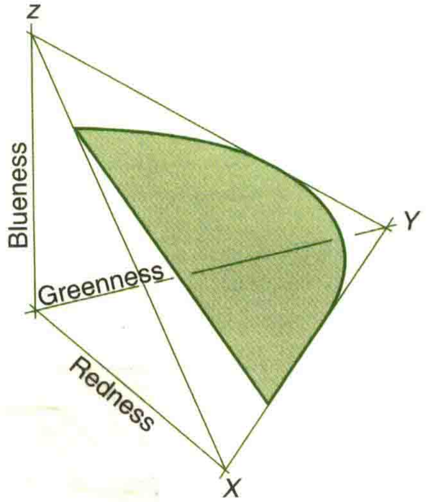
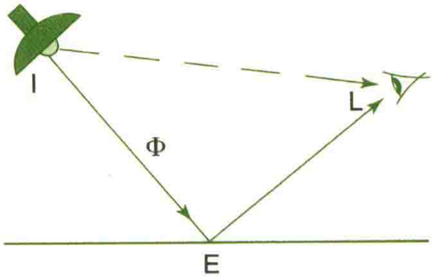
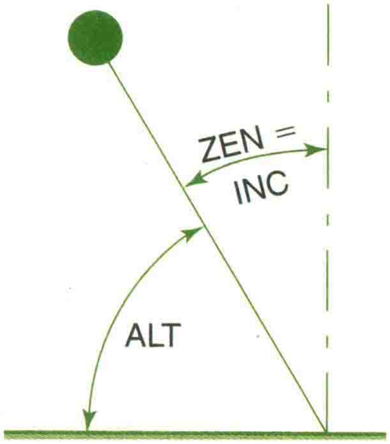
THIRD EDITION

INTRODUCTION TO ARCHITECTURAL SCIENCE

THE BASIS OF SUSTAINABLE DESIGN







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ARCHITECTURAL SCIENCE
The basis of sustainable design

Third edition

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Introduction to

ARCHITECTURAL SCIENCE

The basis of sustainable design

PREFACE TO THE THIRD EDITION

Some terms used in the title of this work need to be defined and explained at the outset.

Architectural Science

The term 'building science' has been well established since at least 1944, when Geeson published his book of that title (English Universities Press) and D. A. G. Reed's book of the same title was published by Longmans. The subject became important after the 1958 Oxford Conference of the RIBA, when it formally became an important part of architectural education.

The same year, the term 'Architectural Science' was introduced by H. J. Cowan, the first professor of that designation at Sydney University, expressing his intention of providing the scientific basis for architectural design. Initially his main concern was the science of materials, construction and structures. He started the publication of the quarterly *Architectural Science Review* and founded the Architectural Science Association (ANZAScA) as primarily an informal grouping of teachers of the subject. Originally this association was concerned with the building fabric, with the physical science aspects of architectural design, later extending the field to include the science of indoor environments, thermal, acoustic and lighting. During my presidency (1982) we included the relevant areas of social sciences.

Subsequently the use of energy and resources in building became the main concern.

Sustainability

In 1972, the United Nations Conference (in Stockholm) on the Human Environment led to the Brundtland Report, and the 1992 UN Conference on Environment and Development (UNCED), the World Summit, in Rio de Janeiro. This had produced the 'Rio Declaration' and the Agenda 21, a programme for the twenty-first century. The extreme green lobby was vociferous in opposing any development, as they thought this to be harmful for the natural environment. However, the third world lobby demanded development, as their right to 'catch up' with the developed world. Finally the consensus has emerged that development is needed and is acceptable as long as it is sustainable. This was defined by Brundtland as 'development that meets the needs of the present without compromising the ability of future generations to meet their own need.'

This became recognised and adapted by (*inter alia*) the International Union of Architects (IUA) Congress in Chicago (1993) and was subsequently endorsed by most national architectural bodies.

Sustainable design

Since then, unfortunately, some extreme exponents of post-modernism came to consider architecture purely as an art-form, denying Sullivan's tenet: 'form follows function'. This has led to the most extravagant, unorthodox, contorted and crazy buildings. The odd few of these can be tolerated here and there in an existing sober and solid urban context, but heaven forbid this becoming the 'norm'. It is pure formalism, at the expense of function and environmental decency.

These became dominant in the glossies, the current fashion in architecture. Many consider 'architectural science' as an oxymoron, some suggesting that in architectural education it is counter-productive, curbing or even destroying any imaginative talent of students. It also gives fuel to the erroneous but general belief of the broad public, that architecture is a luxury, that it is irrelevant to 'real life', to building.

It is contradictory and almost schizophrenic (if not fraudulent) that at the same time many such professionals claim that what they produce is sustainable architecture, sustainable design. Here it is suggested that without science, architecture cannot be sustainable. Science is not opposed to design, it does not compete with or replace design, but it is part and parcel of it. The designer can only exercise his/her imagination if the physical basis is understood. Scientific understanding should permeate the intuitive, inventive design. Science can give valuable design tools but it can also provide checking tools for use as the design develops.

As far as architecture itself is considered, I rather like the 'cocktail shaker' analogy. I know that *analogia non probat*, that analogy is not a proof, but it is usefully indicative. Science is one of the inputs into the shaker, along with materials, construction and structures studies as well as some social sciences. In a cocktail the individual inputs, such as basil, chilli or bitters, may not be enjoyable, but they are essential ingredients. The design studio (and design practice) are the cocktail shakers. The technique of shaking, the rhythm, the movement, the often associated dance-steps, possibly even some singing are unimportant, as long as all the ingredients are there and are well shaken.

Some years ago, the (then) head of a school of architecture where Architectural Science has been abolished as a subject, in response to my query, explained that there is no one to teach it and there is no textbook to present the relevant knowledge in a rigorous and disciplined manner. This gave me the first impetus some ten years ago to attempt to produce such a book. I made use of many of my lecture notes accumulated over a teaching career of some 30 years, but supplementing and extending these with much new matter, with recent developments. What follows is the result of this attempt.

INTRODUCTION

Four chains of thought led to the idea of this book and to the definition of its content:

1. It can no longer be disputed that the resources of this Earth are finite, that its capacity to absorb our wastes is limited, that if we (as a species) want to survive, we cannot continue our ruthless exploitation of the environment. Where our actions would affect the environment, we must act in a sustainable manner. There are many good books that deal with the need for sustainability (e.g. Vale and Vale, 1991; Farmer, 1999; Roaf *et al.*, 2001; Smith, 2001, Beggs, 2002, Brophy and Lewis, 2011). This book assumes that the reader is in agreement with these tenets and needs no further persuasion.
2. Architecture is the art and science of building. There exists a large literature on architecture as an art, on the cultural and social significance of architecture – there is no need to discuss these issues here.
3. The term 'bioclimatic architecture' was coined by Victor Olgyay in the early 1950s and fully explained in his book, *Design with Climate* (1963). He synthesised elements of human physiology, climatology and building physics, with a strong advocacy of architectural regionalism and of designing in sympathy with the environment. In many ways he can be considered an important progenitor of what we now call 'sustainable architecture'.
4. Architecture, as a profession, is involved in huge investments of money and resources. Our professional responsibility is great, not only to our clients and to society, but also for sustainable development. Many excellent books and other publications deal with sustainable development in qualitative terms. However, professional responsibility demands expertise and competence. It is in this narrow area where this work intends to supplement the existing literature.

This book is intended to give an introduction to architectural science, to provide an understanding of the physical phenomena we are to deal with and to provide the tools for realising the many good intentions. Many projects in recent times claim to constitute sustainable development, to be sustainable architecture. But are they really green or sustainable? Some new terms have started appearing in the literature, such as 'greenwash' – meaning that a conventional building is designed and then claimed to be 'green'. Or 'pure rhetoric – no substance', with the same meaning.

My hope is that after absorbing the contents of this modest work, the reader will be able to answer this question. After all, the main aim of any education is to develop a critical faculty.

Building environments affect us through our sensory organs:

1. the eye, i.e. vision, a condition of which is light and lighting; the aim is to ensure visual comfort but also to facilitate visual performance;
2. the ear, i.e. hearing: appropriate conditions for listening to wanted sound must be ensured, but also the elimination (or control) of unwanted sound: noise;
3. thermal sensors, located over the whole body surface, in the skin; this is not just a sensory channel, as the body itself produces heat and has a number of adjustment mechanisms but it can function only within a fairly narrow range of temperatures and only an even narrower range would be perceived as comfortable. Thermal conditions appropriate for human well-being must be ensured.

What is important for the designer is to be able to control the indoor environmental conditions: heat, light and sound. Reyner Banham (1969) in his *Architecture of the Well-tempered Environment* postulated that comfortable conditions can be provided by a building itself (passive control) or by the use of energy (active control), and that if we had an unlimited supply of energy, we could ensure comfort even without a building. In most real cases, it is a mixture (or synergy) of the two kinds of control we would be relying on.

In this day and age, when it is realised that our traditional energy sources (coal, oil, gas) are finite and their rapidly increasing use has serious environmental consequences (CO_2 emissions, global warming, as well as local atmospheric pollution), it should be the designer's aim to ensure the required indoor conditions with little or no use of energy, other than from ambient or renewable sources.

Therefore the designer's task is:

1. to examine the given conditions (site conditions, climate, daylight, noise climate);
2. to establish the limits of desirable or acceptable conditions (temperatures, lighting and acceptable noise levels);
3. to attempt to control these variables (heat, light and sound) by passive means (by the building itself) as far as practicable;
4. to provide for energy-based services (heating, cooling, electric lighting, amplification or masking sound) only for the residual control task.

The building is not just a shelter, or a barrier against unwanted influences (rain, wind, cold), but the building envelope should be considered a *selective filter*: to exclude the unwanted influences, but admit the desirable and useful ones, such as daylight, solar radiation in winter or natural ventilation.

The book consists of four parts:

1. **Heat: the thermal environment**
2. **Light: the luminous environment**
3. **Sound: the sonic environment**
4. **Resources: energy, water, materials**

In each Part the relevant physical principles are reviewed, followed by a discussion of their relationship to humans (comfort and human requirements). Then the control functions of the building (passive controls) are examined as well as associated installations, energy-using 'active' controls. The emphasis is on how these can be considered in design. Part 1 (Heat) is the most substantial, as the thermal behaviour of a building has the greatest effect on energy use and sustainability and its design is fully the architect's responsibility. In other areas there may be specialist consulting engineers to provide assistance.

Each Part concludes with a series of data sheets relating to that Part, together with some 'methods sheets', describing some calculation and design procedures.

CONTENTS

PART 1 HEAT: THE THERMAL ENVIRONMENT

CONTENTS

SYMBOLS AND ABBREVIATIONS (SYMBOL, DEFINITION, UNIT)

asg	alternating solar gain factor	–
asp	aspect ratio	
b	breadth, thickness	m
clo	unit of clothing insulation	
dTe	sol-air excess temperature (difference)	K
er	evaporation rate	kg/h
f	response factor	–
k	linear heat loss coefficient	W/m.K
met	unit of metabolic heat (58.2 W/m^2)	
mr	mass flow rate	kg/s
p	pressure	Pa
pt	total atmospheric pressure	Pa
pv	vapour pressure	Pa
pv_s	saturation vapour pressure	Pa
q	building conductance (spec. heat loss rate)	W/K
qa	total admittance	W/K
qc	envelope conductance	W/K
qv	ventilation conductance	W/K
h	surface conductance	W/m^{2}K
h_c	convective surface conductance	W/m^{2}K
h_r	radiative surface conductance	W/m^{2}K
sM	specific mass (per floor area)	kg/m^2
sQ	swing in heat flow rate (from mean)	W
sT	swing in temperature (from mean)	K

SYMBOLS AND ABBREVIATIONS (Continued)

t	time	hour
v	velocity	m/s
vr	volume flow rate (ventilation rate)	m^3/s, L/s
vR	vapour resistance	MPa.s.m^2/g
y	year	
A	area	m^2
AH	absolute humidity	g/kg
ALT	solar altitude angle	°
AZI	solar azimuth angle	°
C	conductance	W/m^{2}K
Cd	conduction, conducted heat (from body)	W
CDD	cooling degree-days	Kd
CoP	coefficient of performance	–
CPZ	control potential zone	
Cv	convection, convected heat (from body)	W
D	daily total irradiation Wh/m^2	MJ/m^2
D_v	daily total vertical irradiation Wh/m^2	MJ/m^2
DBT	dry bulb temperature	°C
DD	degree-days	Kd
DEC	solar declination angle	°
Dh	degree-hours	Kh
DPT	dew-point temperature	°C
DRT	dry resultant temperature	°C
E	radiant heat emission	W
EnvT	environmental temperature	°C
ET*	new effective temperature	°C
Ev	evaporation heat transfer (from body)	W
G	global irradiance	W/m^2
GT	globe temperature	°C
H	enthalpy (heat content)	kJ/kg
HDD	heating degree-days	Kd
H_L	latent heat content	kJ/kg
H_S	sensible heat content	kJ/kg
HSA	horizontal shadow angle	°
Htg	heating requirement	(kWh) Wh
INC	angle of incidence	°
Kd	Kelvin days	Kd
Kh	Kelvin hours	Kh
L	length (linear thermal bridges)	m
LAT	geographical latitude angle	°
M	metabolic heat production	W
Mb	body mass	kg
MRT	mean radiant temperature	°C
N	number of air changes per hour	–
ORI	orientation angle	°
Q	heat flux or heat flow rate	W
Qc	conduction heat flow rate	W
Qe	evaporative heat loss rate	W
Qi	internal heat gain rate	W
Qs	solar heat gain rate	W
Qv	ventilation heat flow rate	W
R	resistance	m^{2}K/W
$R_{a\text{-}a}$	air-to-air resistance	m^{2}K/W
R_c	cavity resistance	m^{2}K/W
Rd	radiation, radiated heat (from body)	W
RH	relative humidity	%
R_s	surface resistance	m^{2}K/W
R_{si}	internal surface resistance	m^{2}K/W
R_{so}	outside surface resistance	m^{2}K/W
SD	standard deviation	
SET	standard effective temperature	°
SH	saturation point humidity	g/kg
SI	Système International (of units)	
T	temperature	°C
Tb	balance point (base~) temperature	°C
TIL	tilt angle	°
T_i	indoor temperature	°C
Tn	neutrality temperature	°C
T_o	outdoor temperature	°C
T_s	surface temperature	°C
$T_{s\text{-}a}$	sol-air temperature	°C
U	air-to-air (thermal) transmittance	W/m^{2}K
V	volume	m^3
VSA	vertical shadow angle	°
WBT	wet bulb temperature	°C
Y	admittance	W/m^{2}K
α	absorptance, or thermal diffusivity	–
δ	vapour permeability	μg/m.s.Pa
ε	emittance	–
η	efficiency	–
θ	solar gain factor	–
θ_a	alternating solar gain factor	–
κ	conductivity correction factor	–
λ	conductivity	W/m.K
μ	decrement factor	–
π	vapour permeance	μg/m^2.s.Pa
ρ	density, or reflectance	kg/m^3 or –
τ	transmittance	–
φ	time lag	h
σ	Stefan-Boltzmann constant	W/m^{2}K^4
Σ	sum of . . .	–
Δp	pressure difference	Pa
ΔS	rate of change in stored heat	W
ΔT	temperature difference, interval or increment	K

SUBSCRIPTS TO G AND D

first	b	beam~		v	vertical
	d	diffuse~		p	on plane p
	r	reflected~	for G only	n	normal to radiation
second	h	horizontal			

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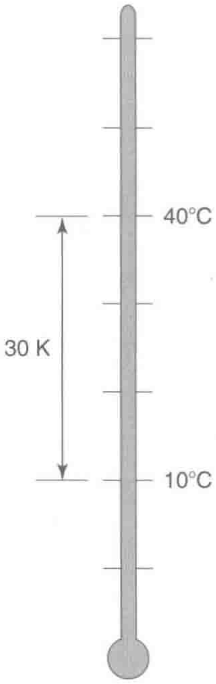

1.1

Temperature scale and interval

1.1 PHYSICS OF HEAT

1.1.1 Heat and temperature

Heat is a form of energy, contained in substances as molecular motion or appearing as electromagnetic radiation in space. Energy is the ability or capacity for doing work and it is measured in the same units. The derivation of this unit from the basic MKS (m, kg, s) units in the SI (Système International) is quite simple and logical, as shown in Table 1.1.

Temperature (T) is the symptom of the presence of heat in a substance. The Celsius scale is based on water: its freezing point taken as 0°C and its boiling point (at normal atmospheric pressure) as 100°C. The Kelvin scale starts with the 'absolute zero', the total absence of heat. Thus 0°C = 273.15°K. The temperature interval is the same in both scales. By convention, a point on the scale is denoted °C (degree Celsius) but the notation for a temperature difference or interval is K (Kelvin), which is a certain length of the scale, without specifying where it is on the overall scale (Fig. 1.1). Thus 40°C–10°C = 30 K, and similarly 65°C–35°C is 30 K but 15°C, as a point on the scale, is 288.15°K.

The **specific heat** concept provides the connection between heat and temperature. This is the quantity of heat required to elevate the temperature of unit mass of a substance by one degree, thus it is measured in units of **J/kg.K**. Its magnitude is different for different materials and it varies between 100 and 800 J/kg.K for metals, 800–1200 J/kg.K for masonry materials (brick, concrete) to water, which has the highest value of all common substances: 4176 J/kg.K (see Data sheet D.1.1).

Table 1.1 Derivation of composite SI units for thermal quantities

length	m	(metre)
mass	kg	(kilogram)
time	s	(second)
velocity, speed	m/s	That is unit length movement in unit time, the everyday unit is km/h, which is 1000m / 3600 s = 0.278 m/s or conversely: 1 m/s = 3.6 km/h
acceleration	m/s^2	That is unit velocity increase in unit time: (m/s)/s
force	$kg.m/s^2$	That which gives unit acceleration to unit mass called newton (**N**)
work, energy	$kg.m^2/s^2$	Unit work is done when unit force is acting over unit length, i.e. N × m called joule (**J**)
power, energy flow rate	$kg.m^2/s^3$	unit energy flow in unit time or unit work done in unit time, i.e. J / s called watt (**W**)
pressure, stress	$kg/m.s^2$	unit force acting on unit area $(kg.m/s^2)/m^2$, i.e. N / m^2 called pascal (**Pa**)

Note: SI unit symbols, derived from personal names, are always capitalised.

EXAMPLE 1.1 SPECIFIC HEAT AND TEMPERATURE

Given 0.5 L (= 0.5 kg) of water at 20°C in an electric jug with an 800 W immersion heater element (efficiency: 1.0 or 100%). How long will it take to bring it to the boil?

requirement: 0.5 kg × 4176 J/kg.K × (100 – 20) K = 167 040 J
heat input 800 W, i.e. 800 J/s, thus the time required is
167 040 J / 800 J/s ≈ 208 s » 3.5 minutes.

Latent heat of a substance is the amount of heat (energy) absorbed by unit mass of the substance at change of state (from solid to liquid or liquid to gaseous) without any change in temperature. This is measured in kJ/kg, e.g. for water:

the latent heat of fusion (ice to water) at 0°C = 335 kJ/kg (= J/g)
the latent heat of evaporation at 100°C = 2261 kJ/kg
at about 18°C = 2400 kJ/kg

At a change of state in the reverse direction, the same amount of heat is released.

Thermodynamics is the science of the flow of heat and of its relationship to mechanical work.

The *first law* of thermodynamics is the principle of conservation of energy. Energy cannot be created or destroyed (except in sub-atomic processes), but only converted from one form to another. Heat and work are interconvertible. In any system, the energy output must equal the energy input, unless there is a +/− storage component.

The *second law* of thermodynamics states that heat (or energy) transfer can take place spontaneously in one direction only: from a hotter to a cooler body, or generally from a higher to a lower grade state (same as water flow will take place only downhill). Only with an external energy input can a machine deliver heat in the opposite direction (water will move upwards only if it is pumped).Temperature can only be increased by energy (work) input, e.g. by a heat pump (see Fig. 1.98 on p. 85). Any machine to perform work must have an energy source and a sink, i.e. energy must flow through the machine: only part of this flow can be turned into work.

Heat flow from a high to a low temperature zone can take place in three forms: conduction, convection and radiation. The magnitude of any such flow can be measured in two ways:

1. as *heat flow rate* (Q), or heat flux, i.e. the total flow in unit time through a defined area of a body or space, or within a defined system, in units of J/s, which is a watt (W). (The most persistent archaic energy flow rate or power unit is the *horsepower*, but in fully metric countries even car engines are now rated in terms of kW.)
2. as *heat flux density* (or density of heat flow rate), i.e. the rate of heat flow through unit area of a body or space, in W/m^2. The multiple kW (kilowatt = 1000 W) is often used for both quantities. (The term 'density' as used here is analogous with e.g. population density, i.e. people per unit area, or with surface density, i.e. kg mass per unit area of a wall or other building element.)