Introduction to Engineering Heat Transfer

This new text integrates fundamental theory with modern computational tools such as EES, MATLAB, and FEHT to equip students with the essential tools for designing and optimizing real-world systems and the skills needed to become effective practicing engineers. Real engineering problems are illustrated and solved in a clear step-by-step manner. Starting from first principles, derivations are tailored to be accessible to undergraduates by separating the formulation and analysis from the solution and exploration steps to encourage a deep and practical understanding. Numerous exercises are provided for homework and self-study and include standard hand calculations as well as more advanced project-focused problems for the practice and application of computational tools. Appendices include reference tables for thermophysical properties, and answers to selected homework problems from the book. Complete with an online package of guidance documents on EES, MATLAB, and FEHT software, sample code, lecture slides, video tutorials, and a test bank and full solutions manual for instructors, this is an ideal text for undergraduate heat transfer courses and a useful guide for practicing engineers.

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"This excellent text on heat transfer continues the tradition of the strong analytical treatment of conduction and convection heat transfer, buttressed by strong EES, FEHT, and MATLAB examples . . . The emphasis on examples is substantial, and the use of the software is tastefully introduced in ways that emphasize the solution instead of the software . . . This edition is well organized, succinctly written, and well supported by software aids. The book is also a valuable reference for those in a wide variety of disciplines desiring to self-learn heat transfer. All the essential elements of a heat transfer course are well represented in this volume."

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Marc Hodes, Tufts University

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Preface

The objective of this book is to provide engineering students with the capability, tools, and confidence to solve real-world heat transfer problems. This objective has resulted in a textbook that differs from existing heat transfer textbooks in an important way. This textbook introduces fundamental heat transfer concepts at an introductory, undergraduate level that is appropriate for a practicing engineer and integrates these concepts with modern computational tools. The text provides extensive examples and problems that utilize these tools. The practicing engineer of today is expected to be proficient with computer tools; engineering education must evolve accordingly. Most real engineering problems cannot be solved using a sequential set of calculations that can be easily carried out with a pencil and a hand calculator. Engineers must have the ability and confidence to utilize the powerful computational tools that are available and essential for design and optimization of real-world systems.

The text reinforces good engineering problem solving technique by delineating the formulation and analysis steps from the solution and exploration steps. In the formulation step, the problem itself is defined and, through appropriate approximations, simplified to the point where it can be represented by a set of mathematical equations. These equations are derived from first principles in the analysis step. Many textbooks stop their presentation at this point. However, the solution step where the equations are solved is equally important. In some cases hand calculations are appropriate for solving the equations. More typically, the complexity of the problem dictates that some type of computational software must be used for the solution step. Each of these steps is essential. It is not possible to move to the solution step until the formulation and analysis steps are complete. Separating these steps forces the student to understand that the computational software cannot be used to "think" for them, but rather provide powerful tools for helping them solve the relevant equations. Computational software is essential for the exploration step in which the engineer carries out parametric, optimization, and design studies that allow a deeper understanding of the problem and provide more useful results. Exploration studies are a natural first step to becoming an effective practicing engineer.

This book integrates the computational software Engineering Equation Solver (EES), MATLAB, and Finite Element Heat Transfer (FEHT) directly with the heat transfer material so that students can see the relevance of these tools. The specific commands and output associated with these software packages are used in the solution and exploration steps of numerous examples so that the integration is seamless and does not detract from the presentation of the heat transfer concepts. The computational software tools used in this book are all common in industry and have existed for more than a decade; therefore, while this software will certainly continue to evolve, it is not likely to disappear. Educational versions of these software packages are available and therefore the use of these tools should not represent an economic hardship to any academic institution or student. These tools are easy to learn and use, allowing students to become proficient with all of them in a reasonable amount of time. Therefore, learning the computer tools will not detract from material coverage. In fact, providing the capability to easily solve the equations developed in the analysis is a motivator to many students. To facilitate this learning process, tutorials for each of the software packages are provided as appendices in this book.

Traditionally, tables and charts have been required to solve heat transfer problems in order to, for example, determine properties, view factors, shape factors, convection relations, and related information. Limited versions of these tables and graphs are provided in the textbook; however, much more extensive libraries have been made available as functions and procedures in the EES software so that they can be easily accessed and used to solve problems. The Heat Transfer Library that has been developed and integrated with EES as part of the preparation of this textbook and the more advanced textbook, *Heat Transfer*, enables a profound shift in the focus of the educational process. It is trivial to obtain, for example, the value of a shape factor or a view factor using the Heat Transfer Library. Therefore, it is possible to assign problems involving design and optimization studies that would be computationally impossible without these computer tools.

Integrating the study of heat transfer with computer tools does not diminish the depth of understanding of the underlying physics that students obtain. Conversely, our experience indicates that the innate understanding of the subject matter is enhanced by appropriate use of these tools for several reasons. First, the software allows the student to tackle practical and relevant problems as opposed to the comparatively simple problems that must otherwise be assigned. Real-world engineering problems are more satisfying to the student. Therefore, the marriage of computer tools with theory motivates students to understand the governing physics as well as to learn how to apply the computer tools. When a solution is obtained, students can carry out a more extensive investigation of its behavior and therefore a more intuitive and complete understanding of the subject of heat transfer. Along with the typical homework problems, each chapter includes several project type problems that allow a guided exploration of advanced topics using computer tools. Real-world problems often require a combination of English and SI units. The EES software provides unit checking that should prevent the student (and practicing) engineer from making unit conversion errors. Therefore, the examples and problems in this book use mixed units.

This book is unusual in its linking of classical theory and modern computing tools. It fills an obvious void that we have encountered in teaching undergraduate heat transfer. The text was developed over many years from our experiences teaching Introduction to Heat Transfer (an undergraduate course) at the University of Wisconsin. It is our hope that this text will not only be useful during the heat transfer course, but also a life-long resource for practicing engineers.

Sample Program of Study

A sample program of study is laid out below for a one-semester undergraduate course. The format assumes that there are 45 lectures within a 15-week semester.

Lecture	*Sections in book*	*Topics*
1	Chapter 1	Introduction
2	2.1–2.2.2	Fourier's Law, 1-D steady-state conduction
3	2.2.3–2.2.5	Resistance concepts and circuits
4	2.3	1-D steady-state with generation
5	2.4	Numerical solutions
6	3.1–3.2	Extended surface approximation and analytical solution
7	3.3	Fin behavior, fin efficiency, and finned surfaces
8	3.4	Numerical solution to extended surface problems
9	4.1–4.2	2-D steady-state conduction, shape factors
10	4.3.1–4.3.3	Finite difference solutions with EES
11	4.3.4–4.3.5	Finite difference solutions using matrix decomposition and Gauss–Seidel iteration
12	4.4	Finite element solutions
13	5.1–5.2	Lumped capacitance approximation and analytical solution
14	5.3	Numerical solution to lumped capacitance problems
15	6.1	1-D transient conduction concepts
16	6.2	Analytical solutions to 1-D transient problems
17	6.3	Numerical solutions to 1-D transient problems
18	6.4.3	Finite element solution to 2-D transient problems
19	7.1–7.2	Laminar and turbulent boundary layer concepts
20	7.3–7.4	The boundary layer equations and dimensional analysis
21	8.1–8.2	External flow correlations and flow over a flat plate
22	8.3–8.5	Flow over extrusions and spheres
23	9.1.1	Internal flow hydrodynamic concepts
24	9.1.2	Internal flow thermal concepts
25	9.2	Internal flow correlations
26	9.3	The energy balance for an internal flow
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Nomenclature

A	area (m^2)
$\underline{\underline{A}}$	the coefficient matrix in a system of linear equations
A_c	cross-sectional area (m^2)
A_p	projected area (m^2)
A_s	surface area (m^2)
$A_{s,fin}$	surface area of a single fin exposed to fluid (m^2)
$A_{s,fins}$	surface area of all of the fins on a finned surface (m^2)
$A_{s,prime}$	surface area of the base of a finned surface that is exposed to fluid (m^2)
$A_{s,total}$	total surface area of fins and base exposed to fluid (m^2)
AR	aspect ratio of a rectangular duct, defined as the ratio of the minimum to the maximum dimensions of the cross-section
AR_{tip}	tip to perimeter surface area ratio for a fin (-)
$\underline{b}$	the constant vector in a system of linear equations
Bi	Biot number (-)
Bo	boiling number (-)
c	specific heat capacity (J/kg-K) speed of light (299,792,000 m/s)
c_v	specific heat capacity at constant volume (J/kg-K)
c_p	specific heat capacity at constant pressure (J/kg-K)
C	thermal capacitance (J/K)
$\dot{C}$	capacitance rate (W/K)
C_1, C_2	undetermined constant of integration (varies)
C_{crit}	critical heat flux constant (-)
C_D	drag coefficient (-)
C_f	local friction coefficient (-)
$\bar{C}_f$	average friction coefficient (-)
C_i	the ith constant in a separation of variables solution (-)
C_{ms}	heat capacity of microscale energy carrier (J/K)
C_N	correction factor for number of tubes in a tube bank (-)
C_{nb}	nucleate boiling constant (-)
C_R	capacitance ratio (-)
Co	convection number (-)
COP	coefficient of performance (-)
D	diameter (m)
D_h	hydraulic diameter (m)
dx	differential distance in the x-direction (m)
e	specific energy (J/kg) surface roughness (m)
E_b	blackbody emissive power (W/m^2)
$E_{b,0-\lambda_1}$	blackbody emissive power for $\lambda < \lambda_1$(W/m^2)
$E_{b,\lambda}$	blackbody spectral emissive power (W/m^2-μm)
ed	energy density (J/kg)
err	iteration error (varies)
f	Moody (or Darcy) friction factor (-)
$F_{0-\lambda_1}$	fraction of blackbody radiation emitted at $\lambda < \lambda_1$ (-)
$F_{i,j}$	view factor from surface i to surface j (-)
$F_{\lambda_1-\lambda_2}$	fraction of blackbody radiation emitted at $\lambda_1 < \lambda < \lambda_2$ (-)
f_l	friction factor associated with the flow of liquid alone (-)
$\bar{f}$	average Moody friction factor (-)
$f_{Fanning}$	Fanning friction factor (-)
fpl	number of fins per length (1/m)
Ec	Eckert number (-)
F_D	drag force (N)
Fo	Fourier number (-)
Fr	Froude number (-)
Fr_{mod}	modified Froude number (-)
g	gravitational acceleration (m/s^2)
G	mass velocity, also known as mass flux (kg/m^2-s)
$\dot{g}$	rate of thermal energy generation (W)

$\dot{g}'''$	rate of thermal energy generation per unit volume (W/m^3)
Ga	Galileo number (-)
Gr	Grashof number (-)
Gz	Graetz number (-)
h	local heat transfer coefficient (W/m^2-K)
$\bar{h}$	average heat transfer coefficient (W/m^2-K)
$\tilde{h}$	dimensionless heat transfer coefficient for flow boiling (-)
h_l	superficial heat transfer coefficient of the liquid phase (W/m^2-K)
$\bar{h}_{eff}$	effective heat transfer coefficient (W/m^2-K)
$\bar{h}_{rad}$	radiation heat transfer coefficient (W/m^2-K)
i	specific enthalpy (J/kg) integer index for spatial location (in numerical problems)
j	integer index for time (in numerical problems)
j_H	Colburn j_H factor (-)
I_c	current (ampere)
IN	amount or rate of some arbitrary quantity entering a system
k	thermal conductivity (W/m-K)
k_c	contraction loss coefficient (-)
k_e	expansion loss coefficient (-)
Kn	Knudsen number (-)
L	length (m)
L_c	corrected length for fin calculation (m)
L_{char}	characteristic length (m)
L_{cond}	conduction length (m)
L_{flow}	length in the flow direction (m)
L_{ms}	average distance between energy carrier interactions (m)
L_{nb}	nucleate boiling length scale (m)
$\dot{m}$	mass flow rate (kg/s)
m	mass (kg)
M	total number of nodes used (in numerical problems)
mL	fin constant (-)
MW	molecular weight (kg/kmol)
N	total number of time steps used (in numerical problems) intermediate dimensionless parameter for flow boiling correlation (-)
n_{ms}	number density of microscale energy carriers (#/m^3)
N_L	number of rows of tubes in the longitudinal direction in a tube bank
Nu	local Nusselt number (-)
Nu_x	local Nusselt number based on the characteristic length x (-)
$\overline{Nu}$	average Nusselt number (-)
NTU	number of transfer units (-)
OUT	amount or rate of some arbitrary quantity leaving a system
p	pressure (Pa)
P	$LMTD$ effectiveness (-)
$\tilde{p}$	dimensionless pressure (-)
p_{atm}	atmospheric pressure (Pa)
p_∞	free stream pressure (Pa)
per	wetted perimeter (m)
per_h	perimeter exposed to heating (m)
Pr	Prandtl number (-)
$\dot{q}$	heat transfer rate (W)
$\dot{q}_{cond}$	heat transfer rate due to conduction (W)
$\dot{q}_{conv}$	heat transfer rate due to convection (W)
$\dot{q}_{fin}$	heat transfer rate to a fin (W)
$\dot{q}_{fin,k\to\infty}$	heat transfer rate to a fin with $k\to\infty$ (W)
$\dot{q}_{no\,fin}$	heat transfer rate that would occur from a surface if fin was removed (W)
$\dot{q}_{rad}$	heat transfer rate due to radiation (W)
$\dot{q}_r$	heat transfer rate in the r-direction (W)
$\dot{q}_x$, $\dot{q}_y$, $\dot{q}_z$	heat transfer rate in the x-, y-, and z-directions (W)
$\dot{q}''$	heat transfer rate per unit area, heat flux (W/m^2)
$\dot{q}''_{conv}$	heat flux due to convection (W/m^2)

$\dot{q}''_{rad}$	heat flux due to radiation (W/m^2)
$\dot{q}''_x$, $\dot{q}''_y$, $\dot{q}''_z$	heat flux in the *x*-, *y*-, and *z*-directions (W/m^2)
$\dot{q}''_s$	surface heat flux (W/m^2)
$\dot{q}''_{s,crit}$	critical heat flux (W/m^2)
$\dot{q}''_{s,nb}$	nucleate boiling heat flux (W/m^2)
Q	total amount of heat transfer (J)
$\tilde{Q}$	dimensionless heat transfer (-)
r	radial coordinate, radius (m)
$\tilde{r}$	dimensionless radial coordinate (-)
R	thermal resistance (K/W)
	gas constant (J/kg-K)
	LMTD capacitance ratio (-)
R_c	contact thermal resistance (K/W)
R_{cond}	thermal resistance to conduction (K/W)
$R_{cond,int}$	thermal resistance to internal conduction within an object (K/W)
$R_{cond,x}$	thermal resistance to conduction in the *x*-direction (K/W)
$R_{cond,y}$	thermal resistance to conduction in the *y*-direction (K/W)
R_{conv}	thermal resistance to convection (K/W)
R_{cyl}	thermal resistance associated with radial conduction through a cylindrical shell (K/W)
R_e	electrical resistance (ohm)
R_f	fouling resistance (K/W)
R_{fin}	thermal resistance of a single fin (K/W)
R_{fins}	thermal resistance of all of the fins on a finned surface (K/W)
R''_f	fouling factor ($K\text{-}m^2/W$)
$R_{i,j}$	space resistance between surfaces *i* and *j* in a radiation problem ($1/m^2$)
R_{pw}	thermal resistance to conduction through a plane wall (K/W)
R_{rad}	thermal resistance associated with radiation (K/W)
R_s	surface resistance in a radiation problem ($1/m^2$)
R_{SF}	shape factor thermal resistance (K/W)
R_{sph}	thermal resistance associated with radial conduction through a spherical shell (K/W)
$R_{surface\text{-}to\text{-}surroundings}$	thermal resistance between the surface of an object and its surroundings (K/W)
R_{total}	total resistance of a finned surface (K/W)
R_{univ}	universal gas constant (8314 J/kmol-K)
R''_c	area-specific contact resistance ($K\text{-}m^2/W$)
Ra	Rayleigh number (-)
Re	Reynolds number (-)
Re_{δ_m}	Reynolds number based on the momentum boundary layer thickness (-)
Re_x	Reynolds number based on the characteristic length *x* (-)
RR	radius ratio, ratio of inner to outer radius of an annular duct (-)
s	a coordinate direction (m)
S	shape factor (m)
	spacing between plates (m)
S_L	tube pitch in the longitudinal direction in a bank of tubes (m)
S_T	tube pitch in the transverse direction in a bank of tubes (m)
St	Stanton number (-)
$STORED$	amount or rate of some arbitrary quantity being stored in a system
t	time (s)
t_j	time at the *j*th time in a numerical solution (s)
t_{sim}	simulation time (s)
T	temperature (K)
$\bar{T}$	average temperature (K)
T_f	film temperature (K)
T_h	solution to a homogeneous differential equation (K)
T_i	temperature of the *i*th node in a numerical solution (K)
T_j	temperature at the *j*th time in a numerical solution (K)

$T_{i,j}$	temperature of the ith node and jth time in a numerical solution (K)
$\hat{T}_i$	an intermediate estimate of the temperature of the ith node in a numerical solution (K)
$\hat{T}_j$	an intermediate estimate of the temperature at the jth time in a numerical solution (K)
T_{ini}	initial temperature (K)
T_p	solution to a particular differential equation (K)
T_{ref}	reference temperature (K)
T_s	surface temperature (K)
T_{sur}	surrounding temperature (K)
T_∞	free stream temperature (K)
th	thickness (m)
$time$	time duration (s)
tol	tolerance (K)
u	velocity in the x-direction (m/s) specific internal energy (J/kg)
UA	conductance (W/K)
u_{char}	characteristic velocity (m/s)
u_f	fluid approach velocity for an external flow (m/s)
u_m	mean velocity (m/s)
u_{max}	maximum velocity (m/s)
u_∞	free stream velocity (m/s)
$\tilde{u}$	dimensionless velocity in the x-direction (-)
U	total internal energy (J)
v	velocity in the y-direction (m/s) velocity in the r-direction (m/s)
v_{ms}	average velocity of microscale energy carriers (m/s)
$\tilde{v}$	dimensionless velocity in the y-direction (-)
V	volume (m^3)
$\dot{V}$	volumetric flow rate (m^3/s)
$\dot{V}_{oc}$	open circuit flow rate produced by a pump with no resistance (m^3/s)
$\dot{w}$	work transfer rate, power (W)
W	total amount of work (J) width (m)
x	x-coordinate (m) direction parallel to a surface and in the flow direction for convection problems (m) thermodynamic quality (-)
$x_{fd,h}$	hydrodynamic entry length (m)
x_i	x-location of the ith node in a numerical solution (m)
$\tilde{x}$	dimensionless x-coordinate (-)
$\underline{X}$	the vector of unknown temperatures in a system of linear equations (K)
X_{tt}	Lockhart Martinelli parameter (-)
y	y-coordinate (m) direction perpendicular to a surface for convection problems (m)
$\tilde{y}$	dimensionless y-coordinate (-)
z	z-coordinate (m)

Greek Symbols

α	absorption coefficient (1/m) thermal diffusivity (m^2/s) ratio of gas side surface area to volume (1/m)
β	volumetric thermal expansion coefficient (1/K)
χ	correction factor for pressure drop in tube bank (-)
δ	boundary layer thickness (m)
δ_m	momentum boundary layer thickness (m)
δ_t	thermal penetration depth (m) thermal boundary layer thickness (m)
δ_{vs}	viscous sublayer thickness (m)
Δi_{vap}	latent heat of vaporization (J/kg)
Δp	pressure drop (Pa)
Δp_{dh}	dead head pressure rise produced by a pump with no flow (Pa)
Δp_{pump}	pressure rise generated by a pump (Pa)
Δt	duration of time step (s)
Δt_{crit}	duration of critical time step (s)
ΔT	temperature difference (K)

ΔT_{cond}	temperature difference due to conduction (K)
$\Delta T_{cond,x}$	temperature difference due to conduction in x-direction (K)
$\Delta T_{cond,y}$	temperature difference due to conduction in the y-direction (K)
ΔT_{conv}	temperature difference due to convection (K)
ΔT_e	excess temperature, surface minus saturation temperature (K)
ΔT_{lm}	log mean temperature difference (K)
Δx	distance between nodes in the x-direction (m)
Δy	distance between nodes in the y-direction (m)
ε	emissivity (-) effectiveness (-)
ε_{fin}	fin effectiveness (-)
ϕ	viscous dissipation function (W/m^3)
η	efficiency (-)
η_{fin}	fin efficiency (-)
η_o	overall efficiency of a finned surface (-)
κ	Von Kármán constant, 0.41 (-)
λ	wavelength (μm)
μ	dynamic viscosity (N-s/m^2)
θ	temperature difference (K)
$\tilde{\theta}$	dimensionless temperature difference (-)
ρ	density (kg/m^3)
ρ_e	electrical resistivity (Ω-m)
σ	Stefan–Boltzmann constant (5.67×10^{-8} W/m^2-K^4) surface tension (N/m) ratio of free flow to frontal area (-)
τ	shear stress (Pa)
τ_s	shear stress at a surface (Pa)
$\overline{\tau_s}$	average shear stress on surface (Pa)
τ_{xx}	viscous stress on the x-face of a control volume in the x-direction (Pa)
τ_{xy}	viscous stress on the x-face of a control volume in the y-direction (Pa)
τ_{yx}	viscous stress on the y-face of a control volume in the x-direction (Pa)
τ_{yy}	viscous stress on the y-face of a control volume in the y-direction (Pa)
τ_{diff}	diffusive time constant (s)
τ_{lumped}	lumped capacitance time constant (s)
υ	kinematic viscosity (m^2/s) frequency (Hz)
ζ	angle relative to horizontal (radian)
ζ_1	the 1st eigenvalue in a separation of variables solution (-)
ζ_i	the ith eigenvalue in a separation of variables solution (-)

Subscripts

b	base
c	contact, corrected
C	cold
$cond$	conduction
$conv$	convection
$crit$	critical time step where simulation becomes unstable critical Reynolds number for laminar-to-turbulent transition
cyl	cylinder
$diff$	diffusive
fc	forced convection
fd	fully developed
fin	fin
h	homogeneous
H	hot solution for constant heat flux boundary condition
in	entering a system, inner (e.g., diameter or radius)
ini	initial, at time $t = 0$
int	internal, within an object
is	inner surface
l,sat	saturated liquid
lam	laminar
max	maximum possible amount
nc	natural convection
p	particular
pw	plane wall

o	overall
os	outer surface
out	leaving a system, outer (e.g., diameter or radius)
rad	radiation
s	at the surface
semi-∞	related to the semi-infinite body solution
SF	shape factor
sph	sphere
surface-to-surroundings	from the surface of an object to the surroundings
T	solution for constant temperature boundary condition
total	total resistance
turb	turbulent
uh	unheated
v,sat	saturated vapor
vs	viscous sublayer
x	in the *x*-direction
y	in the *y*-direction

Superscripts and Abbreviations (Where *a* and *b* are Arbitrary Quantities)

a'	per unit length
a''	per unit area
a'''	per unit volume
$\bar{a}$	average value of a
$\hat{a}$	prediction of a obtained during a predictor step
$\tilde{a}$	dimensionless form of the variable a
a_i	the value of a at node i
a_j	the value of a at time j
$a_{i,j}$	the value of a at node i and time j
a^k	the value of a for iteration k
$a_{x=x_1}$	the value of a evaluated at the x-location x_1
$a(x)$	a is a function only of x
$\frac{da}{dx}$	the ordinary derivative of a with respect to x (a is only a function of x)
$\left.\frac{da}{dx}\right\|_{x=x_1}$	the ordinary derivative of a with respect to x evaluated at x-location x_1
$\frac{\partial a}{\partial x}$	the partial derivative of a with respect to x (a is a function of variables other than x)
$\underline{a}$	a one-dimensional vector of values
$\underline{\underline{a}}$	a two-dimensional matrix of values
$\underline{\underline{a}}^{-1}$	the inverse of $\underline{\underline{a}}$, a two-dimensional matrix of values
$\text{Max}\,(a_i)\; i = 1 \ldots M$	the maximum value of the elements of vector a with indices i = 1 to M
$\text{Min}\,(a_i)\; i = 1 \ldots M$	the minimum value of the elements of vector a with indices i = 1 to M
$\sum_{i=1}^{M} a_i$	the sum of the elements in vector a with indices i = 1 to M
$a\|\|b$	quantity a in parallel with quantity b, shorthand for $\left(\frac{1}{a}+\frac{1}{b}\right)^{-1}$
$O(a)$	order of magnitude of the quantity a