## Critical Phenomena in Natural Sciences

Chaos, Fractals,
Selforganization and Disorder:
Concepts and Tools

Second Edition
With 102 Figures



## Contents

1.	Usef	ful Noti	ions of Probability Theory	1				
	1.1	What	Is Probability?	1				
		1.1.1	First Intuitive Notions	1				
		1.1.2	Objective Versus Subjective Probability	2				
	1.2	Bayesi	an View Point	6				
		1.2.1	Introduction	6				
		1.2.2	Bayes' Theorem	7				
		1.2.3	Bayesian Explanation for Change of Belief	9				
		1.2.4	Bayesian Probability and the Dutch Book	10				
	1.3	Probal	bility Density Function	12				
	1.4	Measu	res of Central Tendency	13				
	1.5	Measu	re of Variations from Central Tendency	14				
	1.6	Momen	nts and Characteristic Function	15				
	1.7	Cumul	lants	16				
	1.8	Maxim	num of Random Variables and Extreme Value Theory.	18				
		1.8.1	Maximum Value Among $N$ Random Variables	19				
		1.8.2	Stable Extreme Value Distributions	23				
		1.8.3	First Heuristic Derivation					
			of the Stable Gumbel Distribution	25				
		1.8.4	Second Heuristic Derivation					
			of the Stable Gumbel Distribution	26				
		1.8.5	Practical Use and Expression of the Coefficients					
			of the Gumbel Distribution	28				
		1.8.6	The Gnedenko-Pickands-Balkema-de Haan Theo-					
			rem					
			and the pdf of Peaks-Over-Threshold	29				
2.	Sums of Random Variables, Random Walks							
	and the Central Limit Theorem							
	2.1	The R	andom Walk Problem	33				
		2.1.1	Average Drift	34				
		2.1.2	Diffusion Law	35				
		2.1.3	Brownian Motion as Solution of a Stochastic ODE .	35				
		2.1.4	Fractal Structure	37				

		2.1.5	Self-Affinity	39
	2.2	Master	and Diffusion (Fokker-Planck) Equations	41
		2.2.1	Simple Formulation	41
		2.2.2	General Fokker-Planck Equation	43
		2.2.3	Ito Versus Stratonovich	44
		2.2.4	Extracting Model Equations from Experimental Data	47
	2.3	The Ce	entral Limit Theorem	48
		2.3.1	Convolution	48
		2.3.2	Statement	50
		2.3.3	Conditions	50
		2.3.4	Collective Phenomenon	51
		2.3.5	Renormalization Group Derivation	52
		2.3.6	Recursion Relation and Perturbative Analysis	55
3.	Large	e Devia	itions	59
	3.1		ant Expansion	59
	3.2		Deviation Theorem	60
		3.2.1	Quantification of the Deviation	
			from the Central Limit Theorem	61
		3.2.2	Heuristic Derivation	
	,		of the Large Deviation Theorem (3.9)	61
	ĺ	3.2.3	Example: the Binomial Law	63
		3.2.4	Non-identically Distributed Random Variables	64
	3.3	Large I	Deviations with Constraints	
		and the	Boltzmann Formalism	66
		3.3.1	Frequencies Conditioned by Large Deviations	66
		3.3.2	Partition Function Formalism	68
		3.3.3	Large Deviations in the Dice Game	70
		3.3.4	Model Construction from Large Deviations	73
		3.3.5	Large Deviations in the Gutenberg–Richter Law	
			and the Gamma Law	76
	3.4	Extrem	e Deviations	78
		3.4.1	The "Democratic" Result	78
		3.4.2	Application to the Multiplication	
			of Random Variables:	
			a Mechanism for Stretched Exponentials	80
		3.4.3	Application to Turbulence and to Fragmentation	83
	3.5	_	Deviations in the Sum of Variables	
		with Po	ower Law Distributions	87
		3.5.1	General Case with Exponent $\mu > 2$	87
		3.5.2	Borderline Case with Exponent $\mu = 2 \dots$	90

4.	Pow	er Law	Distributions	93
	4.1	Stable	Laws: Gaussian and Lévy Laws	93
		4.1.1		93
		4.1.2	The Gaussian Probability Density Function	93
		4.1.3	The Log-Normal Law	94
		4.1.4	The Lévy Laws	96
		4.1.5	Truncated Lévy Laws	
	4.2		Laws	
		4.2.1	How Does One Tame "Wild" Distributions? 1	
		4.2.2	Multifractal Approach	
	4.3	Anom	alous Diffusion of Contaminants	
	1.0		Earth's Crust and the Atmosphere	12
		4.3.1	General Intuitive Derivation	
		4.3.2	More Detailed Model of Tracer Diffusion in the Crust1	
		4.3.3	Anomalous Diffusion in a Fluid	
	4.4		ve Calculation Tools	.10
	4.4		wer Law Distributions	16
	4.5		Inction, Mittag-Leffler Function	.10
	4.0		évy Distributions	1 2
		and L	avy Distributions	.10
5.	Frac	tals an	d Multifractals1	.23
	5.1		ls	
		5.1.1	Introduction	
		5.1.2	A First Canonical Example: the Triadic Cantor Set . 1	
		5.1.3	How Long Is the Coast of Britain?	
		5.1.4	The Hausdorff Dimension	
		5.1.5	Examples of Natural Fractals	
	5.2		ractals	
	0.2	5.2.1	Definition	
		5.2.1	Correction Method for Finite Size Effects	
		0.2.2	and Irregular Geometries	//3
		5.2.3	Origin of Multifractality and Some Exact Results 1	
		5.2.4	C 1	. 40
		0.2.4	Generalization of Multifractality: Infinitely Divisible Cascades	46
	5.3	Scolo	Infinitely Divisible Cascades	
	0.0	5.3.1	Definition	
		5.3.1 $5.3.2$	Relation with Dimensional Analysis	
	E 1	• • • • • •	fultifractal Random Walk	
	5.4			
		5.4.1	A First Step: the Fractional Brownian Motion 1	.მა
		5.4.2	Definition and Properties	- 4
		<b>a</b>	of the Multifractal Random Walk	.54
	5.5	_	lex Fractal Dimensions	F 2
			iscrete Scale Invariance	
		5.5.1	Definition of Discrete Scale Invariance	
		5.5.2	Log-Periodicity and Complex Exponents	ι <b>5</b> 7

		5.5.3	Importance and Usefulness				
			of Discrete Scale Invariance				
		5.5.4	Scenarii Leading to Discrete Scale Invariance 160				
6.	Ran		ring Statistics and Heavy Tails 163				
	6.1		bility Distributions				
	6.2		tion of Rank Ordering Statistics				
	6.3		al and Log-Normal Distributions				
	6.4	The E	xponential Distribution				
	6.5	Power	Law Distributions				
		6.5.1	Maximum Likelihood Estimation 170				
		6.5.2	Quantiles of Large Events				
		6.5.3	Power Laws with a Global Constraint:				
			"Fractal Plate Tectonics"				
	6.6		amma Law				
	6.7	The S	tretched Exponential Distribution				
	6.8	Maxin	num Likelihood and Other Estimators				
		of Stre	etched Exponential Distributions				
		6.8.1	Introduction				
		6.8.2	Two-Parameter Stretched Exponential Distribution 185				
		6.8.3	Three-Parameter Weibull Distribution 194				
		6.8.4	Generalized Weibull Distributions				
7.	Statistical Mechanics: Probabilistic Point of View						
	and		oncept of "Temperature" 199				
	7.1		tical Derivation of the Concept of Temperature 200				
	7.2	Statistical Thermodynamics					
	7.3		Statistical Mechanics as Probability Theory				
		with C	Constraints				
		7.3.1	General Formulation				
		7.3.2	First Law of Thermodynamics 206				
		7.3.3	Thermodynamic Potentials 207				
	7.4	Does t	the Concept of Temperature Apply				
			n-thermal Systems?				
		7.4.1	Formulation of the Problem 208				
		7.4.2	A General Modeling Strategy 210				
		7.4.3	Discriminating Tests				
		7.4.4	Stationary Distribution with External Noise 213				
		7.4.5	Effective Temperature Generated				
			by Chaotic Dynamics				
		7.4.6	Principle of Least Action				
			for Out-Of-Equilibrium Systems				
		717	Superetatistics 210				

8.	Long		Correlations			
	8.1	Criterio	on for the Relevance of Correlations	223		
	8.2	Statistic	cal Interpretation	226		
	8.3	<u>-</u>				
		with Ra	andom Velocities	228		
	8.4	Advanc	ed Results on Correlations	229		
		8.4.1	Correlation and Dependence	229		
		8.4.2	Statistical Time Reversal Symmetry	231		
		8.4.3	Fractional Derivation and Long-Time Correlations $$ .			
9.	Phas	e Trans	sitions: Critical Phenomena			
			rder Transitions	241		
	9.1	Definiti	on	241		
	9.2		odels at Their Critical Points			
		9.2.1	Definition of the Spin Model			
		9.2.2	Critical Behavior			
		9.2.3	Long-Range Correlations of Spin Models			
			at their Critical Points	246		
	9.3	First-O	rder Versus Critical Transitions			
		9.3.1	Definition and Basic Properties			
		9.3.2	Dynamical Landau-Ginzburg Formulation			
		9.3.3	The Scaling Hypothesis: Dynamical Length Scales			
			for Ordering	253		
10.	Transitions, Bifurcations and Precursors					
	10.1	"Supero	critical" Bifurcation	256		
	10.2		Precursory Fluctuations			
	10.3		tical" Bifurcation			
	10.4		and Precursors Near Spinodals			
	10.5		on of an Attractor in the Absence			
			tential	265		
11.	The	Renorn	nalization Group	267		
	11.1		l Framework			
	11.2		blicit Example: Spins on a Hierarchical Network			
		11.2.1	Renormalization Group Calculation			
		11.2.2	Fixed Points, Stable Phases and Critical Points			
		11.2.3	Singularities and Critical Exponents			
		11.2.4	Complex Exponents			
			and Log-Periodic Corrections to Scaling	276		
		11.2.5	"Weierstrass-Type Functions"			
			from Discrete Renormalization Group Equations	279		
	11.3	Critical	lity and the Renormalization Group			
			lidean Systems	283		

	11.4	A Nove	el Application to the Construction	
			ctional Approximants	287
		11.4.1	General Concepts	
		11.4.2	Self-Similar Approximants	
	11.5	Toward	ls a Hierarchical View of the World	
12.	The	Percola	ation Model	293
	12.1		tion as a Model of Cracking	
	12.2	Effectiv	ve Medium Theory and Percolation	296
	12.3		nalization Group Approach to Percolation	
			neralizations	
		12.3.1	Cell-to-Site Transformation	299
		12.3.2	A Word of Caution	
			on Real Space Renormalization Group Techniques :	301
		12.3.3	The Percolation Model	
			on the Hierarchical Diamond Lattice	
	12.4	Directe	d Percolation	
		12.4.1	Definitions	
		12.4.2	Universality Class	306
		12.4.3	Field Theory: Stochastic Partial Differential Equa-	
			tion	
			with Multiplicative Noise	308
		12.4.4	Self-Organized Formulation of Directed Percolation	
			and Scaling Laws	309
13.	Runi	ture Ma	odels	313
-0.	13.1		anching Model	
	10.1	13.1.1	Mean Field Version or Branching	911
		10.1.1	on the Bethe Lattice	314
		13.1.2	A Branching-Aggregation Model	
		10.1.2	Automatically Functioning at Its Critical Point	316
		13.1.3	Generalization of Critical Branching Models	
	13.2		Bundle Models and the Effects	
			ss Redistribution	318
		13.2.1	One-Dimensional System	
		•	of Fibers Associated in Series	318
		13.2.2	Democratic Fiber Bundle Model (Daniels, 1945)	
	13.3	Hierard	chical Model	
		13.3.1	The Simplest Hierarchical Model of Rupture	
		13.3.2	Quasi-Static Hierarchical Fiber Rupture Model	
		13.3.3	Hierarchical Fiber Rupture Model	
			<del>_</del>	328
	13.4	Quasi-S		330
	13.5	-	amical Model of Rupture Without Elasto-Dynamics:	
			hermal Fuse Model"	335

	13.6	Time-to	-Failure and Rupture Criticality				
		13.6.1	Critical Time-to-Failure Analysis	339			
		13.6.2	Time-to-Failure Behavior				
			in the Dieterich Friction Law	343			
14.	Mech	anisms	for Power Laws	345			
	14.1	Tempor	al Copernican Principle				
		and $\mu =$	= 1 Universal Distribution of Residual Lifetimes	346			
	14.2	Change	of Variable	348			
		14.2.1	Power Law Change of Variable Close to the Origin .	348			
		14.2.2	Combination of Exponentials	354			
	14.3	Maximi	zation of the Generalized Tsallis Entropy	356			
	14.4	Superpo	osition of Distributions	359			
		14.4.1	Power Law Distribution of Widths	359			
		14.4.2	Sum of Stretched Exponentials (Chap. 3)	362			
		14.4.3	Double Pareto Distribution by Superposition				
			of Log-Normal pdf's	362			
	14.5	Randon	Walks: Distribution of Return Times to the Origin.	363			
		14.5.1	Derivation	364			
		14.5.2	Applications	365			
	14.6	Sweepir	ng of a Control Parameter Towards an Instability	367			
	14.7	Growth	with Preferential Attachment	370			
	14.8	Multipl	icative Noise with Constraints	373			
		14.8.1	Definition of the Process	373			
		14.8.2	The Kesten Multiplicative Stochastic Process $\ldots\ldots$	374			
		14.8.3	Random Walk Analogy				
		14.8.4	Exact Derivation, Generalization and Applications				
	14.9		oherent-Noise" Mechanism	381			
	14.10		ches in Hysteretic Loops and First-Order Transitions				
			andomness				
	14.11		Optimized Tolerant" (HOT) Systems	389			
		14.11.1	Mechanism for the Power Law Distribution of Fire				
			Sizes	390			
		14.11.2	"Constrained Optimization with Limited Deviations"				
			(COLD)				
		14.11.3	HOT versus Percolation	393			
<b>15.</b>	Self-0	Self-Organized Criticality					
	15.1	What I	s Self-Organized Criticality?				
		15.1.1	Introduction				
		15.1.2	Definition				
	15.2	_	e Models				
		15.2.1	Generalities				
		15.2.2	The Abelian Sandpile				
	15.2	Throch	old Dymamics	409			

## XXII Contents

		15.3.1	Generalization	. 402
		15.3.2	Illustration of Self-Organized Criticality	
			Within the Earth's Crust	. 404
	15.4	Scenari	ios for Self-Organized Criticality	. 406
		15.4.1	Generalities	. 406
		15.4.2	Nonlinear Feedback of the "Order Parameter"	
			onto the "Control Parameter"	. 407
		15.4.3	Generic Scale Invariance	. 409
	}	15.4.4	Mapping onto a Critical Point	. 414
		15.4.5	Mapping to Contact Processes	. 422
		15.4.6	Critical Desynchronization	
		15.4.7	Extremal Dynamics	. 427
		15.4.8	Dynamical System Theory of Self-Organized Criti-	
			cality	. 435
	15.5	Tests o	of Self-Organized Criticality in Complex Systems:	
		the Ex	ample of the Earth's Crust	. 438
16.	Intro	ductio	n to the Physics of Random Systems	. 441
	16.1		dities	
	16.2		andom Energy Model	
	16.3		elf-Averaging Properties	
		16.3.1		
		16.3.2		
17.	Rand	domnes	s and Long-Range Laplacian Interactions	. 457
	17.1		Distributions from Random Distributions of Sources	
			ong-Range Interactions	. 457
		17.1.1	<del>-</del> -	
		17.1.2	Generalization to Other Fields	
			(Electric, Elastic, Hydrodynamics)	. 461
	17.2	Long-F	Range Field Fluctuations Due to Irregular Arrays	
			rces at Boundaries	. 463
		17.2.1		
		17.2.2		
		17.2.3		
Ref	ferenc	es		. 477
. ,				<b>F</b> 0 <b>F</b>
	l			E 0.5