dam to the point where it runs back under the tiles, shingles or slates and into the building.
Traditional solutions include making the roof pitch so steep that snow does not accumulate (Figs 3.33 and 3.34) and/or reducing the eaves to a minimum and doing without gutters. Modern solutions include ventilating the roof space so that the roof is not much warmer than the snow, heating the eaves to prevent the ice dam from forming, and strengthening the eaves and providing additional waterproofing at the edge of the roof.

**Downpipes**

Downpipes are a significant feature of the appearance of buildings with pitched roofs, and are too often overlooked. Nineteenth-century architects, such as C.F. Voysey, were better at using downpipes for
decorative effect (Fig. 3.35) than most twentieth-century architects were. If there is just one downpipe for a length of gutter, the best place for it from the point of view of water removal is in the middle. If there are two, they should be at the quarter points, and so on.

The total area of downpipe required for a given horizontal area of roof depends on the maximum rainfall. In Australia, where the rainfall is often heavy, a ratio of downpipe area to roof area of about 1:15,000 is used as a rule of thumb. Then one can either decide on the number of downpipes and calculate their cross-sectional area or decide on the size of the downpipe and calculate the number.

Round downpipes are more efficient and more elegant, but rectangular downpipes are easier to fix and can be used to conceal movement joints. Common diameters for downpipes are 75 mm (3 in) or 100 mm (4 in). As a rule of thumb, rectangular downpipes should not have a short dimension of less than 50 mm (2 in) or a long dimension greater than twice the short dimension.

Weatherproofing by the use of pressure gradients

Weatherproofing by the use of pressure gradients is most often discussed, and most easily explained, in terms of jointing, but it applies at much larger scales.

To start with, consider a joint about 12 mm (1/2 in) wide and 75 mm (3 in) deep sealed at the back. Wind blows against the outside of the joint and therefore tends to blow water into it. However, if the seal is good, there is no way for the air to escape, so the pressure within the joint will rapidly come to equal the outside pressure. Since the pressure is balanced, water is no longer forced into the joint. The same principle is often used in excluding water at the opening sections of windows.

This same principle applies to openings at the scale of windows and doors. Traditional openings were set in thick walls so that their depth was quite significant in proportion to their width and height. The addition of heavy mouldings at the side, a strongly projecting sill and a still more projecting pediment were sufficient to ensure a permanent zone of
positive pressure over the opening, provided of course that the windows or doors were shut. Similar results can be obtained by the use of external sunshading (3.3.30). Modern curtain-wall buildings often have no such protection, and even some modern masonry buildings have unwisely imitated them and placed their windows as near the outside as possible.

**Maintenance**

At several points in this chapter reference has been made to maintenance. Thoughtful detailing and selection of materials can reduce maintenance. For example, hard, dense finishing materials can be used in areas exposed to heavy wear and tear, such as the external facings of ground floors, sills, door jambs and skirtings. Proper consideration of weathering can cut down on external cleaning. Nevertheless, maintenance will always be needed.

Paint and plaster will have to be renewed. Windows must be cleaned constantly. In urban areas, stones, brick and concrete will require occasional steam cleaning. Sealants will have to be replaced. Light bulbs will have to be changed. Machinery will have to be replaced, since its life is usually much shorter than that of the building.

**Accessibility**

Any one of these operations can be appallingly difficult and expensive, or relatively simple. The main factor is accessibility and accessibility depends largely on design. Oddly, it is in medium-size buildings that the most problems arise. One- or two-storey buildings can be reached by ladder. In the case of tall glass curtain-wall buildings it is obvious that something must be done and elaborate systems, with gondolas hung from travelling cranes at the top of the building, are usually installed. In buildings of four to ten storeys and large multi-storey internal spaces or atriums, maintenance needs are often overlooked.

Some solutions to external maintenance access include:

- having permanent maintenance access ways, which on the exterior can also serve as sun shields
- using a mobile extendable platform or ‘cherry picker’, which demands
first that such a piece of equipment be available and second that there be space and suitable surfaces to get it and the lorry in which it is mounted into position

- providing for access from inside the building, by providing sufficient opening windows.

Regulations often lay down permissible methods of access. As a little reflection will show, the maintenance of any large internal space can be still more difficult; a suspended gondola on a travelling crane near the roof may be the only solution.
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