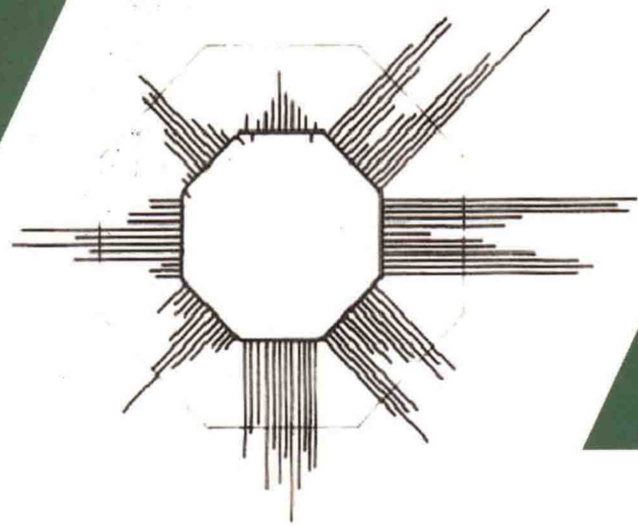
Second edition



Introduction to Architectural Science

The Basis of Sustainable Design

Steven V Szokolay

Architectural Press

Introduction to ARCHITECTURAL SCIENCE

The Basis of Sustainable Design

Steven V. Szokolay

Second edition

ELSEVIER

AMSTERDAM • BOSTON • HEIDELBERG • LONDON • NEW YORK • OXFORD
PARIS • SAN DIEGO • SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

Architectural Press is an imprint of Elsevier

Architectural Press is an imprint of Elsevier
Linacre House, Jordan Hill, Oxford OX2 8DP, UK
30 Corporate Drive, Suite 400, Burlington, MA 01803, USA

Second edition 2008

British Library Cataloguing in Publication Data
Szokolay, S. V.
Introduction to architectural science : the basis of sustainable design. – 2nd ed.
1. Architectural design 2. Buildings – Environmental engineering 3. Sustainable architecture
I. Title
721'.046

Library of Congress Catalog Number: 2008924601

ISBN: 978-0-7506-8704-1

Typeset by Charon Tec Ltd., A Macmillan Company. (www.macmillansolutions.com)

Printed and bound by Uniprint

08 09 10 11   11 10 9 8 7 6 5 4 3 2 1

Introduction to

ARCHITECTURAL SCIENCE

The Basis of Sustainable Design

PREFACE TO THE SECOND EDITION

Much has changed in the 3 years since the first edition of this book.

The physics of heat, light, sound and energy is still the same, so there is little change in the first three parts. Apart from the correction of a few errors, a few new developments are mentioned, some new methods are included and statistics updated.

Part 4 has many new elements that reflect societal changes, especially changes in public attitudes. Three years ago there were many who denied global warming or who regarded renewable energy technologies as 'kids' stuff'. Today only a few of these survive. Global warming is recognized as a fact by politicians as well as the general public. As the general public is better informed, politicians are forced to pay at least lip service to sustainability. Some actions have also been taken, albeit rather timidly.

There is significant progress in renewable energy technologies, both at the scientific and at the practical engineering level. Real life projects are multiplying and increasing in size. Numerous large wind farms and solar power stations are already operating and many are being developed. It is most encouraging that private capital started funding large renewable energy projects. There is also a large increase in small scale, 'distributed' power generation. Architects and the building industry started moving in the direction of sustainable practice as well.

What I said in the original 'Introduction' is just as valid now, as it then was, but the importance of having a critical attitude is even greater now than it was 3 years ago. Unfortunately there are many charlatans around, many use the label of 'sustainable' without the substance, some are ignorant or downright fraudulent. Few dare to say to them that the 'emperor has no clothes'.

I can only hope that this book, besides assisting the designer or the student will also contribute to developing such a critical attitude, thus lead to a progressive improvement.

INTRODUCTION

Four chains of thought lead 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, 1991; Farmer, 1999; Roaf, 2001; Smith, 2001; Beggs, 2002). 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 for discussing these issues here.
3 The term 'bioclimatic architecture' has been coined by Victor Olgyay in the early 1950s and fully explained in his book *Design with climate* (1963). He synthesized 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 as an important progenitor of what we now call 'sustainable architecture'.
4 Architecture, as a profession is instrumental 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 this narrow area where this work intends to supplement the existing literature.

The 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 realizing the many good intentions. Many projects in recent times are claimed to constitute sustainable development, to be sustainable architecture. But are they really green or sustainable? Some new terms started appearing in the literature, such as 'green wash' – 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. Rayner Banham (1969) in his *Architecture of the well-tempered environment* postulated that comfortable conditions can be provided by a building (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 realized 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 and 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 as 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**

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. The first part (Heat) is the most substantial, as the thermal behaviour of a building has greatest effect on energy use and sustainability and its design is fully the architect's responsibility.

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

CONTENTS

PART 1 HEAT: THE THERMAL ENVIRONMENT

CONTENTS

SYMBOLS AND ABBREVIATIONS

		Units
asg	alternating solar gain factor	–
b	breadth, thickness	m
clo	unit of clothing insulation	
dTe	sol–air excess temperature (difference)	K
er	evaporation rate	kg/h
f	response factor	–
g	vapour quantity	
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 (specfic 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^2K
h_c	convective surface conductance	W/m^2K
h_r	radiative surface conductance	W/m^2K
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
t	time	h
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^2K
CDD	cooling degree-days	Kd
CoP	coefficient of performance	–
CPZ	control potential zone	
Cd	conduction, conducted heat (from body)	W
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
DEC	solar declination angle	°

		Units
DD	degree-days	Kd
Dh	degree-hours	Kh
DPT	dew-point temperature	°C
DRT	dry resultant temperature	°C
E	radiant heat emission	W
EnvT	environmental temperature	°C
Ev	evaporation heat transfer (from body)	W
ET*	new effective temperature	°C
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
HVAC	Heating, Ventilation and Air Conditioning	–
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
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^2K/W
R_{a-a}	air-to-air resistance	m^2K/W
R_c	cavity resistance	m^2K/W
Rd	radiation, radiated heat (from body)	W
RH	relative humidity	%
R_s	surface resistance	m^2K/W
R_{si}	internal surface resistance	m^2K/W
R_{so}	outside surface resistance	m^2K/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

(*Continued*)

SYMBOLS AND ABBREVIATIONS (Continued)

		Units
T_o	outdoor temperature	°C
T_s	surface temperature	°C
T_{s-a}	sol–air temperature	°C
U	air-to-air (thermal) transmittance	W/m^2K
V	volume	m^3
VSA	vertical shadow angle	°
WBT	wet-bulb temperature	°C
Y	admittance	W/m^2K
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	$\mu g/m^2$ s Pa
ρ	density or reflectance	kg/m^3 or –

		Units
τ	transmittance	
ϕ	time lag	h
σ	stefan–Boltzmann constant	W/m^2K^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~
	d	diffuse~
	r	reflected~
Second	h	horizontal
	v	vertical
	p	on plane p
For G only	n	normal to radiation

LIST OF FIGURES

(*Continued*)

LIST OF FIGURES (Continued)

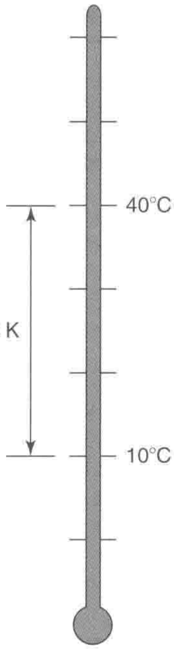
(*Continued*)

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF WORKED EXAMPLES

LIST OF EQUATIONS



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 − 10°C = 30 K, and similarly 65 − 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 1000 m/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 named 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 named 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 named 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 named pascal (**Pa**)

SI unit symbols, derived from personal names, are always capitalized.

EXAMPLE 1.1

Given 0.5 L (=0.5 kg) of water at 20°C in an electric jug with an 800W 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 800W, i.e. 800 J/s, thus the time required is
167 040 J/800 J/s = 208 s ≈ 3.5 min

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 J/kg, e.g. for water:

latent heat of fusion (ice to water) at 0°C = 335 kJ/kg
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). 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:

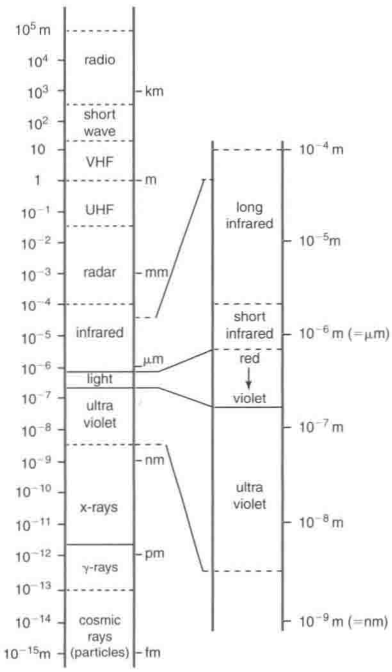
1 as *heat flow rate* (Q), or heat flux, i.e. the total flow in unit time through a defined area of a body or space, or within a defined system, in units of J/s, which is a watt (W) (The most persistent archaic energy flow rate or power unit is the *horsepower*, but in fully metric countries even car 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, for example, 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.)

A non-standard, but accepted and very convenient unit of energy is derived from this heat flux unit: the watt-hour (Wh). This is the amount of energy delivered or expended if a flow rate (flux) of 1 W is maintained for an hour. As 1 h = 3600 s and

$$1\,\text{W} = 1\,\text{J/s}$$
$$1\,\text{Wh} = 3600\,\text{s} \times 1\,\text{J/s} = 3600\,\text{J} \quad \text{or} \quad 3.6\,\text{kJ (kilojoule)}^{1}$$

The multiple kWh (kilowatt-hour) is often used as a practical unit of energy (e.g. in electricity accounts) 1 kWh = 3 600 000 J or 3600 kJ or 3.6 MJ (megajoule).



1.2.
The full electromagnetic spectrum and its solar segment.

Wave-band summary

< 280 nm	UV 'C'
280–315	UV 'B'
315–380	UV 'A'
380–780	light
Overlap with thermal:	
700–2300	short IR
2300–10 000	long IR

1.1.2 Heat flow

As water flows from a higher to a lower position, so heat flows from a higher temperature zone (or body) to a lower temperature one. Such heat flow can take place in three forms:

1. *Conduction* within a body or bodies in contact, by the 'spread' of molecular movement.
2. *Convection* from a solid body to a fluid (liquid or gas) or vice versa (in a broader sense it is also used to mean the transport of heat from one surface to another by a moving fluid, which, strictly speaking, is 'mass transfer'). The magnitude of convection heat flow rate depends on
   - **a** area of contact (A, m^2) between the body and the fluid
   - **b** the difference in temperature (ΔT, in K) between the surface of the body and the fluid
   - **c** a convection coefficient (h_c) measured in W/m^2K, which depends on the viscosity of the fluid and its flow velocity as well as on the physical configuration that will determine whether the flow is laminar or turbulent (see Section 1.1.2.2 below).
3. *Radiation* from a body with a warmer surface to another which is cooler. Thermal radiation is a wavelength band of electromagnetic radiation, normally taken as 700–10 000 nm[2] 10 μm)[3]

   'short infrared': 700–2300 nm (2.3 μm) (see note in 1.3.1.2a) and
   'long infrared': 2.3–10 μm (some suggest up to 70 μm)

   The temperature of the emitting body determines the wavelength. The sun with its 6000°C surface emits short infrared (as well as visible and ultraviolet (UV)), bodies at terrestrial temperatures (<100°C) emit long infrared radiation. (Fig. 1.2 shows these bands in relation to the full electromagnetic spectrum).

In all three forms the magnitude of flux (or of flux density) depends on the temperature difference between the points (or surfaces) considered, whilst the flux (heat flow rate) in conduction also depends on the cross-sectional area of the body available.

[1] For all prefixes used with SI units see Table 4.1.
[2] 1 nm (nanometre) = 10^{-9} m
[3] 1 μm (micrometer) = 10^{-6} m