## Contents

Acki	ogue nowledg	ements	
	12.4	Within Shapes Are Possible?	
		Nobius Transformations are anoitamiotensiT suid6M	
		ACTI	
		The Nature of Space	
		Three-Dimensional Hyperbolic Geometry, and American Pennich	
L	Euclie	dean and Non-Euclidean Geometry	
	1.1	Euclidean and Hyperbolic Geometry	
	1.2	Spherical Geometry	
	1.3	The Angular Excess of a Spherical Triangle	
	1.4	Intrinsic and Extrinsic Geometry of Curved Surfaces	
	1.5	Constructing Geodesics via Their Straightness	
	1.6	The Nature of Space	
	The	ture of Plane Curves	
	Gauss	sian Curvature	
	2.1	Introduction	
	2.2	The Circumference and Area of a Circle	
	2.3	The Local Gauss-Bonnet Theorem	
	2.0	The Local Gauss Donate Theorem	
	Exerci	ises for Prologue and Act I	
		Geometric Interpretation of S and Simplification of [S] 905 q2-E mi e	
		Secureure interpretation of a and attribution of its in a more of the Correlation of the completely Determined by Three Curvatures	
		ACT II as to saturavino Isqionin	
		The Metric	
		The Three Fundamental Forms surroll strategy and a refull to toors	
	Mann	ing Surfaces: The Metric	
	Mapp	ing Surfaces: The Wettic	
	4.1	Introduction	
	4.2	The Projective Map of the Sphere	
	4.3	The Metric of a General Surface	
	4.4	The Metric Curvature Formula	
	4.5	Conformal Maps	
	4.6	Some Visual Complex Analysis	
	4.7	The Conformal Stereographic Map of the Sphere	
	4.8	Stereographic Formulas	
	4.9	Stereographic Preservation of Circles	
ir	The P	seudosphere and the Hyperbolic Plane	
	17 W	11.7.3 Newton's Ceometrical Demonstration of Kepler's Second La	
	5.1	Beltrami's Insight The Tractrity and the Poored conhere	
	5.2	The Tractrix and the Pseudosphere	
	5.3	A Conformal Map of the Pseudosphere	
	5.4	The Beltrami-Poincaré Half-Plane	

	5.5	Using Optics to Find the Geodesics	58
	5.6	The Angle of Parallelism	60
	5.7	The Beltrami-Poincaré Disc	62
6	Isome	etries and Complex Numbers	65
	6.1	Introduction	65
	6.2	Möbius Transformations	67
	6.3	The Main Result	72
	6.4	Einstein's Spacetime Geometry	74
	6.5	Three-Dimensional Hyperbolic Geometry	79
7	Exerci	ises for Act II	83
		ACT III	
		Curvature Dischool and Dischool	
0	C	The Nature of Space	97
8	Curva	ature of Plane Curves	
	8.1	Introduction	97
	8.2	The Circle of Curvature	98
	8.3	Newton's Curvature Formula	100
	8.4	Curvature as Rate of Turning	8.5 101
	8.5	Example: Newton's Tractrix	104
9	Curve	es in 3-Space	106
10	The P	rincipal Curvatures of a Surface	109
	10.1	Euler's Curvature Formula	109
	10.1	Proof of Euler's Curvature Formula	110
	10.2		115
	10.0	Surfaces of Revolution	
11	Geod	esics and Geodesic Curvature	115
	11.1	Geodesic Curvature and Normal Curvature	115
	11.2		117
	11.3	Geodesics are "Straight"	118
	11.4	Intrinsic Measurement of Geodesic Curvature	119
	11.5	A Simple Extrinsic Way to Measure Geodesic Curvature	120
	11.6	A New Explanation of the Sticky-Tape Construction of Geodesics	120
	11.7	Geodesics on Surfaces of Revolution	121
		11.7.1 Clairaut's Theorem on the Sphere	121
		11.7.2 Kepler's Second Law	123
		11.7.3 Newton's Geometrical Demonstration of Kepler's Second Lav	
		11.7.4 Dynamical Proof of Clairaut's Theorem	126
		11.7.5 Application: Geodesics in the Hyperbolic Plane (Revisited)	128

12	The Ex	trinsic Curvature of a Surface	130
	12.1	Introduction	130
	12.2	The Caberical Man	130
	12.3	Extrinsic Curvature of Surfaces	131
	12.4	What Shapes Are Possible?	135
	12.1		
13	Gauss'	s Theorema Egregium	138
186		18.3.1 Flattening Polyhedra	138
	13.1	Introduction  Conver's Partiful Theorem (1916)	138
	13.2	Gauss's Beautiful Theorem (1816)	140
	13.3	Gauss's Theorema Egregium (1827)	140
14	The Cu	arvature of a Spike	143
	14.1	Introduction	143
	14.2	Curvature of a Conical Spike	143
	14.3	The Intrinsic and Extrinsic Curvature of a Polyhedral Spike	145
	14.4	The Polyhedral Theorema Egregium	147
	26.3	The Polyment Proportion Lagregonia	
15	The Sh	ape Operator	149
	Ceomat	ric Proof of the Metric Curvature For 1996 and go sbleid 1009V	149
	15.1	Directional Derivatives  The Character Constant	151
	15.2	The Shape Operator S	151
	15.3	The Geometric Effect of S	132
	15.4	DETOUR: The Geometry of the Singular Value Decomposition and of the Transpose	154
	15.5	The General Matrix of S	158
	15.6	Geometric Interpretation of S and Simplification of [S]	159
	15.7	[S] Is Completely Determined by Three Curvatures	161
	15.7	A company to this Diversitions	162
	15.9	Classical Taumin alass and Nichabian.	102
	13.9	The Three Fundamental Forms	164
16	Introd	uction to the Global Gauss-Bonnet Theorem	165
10			
	16.1	Some Topology and the Statement of the Result	165
	16.2	Total Curvature of the Sphere and of the Torus	168
		16.2.1 Total Curvature of the Sphere	168
	28.3	16.2.2 Total Curvature of the Torus	169
	16.3	Seeing $\mathcal{K}(S_g)$ via a Thick Pancake	170
	16.4	Seeing $K(S_g)$ via Bagels and Bridges	171
	16.5	The Topological Degree of the Spherical Map	172
	16.6	Historical Note Project into the Surface as You Gol	174
17	First (F	Heuristic) Proof of the Global Gauss-Bonnet Theorem	175
	17.1	Total Curvature of a Plane Loop:	
		Hopf's Umlaufsatz	175
	17.2	Total Curvature of a Deformed Circle	178
	17.3	Heuristic Proof of Hopf's Umlaufsatz	179

	17.4	Total Curvature of a Deformed Sphere		180
	17.5	Heuristic Proof of the Global Gauss–Bonnet Theorem		181
18	Secon	d (Angular Excess) Proof of the Global Gauss-Bonne	t Theorem	183
131		Curvature of Surfaces		6
	18.1 18.2	The Euler Characteristic  Fulor's (Empirical) Polyhodral Formula		183 183
	18.3	Euler's (Empirical) Polyhedral Formula Cauchy's Proof of Euler's Polyhedral Formula		186
	10.5	18.3.1 Flattening Polyhedra		186
		18.3.2 The Euler Characteristic of a Polygonal Net		187
	18.4	Legendre's Proof of Euler's Polyhedral Formula		188
	18.5	Adding Handles to a Surface to Increase Its Genus		190
	18.6	Angular Excess Proof of the Global Gauss–Bonnet Theorem	n	193
40				40
19	Third	(Vector Field) Proof of the Global Gauss–Bonnet The	orem	195
	19.1	Introduction		195
	19.2	Vector Fields in the Plane		195
	19.3	The Index of a Singular Point		196
	19.4	The Archetypal Singular Points: Complex Powers		198
	19.5	Vector Fields on Surfaces		201
		19.5.1 The Honey-Flow Vector Field		201
		19.5.2 Relation of the Honey-Flow to the Topographic M	Iap	203
		19.5.3 Defining the Index on a Surface		204
	19.6	The Poincaré–Hopf Theorem		206
		19.6.1 Example: The Topological Sphere		206
		19.6.2 Proof of the Poincaré–Hopf Theorem		207
		19.6.3 Application: Proof of the Euler–L'Huilier Formula	a D.C.I	208
		19.6.4 Poincaré's Differential Equations Versus Hopf's L	ine Fields	210
	19.7	Vector Field Proof of the Global Gauss–Bonnet Theorem		214
	19.8	The Road Ahead		218
20	Exerci	ses for Act III		219
		ACT IV		
		Parallel Transport		
		CALL CARE CARE CARE CARE CARE CARE CARE CARE		
21	An Hi	storical Puzzle		231
22	Extrin	sic Constructions		233
				220
	22.1	Project into the Surface as You Go!  Coodesies and Parallel Transport		233
	22.2	Geodesics and Parallel Transport  Potato-Peoler Transport		235
	22.3	Potato-Peeler Transport		236
23	Intrin	sic Constructions		240
	23.1	Parallel Transport via Geodesics		240
	23.2	The Intrinsic (aka, "Covariant") Derivative	Delinary C'AT	243
		The Little (and, Covariant ) Delivative		- I

24	Holonomy Washington Wa				
	24.1	Example: The Sphere		245	
	24.2	Holonomy of a General Geodesic Triangle		246	
	24.3	Holonomy Is Additive		248	
	24.4	Example: The Hyperbolic Plane		248	
		29.5.3 The General Riemann Curvature Formula montounum			
25	An In	tuitive Geometric Proof of the Theorema Egregium		252	
	25.1	Introduction		252	
	25.2	Some Notation and Reminders of Definitions		253	
	25.3	The Story So Far		253	
	25.4	The Spherical Map Preserves Parallel Transport		254	
	25.5	The Beautiful Theorem and Theorema Egregium Explained		256	
26	Fourt	h (Holonomy) Proof of the Global Gauss-Bonnet Theorem		257	
				0.55	
	26.1	Introduction		257	
	26.2	Holonomy Along an Open Curve?		257	
	26.3	Hopf's Intrinsic Proof of the Global Gauss–Bonnet Theorem		258	
27	Geom	etric Proof of the Metric Curvature Formula		261	
	27.1	Introduction		261	
	27.2	The Circulation of a Vector Field Around a Loop		262	
	27.3	Dry Run: Holonomy in the Flat Plane		264	
	27.4	Holonomy as the Circulation of a Metric-Induced			
		Vector Field in the Map		266	
	27.5	Geometric Proof of the Metric Curvature Formula		268	
28	Curva	ture as a Force between Neighbouring Geodesics		269	
	28.1	Introduction to the Jacobi Equation		269	
	39.5	28.1.1 Zero Curvature: The Plane		269	
		28.1.2 Positive Curvature: The Sphere		270	
		28.1.3 Negative Curvature: The Pseudosphere		272	
	28.2	Two Proofs of the Jacobi Equation		274	
		28.2.1 Geodesic Polar Coordinates		274	
		28.2.2 Relative Acceleration = Holonomy of Velocity		276	
	28.3	The Circumference and Area of a Small Geodesic Circle		278	
29	Riem	ann's Curvature		280	
000					
	29.1	Introduction and Summary		280	
	29.2	Angular Excess in an n-ivianifold		281	
	29.3	Parallel Transport: Three Constructions		282	
		29.3.1 Closest Vector on Constant-Angle Cone		282	
		29.3.2 Constant Angle within a Parallel-Transported Plane		283	
		29.3.3 Schild's Ladder		284	

	29.4	The Int	rinsic (aka "Covariant") Derivative Vv		284
	29.5	The Rie	emann Curvature Tensor		286
		29.5.1	Parallel Transport Around a Small "Parallelogram"		286
		29.5.2	Closing the "Parallelogram" with the Vector		
			Commutator		287
		29.5.3	The General Riemann Curvature Formula		288
		29.5.4	Riemann's Curvature Is a Tensor		293
		29.5.5	Components of the Riemann Tensor		292
		29.5.6	For a Given wo, the Vector Holonomy Only Depends of	25.1	
			the Plane of the Loop and Its Area		293
		29.5.7	Symmetries of the Riemann Tensor		294
		29.5.8	Sectional Curvatures		296
		29.5.9	Historical Notes on the Origin of the Riemann Tensor		297
	29.6	The Jac	obi Equation in an n-Manifold		299
		29.6.1	Geometrical Proof of the Sectional Jacobi Equation		299
		29.6.2	Geometrical Implications of the Sectional		
			Jacobi Equation		300
		29.6.3	Computational Proofs of the Jacobi Equation		
			and the Sectional Jacobi Equation		301
	29.7	The Ric	cci Tensor		302
		29.7.1	Acceleration of the Area Enclosed by a Bundle		
			of Geodesics		302
		29.7.2	Definition and Geometrical Meaning of the		
			Ricci Tensor		304
	29.8	Coda			306
		19.6.2	Proof of the Poincaré-Hopf Theorets Malt ni blei'l rote		
30	Einste	in's Cur	ved Spacetime		307
	30.1	Introdu	action: "The Happiest Thought of My Life."		307
	30.2		ational Tidal Forces		308
	30.3	Newton	n's Gravitational Law in Geometrical Form		312
	30.4		acetime Metric		314
	30.5		me Diagrams		315
	30.6	*	n's Vacuum Field Equation		
			metrical Form		317
	30.7	The Sch	nwarzschild Solution		
		and the	First Tests of the Theory		319
	30.8	Gravita	ational Waves		323
	30.9	The Eir	nstein Field Equation (with Matter)		
		in Geor	metrical Form		326
	30.10	Gravita	ational Collapse to a Black Hole		329
	30.11	The Co	smological Constant:		
			reatest Blunder of My Life."		331
	30.12	The En	.3.1 Closest Vector on Constant-Angle Cone		333
			13.2 Constant Angle within a Parallel-Transported Plan		
31	Exerci	ses for A	ct IV		334

## 37.9.2 A Special 2-Dimensic ACT Vex Vector Field amro 1-8 4288

		with the design of the second		
		Forms		
		37.9.5 The Topological Stability of the Circulation 8 emuloy of T		
32	1-Forn	The Volume 3-Form in Spherical Polar Coordinates		345
	32.1	Introduction		345
	32.2	Definition of a 1-Form		346
	32.3	Examples of 1-Forms		347
		32.3.1 Gravitational Work		347
		32.3.2 Visualizing the Gravitational Work 1-Form		348
		32.3.3 Topographic Maps and the Gradient 1-Form		349
		32 3 4 Row Vectors		352
		32 3 5 Dirac's Bras	36.1	352
	32.4	Basis 1-Forms		352
	32.5	The Leibniz Kuie iof Forms		354
	32.6	The Gradient as a 1-Form: <b>d</b> f		354
		32.6.1 Review of the Gradient as a Vector: ∇f		354
		32.6.2 The Gradient as a 1-Form: df		355
		32.6.3 The Cartesian 1-Form Basis: {dx <sup>j</sup> }		356
		32.6.4 The 1-Form Interpretation of $df = (\partial_x f) dx + (\partial_y f) dy$		357
	32.7	Adding 1-Forms Geometrically		357
		38.4.1 The Duals & of my in Terms of the Duals dx of e.		
33	Tenso			360
	33.1	Definition of a Tensor: Valence		360
	33.2	Example: Linear Algebra		361
	33.3	New Tensors from Old		361
	33.3	33.3.1 Addition		361
		33.3.2 Multiplication: The Tensor Product		361
	33.4	Components		362
	33.5	Relation of the Metric Tensor to the Classical Line Element		363
	33.6	Example: Linear Algebra (Again)		364
	33.7	Contraction		365
	33.8	Changing Valence with the Metric Tensor		366
	33.9	Symmetry and Antisymmetry		368
	00.7	Proof of the Menic Lurvature Formula and the Labither agreement		
34	2-Forn	The Boundary of a Boundary Is Zargl seamaupint Lemma. L.8.82		370
413				451
	34.1	Definition of a 2-Form and of a p-Form		370
	34.2	Example: The Area 2-Form		371
	34.3	The Wedge Product of Two 1-Forms		372
	34.4	The Area 2-Form in Polar Coordinates		374
	34.5	Basis 2-Forms and Projections		375
	34.6	Associating 2-Forms with Vectors in $\mathbb{R}^3$ : Flux		376
	34.7	Relation of the Vector and Wedge Products in $\mathbb{R}^3$		379
	34.8	The Faraday and Maxwell Electromagnetic 2-Forms		381

5 3-	3-Forms				
35	1 A 3-Form Requires Three Dimensions				
35	20 5 1 Parallal Francesco Market Market Market Cover 1 "Parallal cover 1 and 1				
35	The first term of the first term of the profit of the prof				
35	The Volume 3-Form in Spherical Polar Coordinates				
35	The Wedge Product of Three 1-Forms				
	and of p 1-Forms				
35	Basis 3-Forms				
35	7 Is $\Psi \wedge \Psi \neq 0$ Possible?				
Di	fferentiation				
36	1 The Exterior Derivative of a 1-Form				
36					
36	PATTER-1 SINGLE				
36	4 Closed and Exact Forms				
	36.4.1 A Fundamental Result: $d^2 = 0$				
	36.4.2 Closed and Exact Forms				
	36.4.3 Complex Analysis: Cauchy–Riemann Equations				
36	Taring the second of the secon				
36	6 Maxwell's Equations				
	vilsamento amos amos i guidos				
In	tegration				
37	1 The Line Integral of a 1-Form				
	37.1.1 Circulation and Work				
	37.1.2 Path-Independence ←⇒ Vanishing Loop Integrals				
	37.1.3 The Integral of an Exact Form: $\varphi = \mathbf{d}f$				
37	The Exterior Derivative as an Integral				
	37.2.1 <b>d</b> (1-Form)				
	37.2.2 d(2-Form)				
37.	Fundamental Theorem of Exterior Calculus				
	(Generalized Stokes's Theorem)				
	37.3.1 Fundamental Theorem of Exterior Calculus				
	37.3.2 Historical Aside				
	37.3.3 Example: Area				
37.	The Boundary of a Boundary Is Zero!				
37.	The Classical Integral Theorems of Vector Calculus				
	$37.5.1  \Phi = 0\text{-Form}$				
	$37.5.2  \Phi = 1\text{-Form}$				
	$37.5.3  \Phi = 2\text{-Form}$				
37.	6 Proof of the Fundamental Theorem of Exterior Calculus				
37.	7 Cauchy's Theorem				
37.					
37.	9 A Primer on de Rham Cohomology				
	37.9.1 Introduction				

		37.9.2	A Special 2-Dimensional Vortex Vector Field	419
		37.9.3	The Vortex 1-Form Is Closed	420
		37.9.4	Geometrical Meaning of the Vortex 1-Form	420
		37.9.5	The Topological Stability of the Circulation	
			of a Closed 1-Form	421
		37.9.6	The First de Rham Cohomology Group	423
		37.9.7	The Inverse-Square Point Source in $\mathbb{R}^3$	424
		37.9.8	The Second de Rham Cohomology Group	426
		37.9.9	The First de Rham Cohomology Group of	
			the Torus	428
38	Differ	ential Ge	eometry via Forms	430
	38.1	Introdu	ction: Cartan's Method of Moving Frames	430
	38.2		tion 1-Forms	432
	00.2	38.2.1	Notational Conventions and Two Definitions	432
		38.2.2	Connection 1-Forms	432
		TELESCOPE TERM	WARNING: Notational Hazing Rituals Ahead!	434
	38.3		itude Matrix	435
	fusion of	38.3.1	The Connection Forms via the Attitude Matrix	435
		38.3.2	Example: The Cylindrical Frame Field	436
	38.4		s Two Structural Equations	438
		38.4.1	The Duals $\theta^i$ of $m_i$ in Terms of the Duals $dx^j$ of $e_j$	438
		38.4.2	Cartan's First Structural Equation	439
		38.4.3	Cartan's Second Structural Equation	440
		38.4.4	Example: The Spherical Frame Field	441
	38.5	The Six	Fundamental Form Equations of a Surface	446
		38.5.1	Adapting Cartan's Moving Frame to a Surface:	
			The Shape Operator and the Extrinsic Curvature	446
		38.5.2	Example: The Sphere	447
		38.5.3	Uniqueness of Basis Decompositions	447
		38.5.4	The Six Fundamental Form Equations of a Surface	448
	38.6		rical Meanings of the Symmetry Equation	
			Peterson-Mainardi-Codazzi Equations	449
	38.7		rical Form of the Gauss Equation	450
	38.8	Proof of	the Metric Curvature Formula and the Theorema Egregium	451
		38.8.1	Lemma: Uniqueness of $\omega_{12}$	451
	, I have	38.8.2	Proof of the Metric Curvature Formula	451
	38.9		Curvature Formula	452
	38.10		s Lemma	
	38.11		nn's Rigid Sphere Theorem	101
	38.12		rvature 2-Forms of an n-Manifold	455
			Introduction and Summary	455
		38.12.2	The Generalized Exterior Derivative	457

Co	ntents					
		38.12.3	Extracting the Riemann Tensor from the Curvature	37.9.2 s		
			2-Forms			459
		38.12.4	The Bianchi Identities Revisited			459
	38.13	The Cur	vature of the Schwarzschild Black Hole		4	460
39	Exerci	ses for A			4	165
Fur	ther Read	ling	The Inverse-Square Point Source in IC amon-		4	175
	inoranhu	Rocks 2 D				185
Inde	ex				4	191
		The Exter				

Proof of the Fundamental Bigging Avidante of the Fundamental Bigging Avidante of the Fundamental Bigging of the Fundamental Bigging Avidamental Bigging of the Fundamental Bigging of t