The Topology of Chaos

Robert Gilmore

Physics Department
Drexel University
Philadelphia, PA 19104
robert.gilmore@drexel.edu

Colloquium, Physics Department
University of Georgia, Athens, GA

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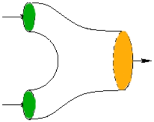

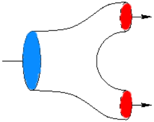

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Outline

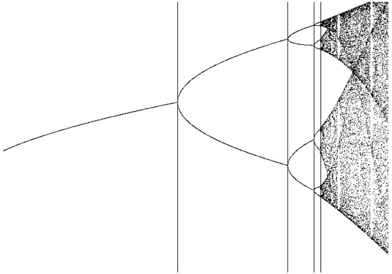
Background

J. R. Tredicce

Can you explain my data?

I dare you to explain my data!

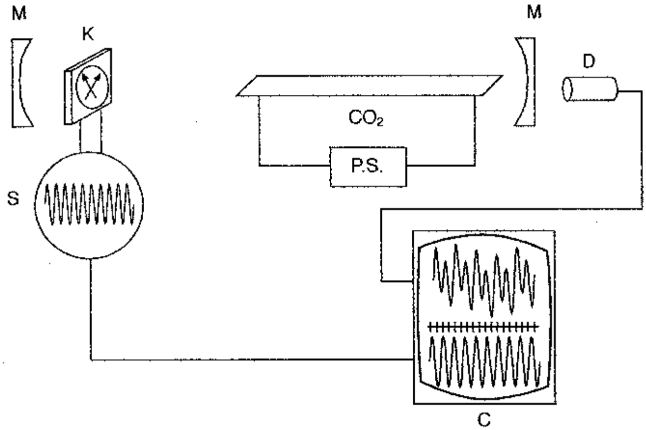
Where is Tredicce coming from?



Feigenbaum:

$$\alpha = \quad 4.66920\ 16091\ .....$$
$$\delta = -2.50290\ 78750\ .....$$

Laser with Modulated Losses Experimental Arrangement



Original Objectives

Construct a simple, algorithmic procedure for:

- Classifying strange attractors
- Extracting classification information

from experimental signals.

Result

There is now a classification theory.

1. It is topological
2. It has a hierarchy of 4 levels
3. Each is discrete
4. There is rigidity and degrees of freedom
5. It is applicable to R^3 only — for now

The 4 Levels of Structure

- **Basis Sets of Orbits**
- **Branched Manifolds**
- **Bounding Tori**
- **Extrinsic Embeddings**

Organization

LINKS OF PERIODIC ORBITS

organize

BOUNDING TORI

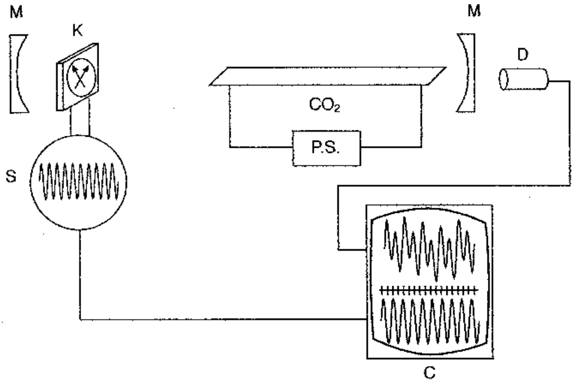
organize

BRANCHED MANIFOLDS

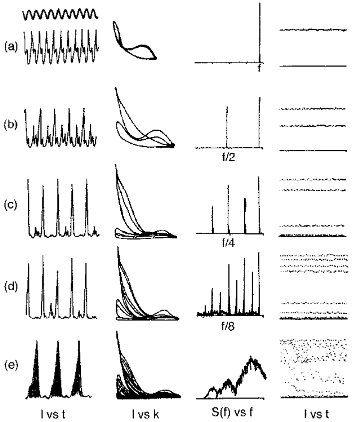
organize

LINKS OF PERIODIC ORBITS

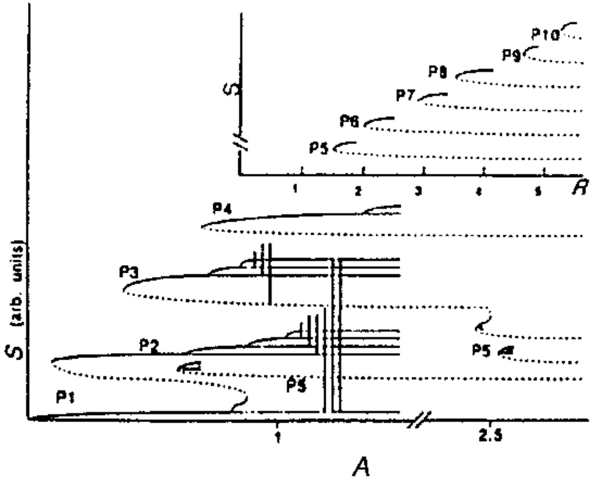
Laser Experimental Arrangement



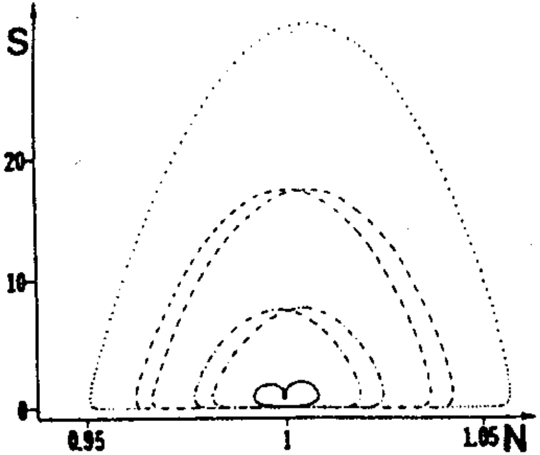
Oscilloscope Traces



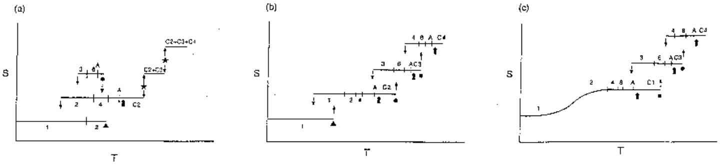
Bifurcation Schematics



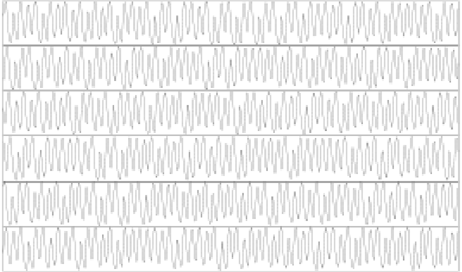
Coexisting Basins of Attraction

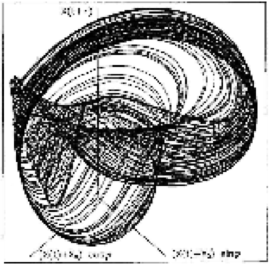


Bifurcation Perestroikas



Experimental Data: LSA





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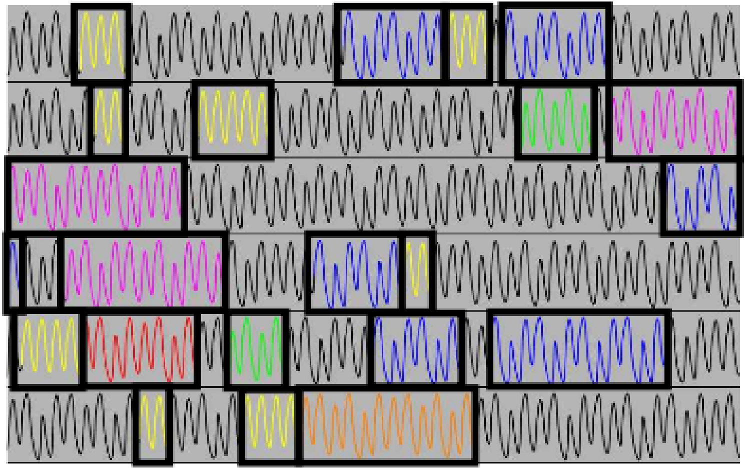
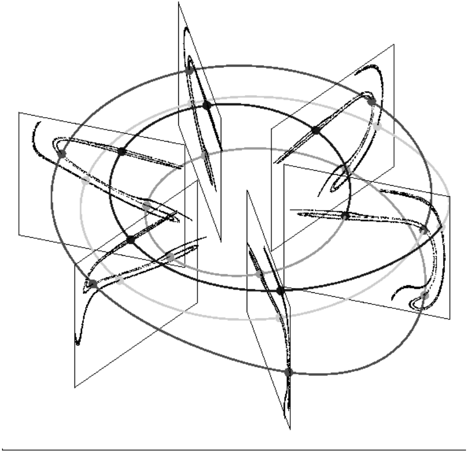
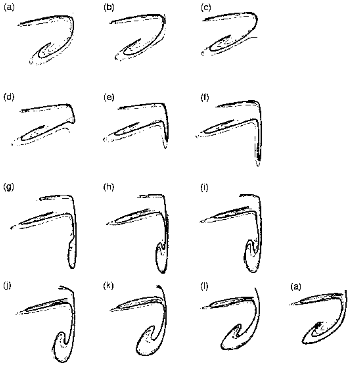
Experimental Data: LSA



Stretching & Squeezing in a Torus



Rotating the Poincaré Section around the axis of the torus



Rotating the Poincaré Section around the axis of the torus

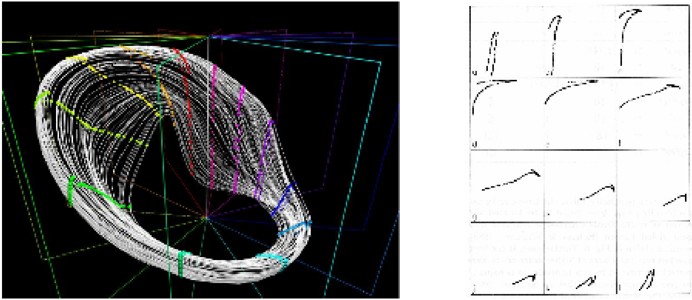


Figure 2. Left: Intersections of a chaotic attractor with a series of section planes are computed. Right: Their evolution from plane to plane shows the interplay of the stretching and squeezing mechanisms.

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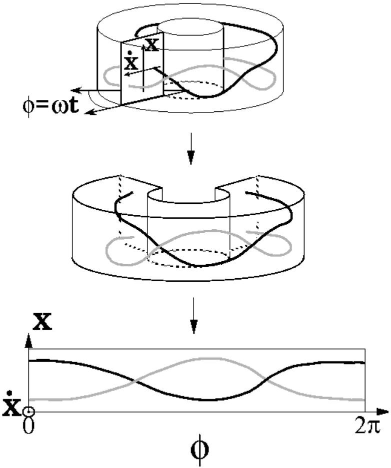
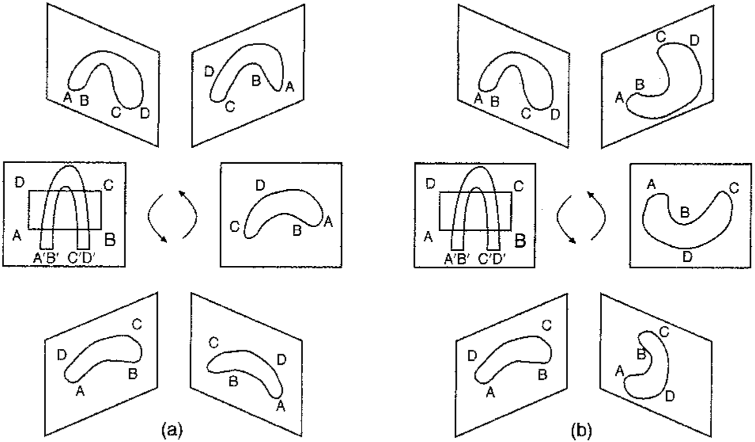
Cutting Open a Torus

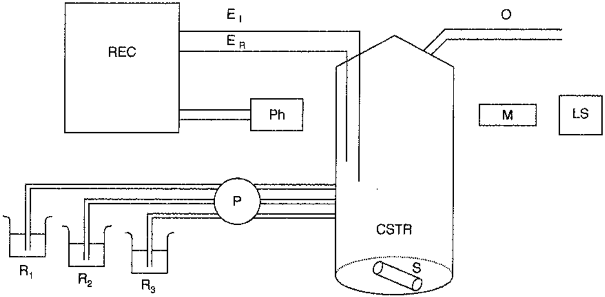


Global Torsion



A Chemical Experiment

The Belousov-Zhabotinskii Reaction



Chaos

Motion that is

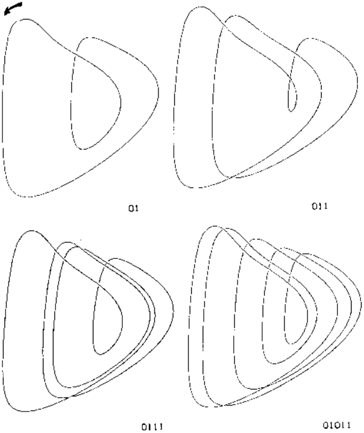
- **Deterministic:** $\frac{dx}{dt} = f(x)$
- **Recurrent**
- **Non Periodic**
- **Sensitive to Initial Conditions**

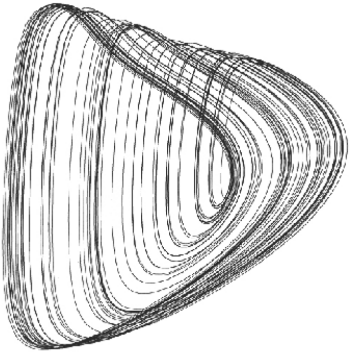
Strange Attractor

The Ω limit set of the flow. There are unstable periodic orbits "in" the strange attractor. They are

- **"Abundant"**
- **Outline the Strange Attractor**
- **Are the Skeleton of the Strange Attractor**

UPOs Outline Strange attractors





BZ reaction

UPOs Outline Strange attractors

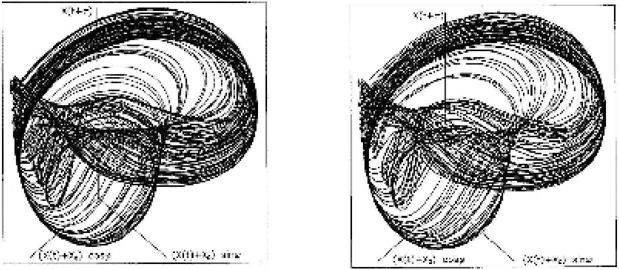


Figure 5. Left: a chaotic attractor reconstructed from a time series from a chaotic laser ; Right : Superposition of 12 periodic orbits of periods from 1 to 10.

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Organization of UPOs in R^3: Gauss Linking Number

$$LN(A,B) = \frac{1}{4\pi} \oint \oint \frac{(\mathbf{r}_A - \mathbf{r}_B)\cdot d\mathbf{r}_A \times d\mathbf{r}_B}{|\mathbf{r}_A - \mathbf{r}_B|^3}$$

Interpretations of LN $\simeq$ # Mathematicians in World

Linking Number of Two UPOs

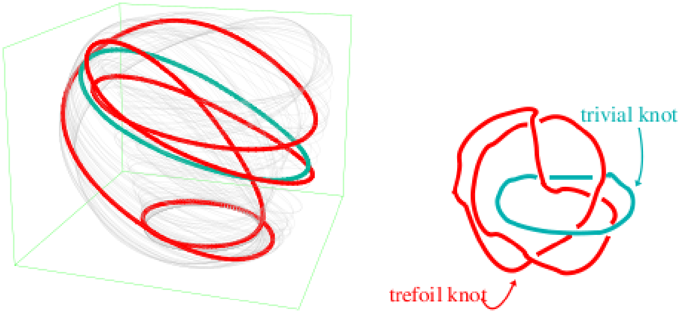

Figure 6. Left: two periodic orbits of periods 1 and 4 embedded in a strange attractor; Right: a link of two knots that is equivalent to the pair of periodic orbits up to continuous deformations without crossings.

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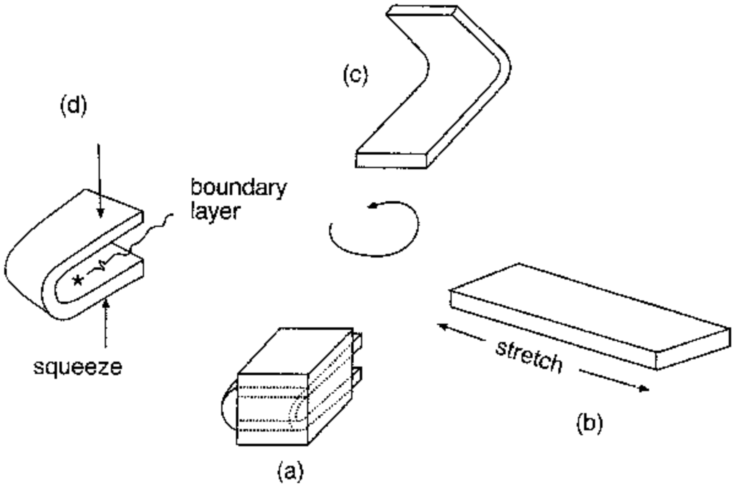
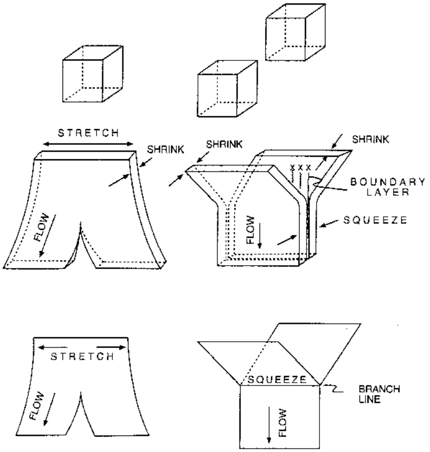
One Stretch-&-Squeeze Mechanism



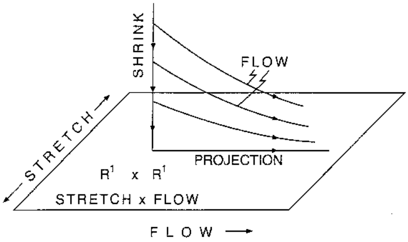
Stretching — Squeezing



Birman - Williams Projection

Identify x and y if

$$\lim_{t\to\infty} |x(t) - y(t)| \to 0$$



Birman - Williams Theorem

If:

Then:

Birman - Williams Theorem

If: **Certain Assumptions**

Then:

Birman - Williams Theorem

If: **Certain Assumptions**

Then: **Specific Conclusions**

Assumptions, B-W Theorem

A flow $\Phi_t(x)$

- **on** R^n **is dissipative,** $\underline{n=3}$**, so that** $\lambda_1 > 0, \lambda_2 = 0, \lambda_3 < 0$.
- **Generates a** **<u>hyperbolic</u>** **strange attractor** $\mathcal{SA}$

IMPORTANT: The underlined assumptions can be relaxed.

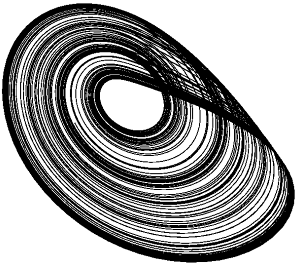
Conclusions, B-W Theorem

- **The projection maps the strange attractor $\mathcal{SA}$ onto a 2-dimensional branched manifold $\mathcal{BM}$ and the flow $\Phi_t(x)$ on $\mathcal{SA}$ to a semiflow $\overline{\Phi}(x)_t$ on $\mathcal{BM}$.**
- **UPOs of $\Phi_t(x)$ on $\mathcal{SA}$ are in 1-1 correspondence with UPOs of $\overline{\Phi}(x)_t$ on $\mathcal{BM}$. Moreover, every link of UPOs of $(\Phi_t(x), \mathcal{SA})$ is isotopic to the correspond link of UPOs of $(\overline{\Phi}(x)_t, \mathcal{BM})$.**

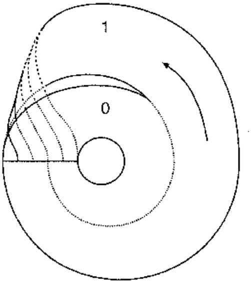
Remark: "One of the few theorems useful to experimentalists."

Rössler:

Attractor



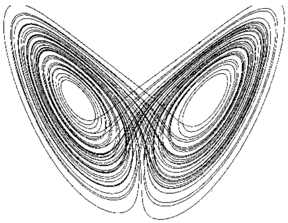
Branched Manifold



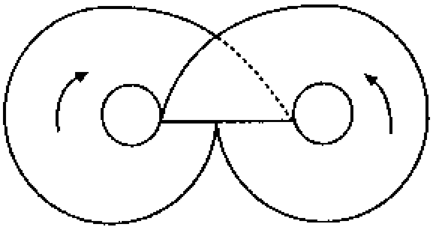
A Mechanism with Symmetry

Lorenz:

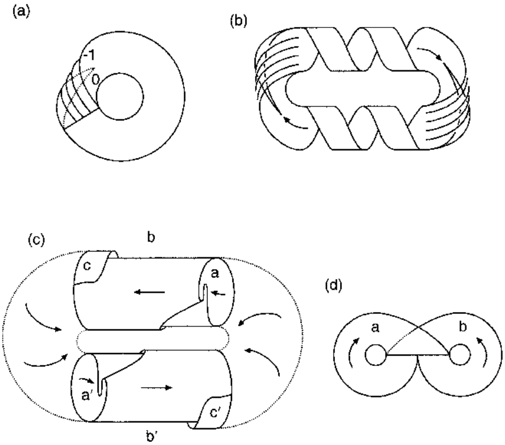
Attractor



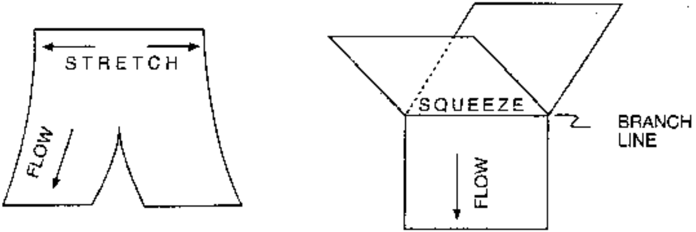
Branched Manifold



Inequivalent Branched Manifolds



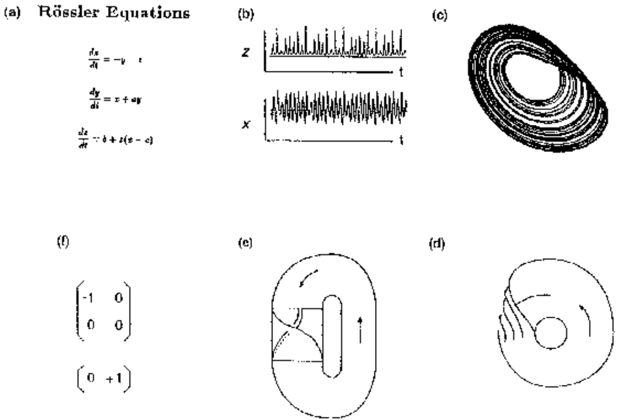
Any branched manifold can be built up from stretching and squeezing units



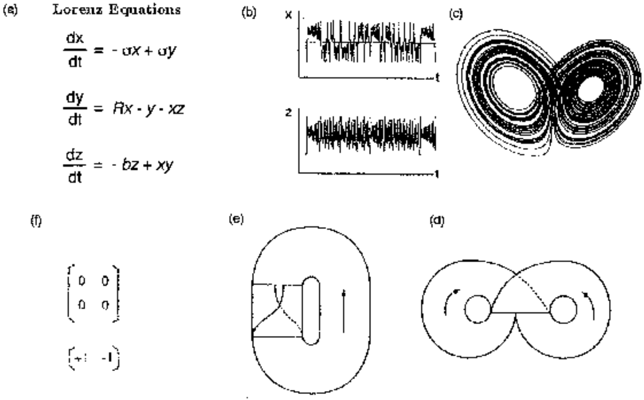
subject to the conditions:

- **Outputs to Inputs**
- **No Free Ends**

Rossler System



Lorenz System



Poincaré Smiles at Us in R^3

- **Determine organization of UPOs** $\Rightarrow$
- **Determine branched manifold** $\Rightarrow$
- **Determine equivalence class of** $\mathcal{SA}$

Topological Analysis Program

Locate Periodic Orbits

Create an Embedding

Determine Topological Invariants (LN)

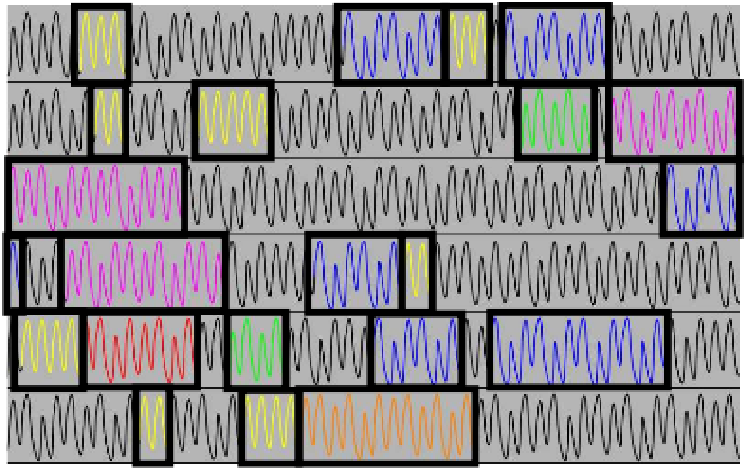
Identify a Branched Manifold

Verify the Branched Manifold

Model the Dynamics

Validate the Model

Method of Close Returns



Embeddings

Many Methods: Time Delay, Differential, Hilbert Transforms, SVD, Mixtures, ...

Tests for Embeddings: Geometric, Dynamic, Topological†

None Good

We Demand a 3 Dimensional Embedding

An Embedding and Periodic Orbits

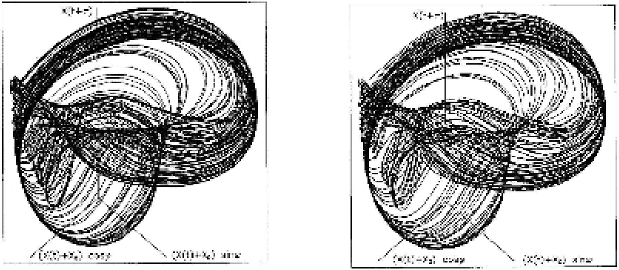


Figure 5. Left: a chaotic attractor reconstructed from a time series from a chaotic laser ; Right : Superposition of 12 periodic orbits of periods from 1 to 10.

Linking Number of Orbit Pairs

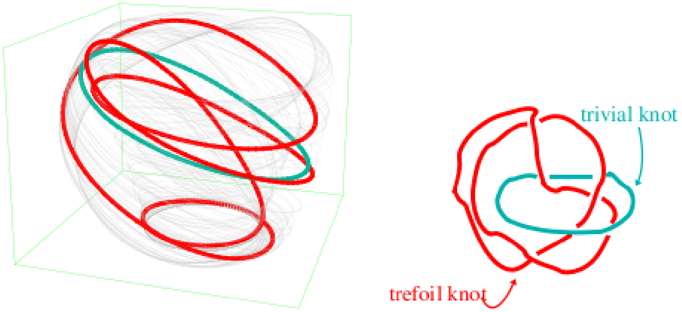


Figure 6. Left: two periodic orbits of periods 1 and 4 embedded in a strange attractor; Right: a link of two knots that is equivalent to the pair of periodic orbits up to continuous deformations without crossings.

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Compute Table of Expt'l LN

Table 7.2 Linking numbers for all the surrogate periodic orbits, to period 8, extracted from Belousov–Zhabotinskii data[a]

Orbit	Symbolics	1	2	3	4	5	6	7	8a	8b
1	1	0	1	1	2	2	2	3	4	3
2	01	1	1	2	3	4	4	5	6	6
3	011	1	2	2	4	5	6	7	8	8
4	0111	2	3	4	5	8	8	11	13	12
5	01 011	2	4	5	8	8	10	13	16	15
6	011 0M1	2	4	6	8	10	9	14	16	16
7	01 01 011	3	5	7	11	13	14	16	21	21
8a	01 01 0111	4	6	8	13	16	16	21	23	24
8b	01 011 011	3	6	8	12	15	16	21	24	21

[a] All indices are negative.

Compare w. LN From Various $\mathcal{BM}$

Table 2.1 Linking numbers for orbits to period five in Smale horseshoe dynamics.

	$1s$	$1f$	2_1	$3f$	$3s$	4_1	4_2f	4_2s	5_3f	5_3s	5_2f	5_2s	5_1f	5_1s
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	1	1	1	2	1	1	1	1	2	2	2	2
01	0	1	1	2	2	3	2	2	2	2	3	3	4	4
001	0	1	2	2	3	4	3	3	3	3	4	4	5	5
011	0	1	2	3	2	4	3	3	3	3	5	5	5	5
0111	0	2	3	4	4	5	4	4	4	4	7	7	8	8
0001	0	1	2	3	3	4	3	4	4	4	5	5	5	5
0011	0	1	2	3	3	4	4	3	4	4	5	5	5	5
00001	0	1	2	3	3	4	4	4	4	5	5	5	5	5
00011	0	1	2	3	3	4	4	4	5	4	5	5	5	5
00111	0	2	3	4	5	7	5	5	5	5	6	7	8	9
00101	0	2	3	4	5	7	5	5	5	5	7	6	8	9
01101	0	2	4	5	5	8	5	5	5	5	8	8	8	10
01111	0	2	4	5	5	8	5	5	5	5	9	9	10	8

The Topology of Chaos

Robert Gilmore

Introduction-01

Introduction-02

Overview-01

Overview-02

Overview-03

Overview-04

Overview-05

Overview-06

Overview-07

Experimental-01

Experimental-02

Experimental-

Guess Branched Manifold

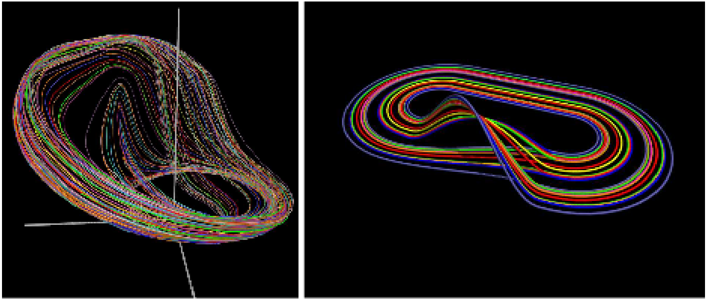

Figure 7. "Combing" the intertwined periodic orbits (left) reveals their systematic organization (right) created by the stretching and squeezing mechanisms.

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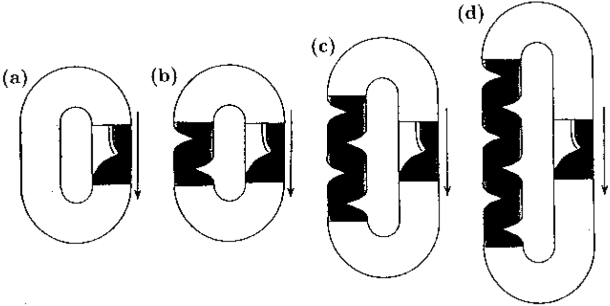
Identification & ‘Confirmation’

- $\mathcal{BM}$ Identified by LN of small number of orbits
- Table of LN GROSSLY overdetermined
- Predict LN of additional orbits
- Rejection criterion

What Do We Learn?

- $\mathcal{BM}$ Depends on Embedding
- Some things depend on embedding, some don't
- Depends on Embedding: Global Torsion, Parity, ..
- Independent of Embedding: Mechanism



Evolution Under Parameter Change

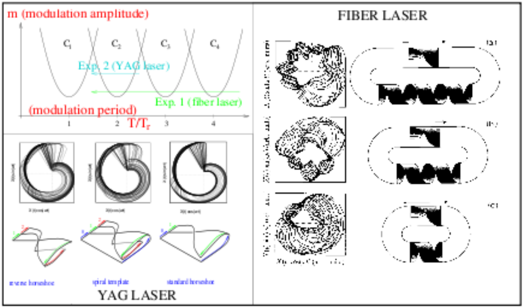


Figure 11. Various templates observed in two laser experiments. Top left: schematic representation of the parameter space of forced nonlinear oscillators showing resonance tongues. Right: templates observed in the fiber laser experiment: global torsion increases systematically from one tongue to the next [40]. Bottom left: templates observed in the YAG laser experiment (only the branches are shown): there is a variation in the topological organization across one chaotic tongue [39, 41].

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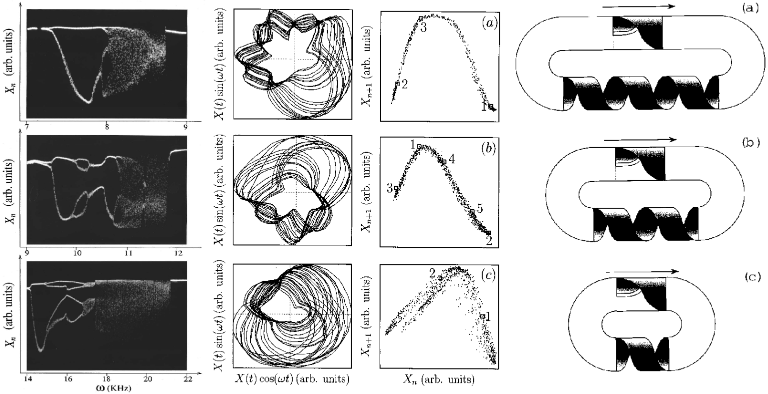
Evolution Under Parameter Change



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Analysis of Nonstationary Data

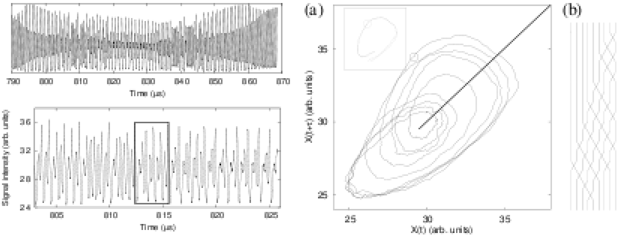

Figure 16. Top left: time series from an optical parametric oscillator showing a burst of irregular behavior. Bottom left: segment of the time series containing a periodic orbit of period 9. Right: embedding of the periodic orbit in a reconstructed phase space and representation of the braid realized by the orbit. The braid entropy is $h_T = 0.377$, showing that the underlying dynamics is chaotic. Reprinted from [61].

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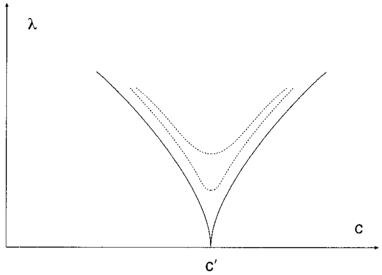
Model the Dynamics

A hodgepodge of methods exist: # Methods $\simeq$ # Physicists

Validate the Model

Needed: Nonlinear analog of χ^2 test. OPPORTUNITY: Tests that depend on entrainment/synchronization.



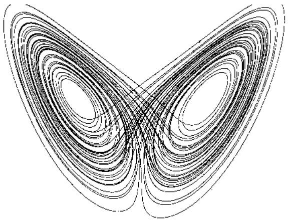
Compare with Original Objectives

Construct a simple, algorithmic procedure for:

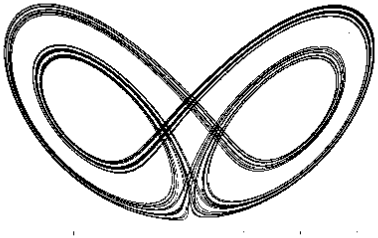
- Classifying strange attractors
- Extracting classification information

from experimental signals.

There Are Some Missing Orbits

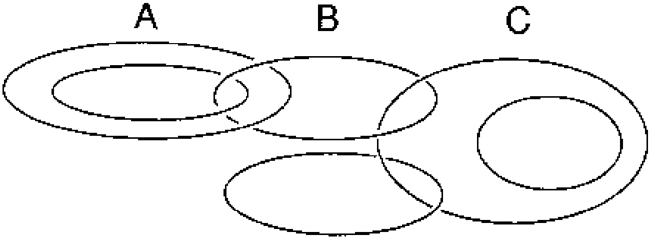


Lorenz



Shimizu-Morioka

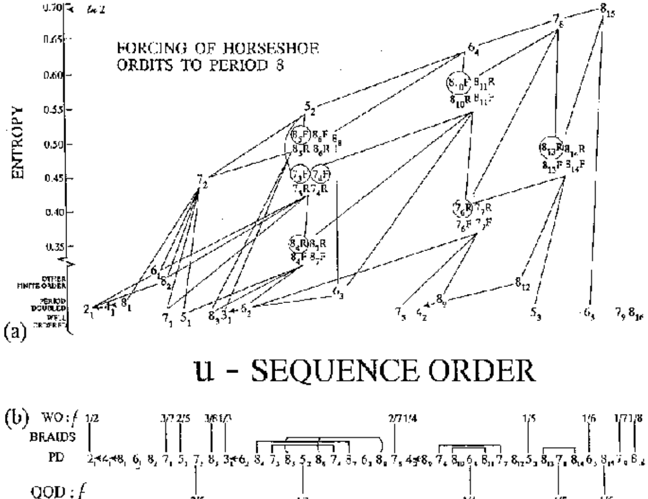
Orbit Forcing



A $\Rightarrow$ B B $\Rightarrow$ C

A $\Rightarrow$ C

Forcing Diagram - Horseshoe



Status of Problem

- Horseshoe organization - active
- More folding - barely begun
- Circle forcing - even less known
- Higher genus - new ideas required

Constraints on Branched Manifolds

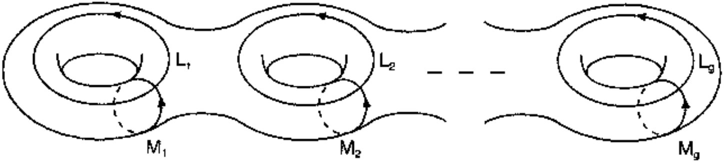
"Inflate" a strange attractor

Union of ϵ ball around each point

Boundary is surface of bounded 3D manifold

Torus that bounds strange attractor

Torus, Longitudes, Meridians



Surface Singularities

Flow field: three eigenvalues: +, 0, −

Vector field "perpendicular" to surface

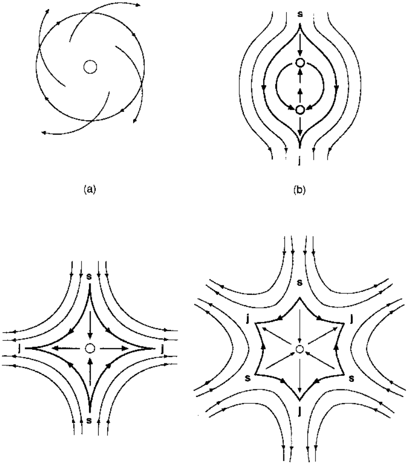
Eigenvalues on surface at fixed point: +, −

All singularities are regular saddles

$\sum_{s.p.}(-1)^{\text{index}} = \chi(S) = 2 - 2g$

 # fixed points on surface = index = 2g - 2

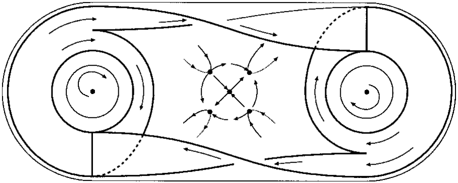
Flow Near a Singularity



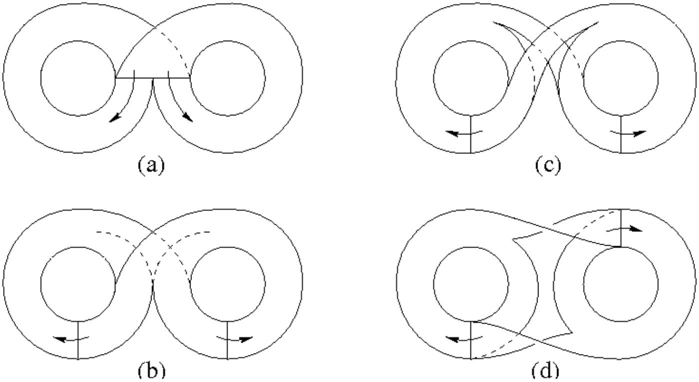
(a) (b)

(c) (d)

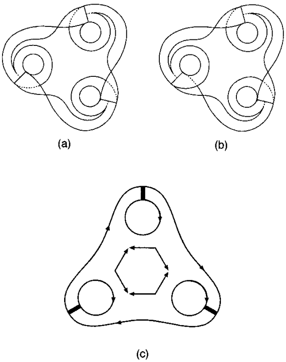
Torus Bounding Lorenz-like Flows



Twisting the Lorenz Attractor



Two possible branched manifolds in the torus with g=4.



Bounding Tori contain all known Strange Attractors

Tab.1. All known strange attractors of dimension $d_L < 3$ are bounded by one of the standard dressed tori.

Strange Attractor	Dressed Torus	Period $g-1$ Orbit
Rossler, Duffing, Burke and Shaw	A_1	1
Various Lasers, Gateau Roule	A_1	1
Neuron with Subthreshold Oscillations	A_1	1
Shaw-van der Pol	$A_1 \cup A_1^{(1)}$	$1 \cup 1$
Lorenz, Shimizu-Morioka, Rikitake	A_2	$(12)^2$
Multispiral attractors	A_n	$(12^{n-1})^2$
C_n Covers of Rossler	C_n	1^n
C_2 Cover of Lorenz$^{(a)}$	C_4	1^4
C_2 Cover of Lorenz$^{(b)}$	A_3	$(122)^2$
C_n Cover of Lorenz$^{(a)}$	C_{2n}	1^{2n}
C_n Cover of Lorenz$^{(b)}$	P_{n+1}	$(1n)^n$
$2 \rightarrow 1$ Image of Fig. 8 Branched Manifold	A_3	$(122)^2$
Fig. 8 Branched Manifold	P_3	$(14)^4$

$^{(a)}$ Rotation axis through origin.
$^{(b)}$ Rotation axis through one focus.

Labeling Bounding Tori

Poincaré section is disjoint union of g-1 disks

Transition matrix sum of two g-1 $\times$ g-1 matrices

One is cyclic g-1 $\times$ g-1 matrix

Other represents union of cycles

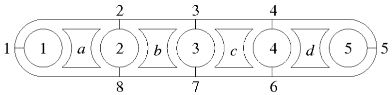
Labeling via (permutation) group theory

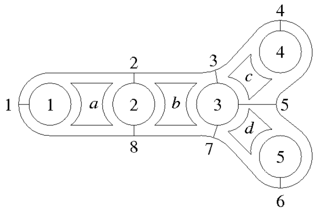
Bounding Tori of Low Genus

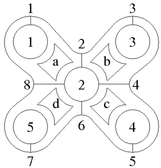
TABLE I: Enumeration of canonical forms up to genus 9

g	m	$(p_1, p_2, \dots p_m)$	$n_1 n_2 \dots n_{g-1}$
1	1	(0)	1
3	2	(2)	11
4	3	(3)	111
5	4	(4)	1111
5	3	(2,2)	1212
6	5	(5)	11111
6	4	(3,2)	12112
7	6	(6)	111111
7	5	(4,2)	112121
7	5	(3,3)	112112
7	4	(2,2,2)	122122
7	4	(2,2,2)	131313
8	7	(7)	1111111
8	6	(5,2)	1211112
8	6	(4,3)	1211121
8	5	(3,2,2)	1212212
8	5	(3,2,2)	1221221
8	5	(3,2,2)	1313131
9	8	(8)	11111111
9	7	(6,2)	11111212
9	7	(5,3)	11112112
9	7	(4,4)	11121112
9	6	(4,2,2)	11122122
9	6	(4,2,2)	11131313
9	6	(4,2,2)	11212212
9	6	(4,2,2)	12121212
9	6	(3,3,2)	11212122
9	6	(3,3,2)	11221122
9	6	(3,3,2)	11221212
9	6	(3,3,2)	11311313
9	5	(2,2,2,2)	12221222
9	5	(2,2,2,2)	12313132
9	5	(2,2,2,2)	14141414

Some Genus-9 Bounding Tori

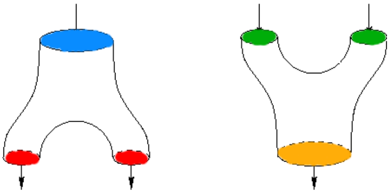






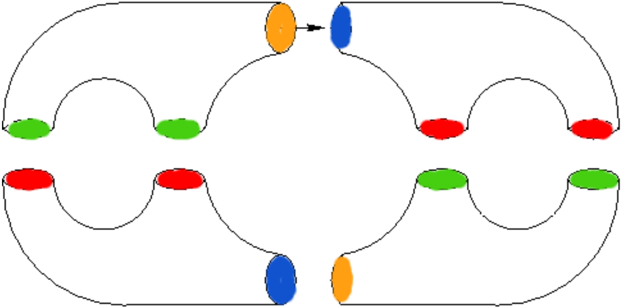
Aufbau Princip for Bounding Tori

Any bounding torus can be built up from equal numbers of stretching and squeezing units



- **Outputs to Inputs**
- **No Free Ends**
- **Colorless**

Application: Lorenz Dynamics, g=3



Poincaré Section

Construction of Poincaré Section

P. S. = Union 

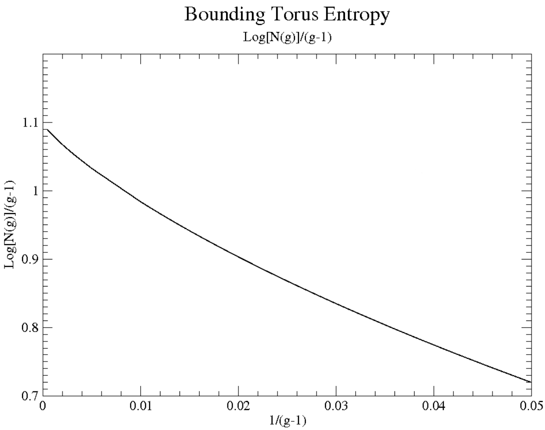
Components = g-1

The Growth is Exponential

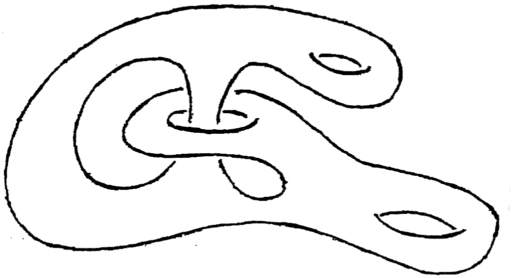
TABLE I: Number of canonical bounding tori as a function of genus, g.

g	$N(g)$	g	$N(g)$	g	$N(g)$
3	1	9	15	15	2211
4	1	10	28	16	5549
5	2	11	67	17	14290
6	2	12	145	18	36824
7	5	13	368	19	96347
8	6	14	870	20	252927

The Growth is Exponential
The Entropy is log 3



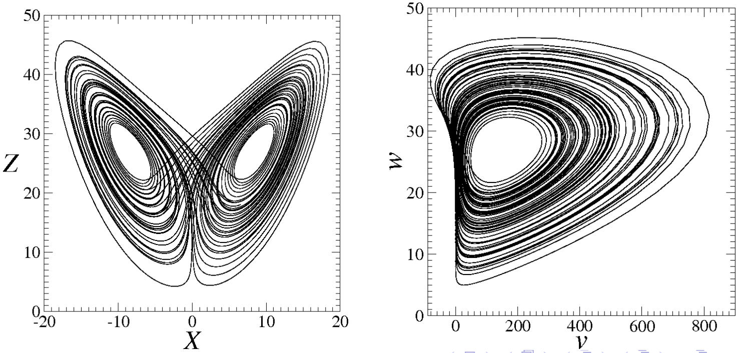
Extrinsic Embedding of Intrinsic Tori



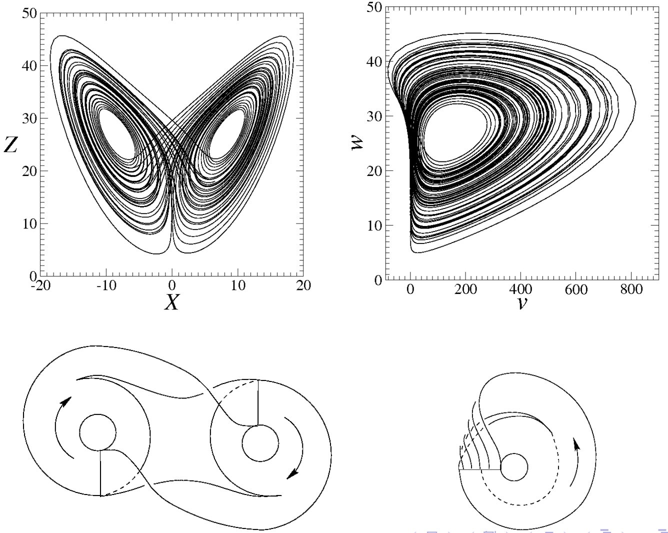
Partial classification by links of homotopy group generators.
Nightmare Numbers are Expected.

Modding Out a Rotation Symmetry

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \rightarrow \begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{pmatrix} Re\ (X+iY)^2 \\ Im\ (X+iY)^2 \\ Z \end{pmatrix}$$

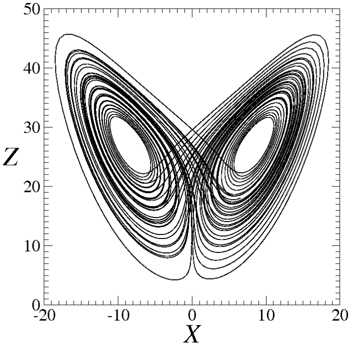


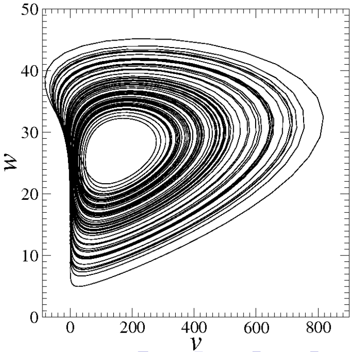
Lorenz Attractor and Its Image



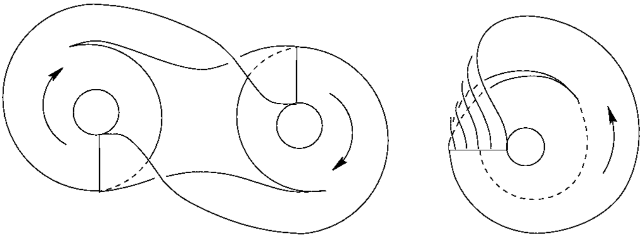
Creating a Cover with Symmetry

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \leftarrow \begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{pmatrix} Re\ (X+iY)^2 \\ Im\ (X+iY)^2 \\ Z \end{pmatrix}$$

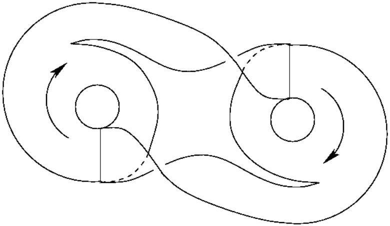


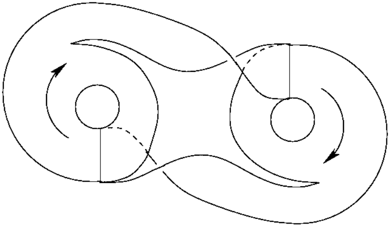


Cover-Image Branched Manifolds



Two Two-fold Lifts Different Symmetry

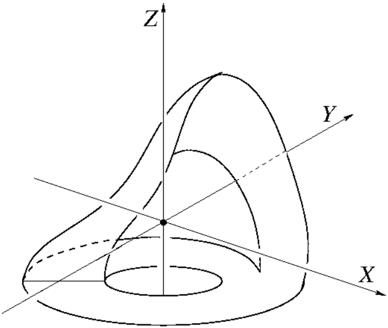




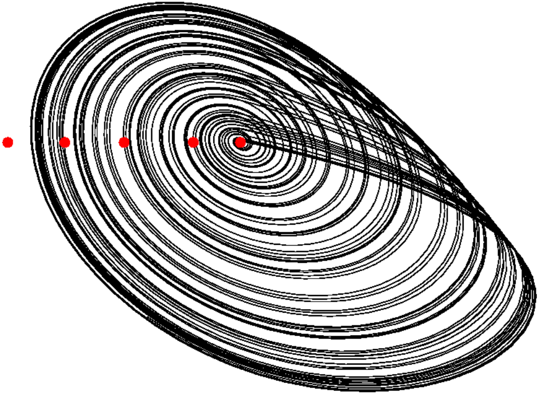
Rotation Symmetry

Inversion Symmetry

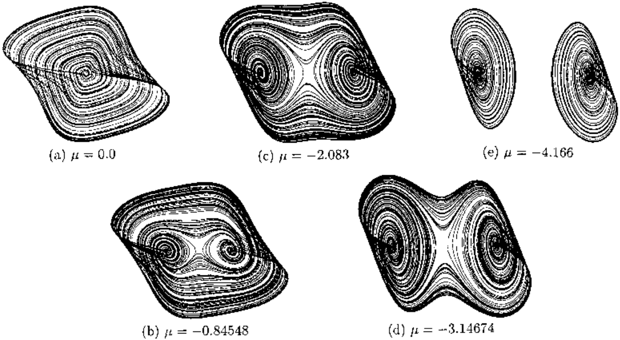
Topological Index: Choose Group
Choose Rotation Axis (Singular Set)

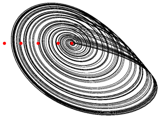


Different Rotation Axes Produce Different (Nonisotopic) Lifts

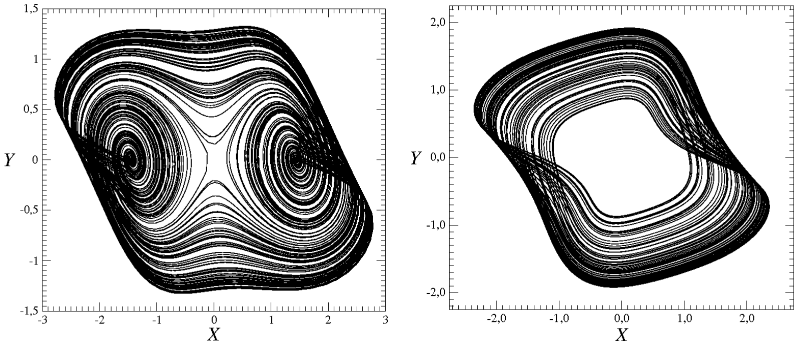


Nonisotopic Locally Diffeomorphic Lifts

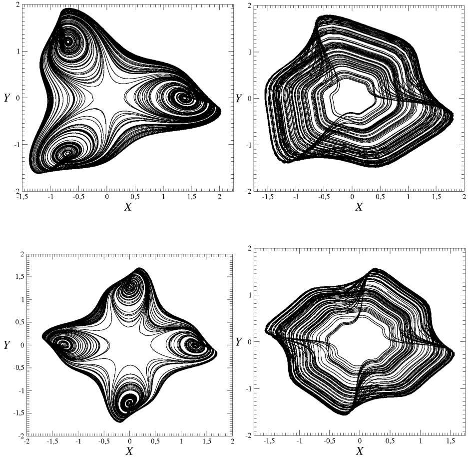




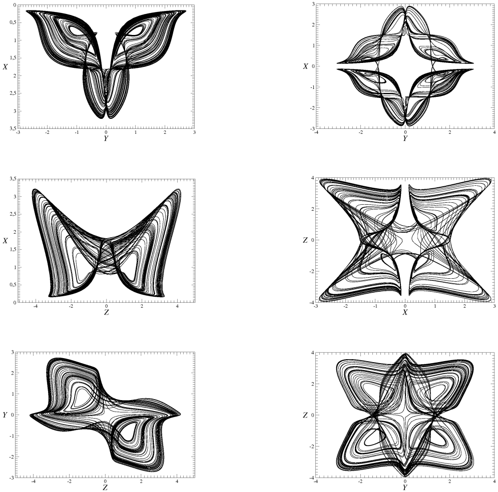
Two Two-fold Covers Same Symmetry



Three-fold, Four-fold Covers



Two Inequivalent Lifts with V_4 Symmetry



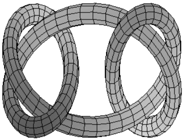
Algorithm

- Construct Invariant Polynomials, Syzygies, Radicals
- Construct Singular Sets
- Determine Topological Indices
- Construct Spectrum of Structurally Stable Covers
- Structurally Unstable Covers Interpolate

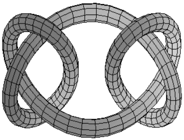
Symmetries Due to Symmetry

- Schur's Lemmas & Equivariant Dynamics
- Cauchy Riemann Symmetries
- Clebsch-Gordon Symmetries
- Continuations
  - Analytic Continuation
  - Topological Continuation
  - Group Continuation

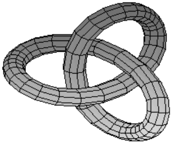
Covers of a Trefoil Torus



Granny Knot

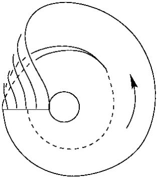


Square Knot

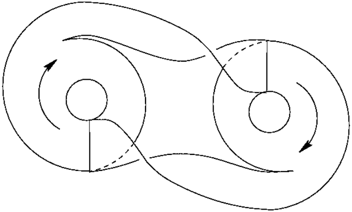


Trefoil Knot

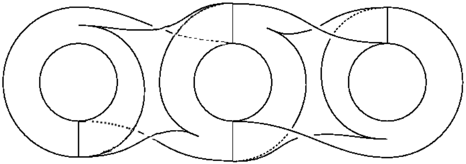
Covers of Covers of Covers



Rossler

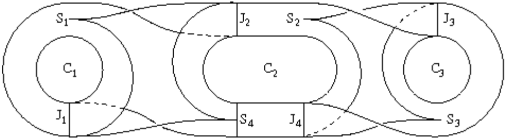


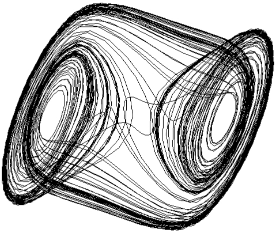
Lorenz



Ghrist

EveryKnot Lives Here



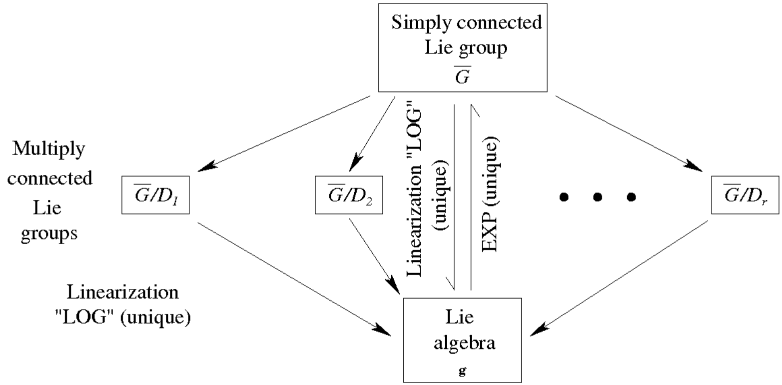


Local Stuff

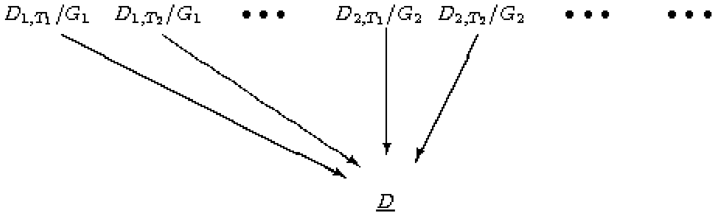
Groups:
Local Isomorphisms
Cartan's Theorem

Dynamical Systems:
Local Diffeomorphisms
??? Anything Useful ???

Cartan's Theorem for Lie Groups



Locally Diffeomorphic Covers of $\underline{D}$



$\underline{D}$: Universal Image Dynamical System

Local Isomorphisms & Diffeomorphisms

Local Isomorphisms & Diffeomorphisms

Lie Groups

Useful Analogs

Local Isomorphisms & Diffeomorphisms

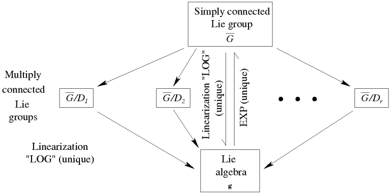
Lie Groups

Local Isomorphisms

Local Isomorphisms & Diffeomorphisms

Lie Groups

Local Isomorphisms

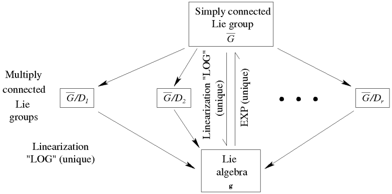


Local Isomorphisms & Diffeomorphisms

Lie Groups

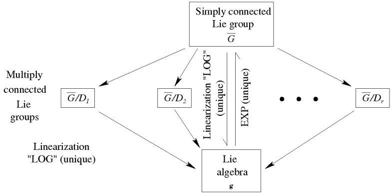
Dynamical Systems

Local Isomorphisms



Local Isomorphisms & Diffeomorphisms

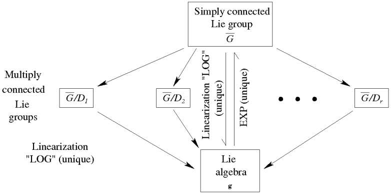
Lie Groups	Dynamical Systems
Local Isomorphisms	Local Diffeos

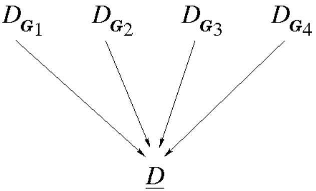


Useful Analogs

Local Isomorphisms & Diffeomorphisms

Lie Groups	**Dynamical Systems**
Local Isomorphisms	**Local Diffeos**





Rotating the Attractor

$$\frac{d}{dt}\left[\begin{array}{c} X \\ Y \end{array}\right] = \left[\begin{array}{c} F_1(X,Y) \\ F_2(X,Y) \end{array}\right] + \left[\begin{array}{c} a_1 \sin(\omega_d t + \phi_1) \\ a_2 \sin(\omega_d t + \phi_2) \end{array}\right]$$

$$\left[\begin{array}{c} u(t) \\ v(t) \end{array}\right] = \left[\begin{array}{cc} \cos \Omega t & -\sin \Omega t \\ \sin \Omega t & \cos \Omega t \end{array}\right] \left[\begin{array}{c} X(t) \\ Y(t) \end{array}\right]$$

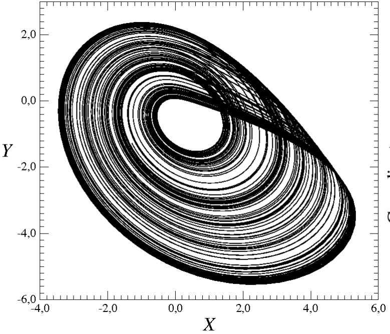
$$\frac{d}{dt}\left[\begin{array}{c} u \\ v \end{array}\right] = R\mathbf{F}(R^{-1}\mathbf{u}) + R\mathbf{t} + \Omega \left[\begin{array}{c} -v \\ +u \end{array}\right]$$

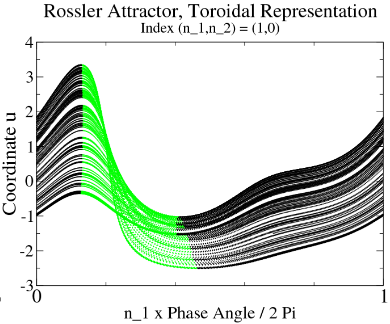
$\Omega = n\ \omega_d$ — Global Diffeomorphisms

$q\ \Omega = p\ \omega_d$ — Local Diffeomorphisms (p-fold covers)

Rossler Attractor: Two Representations

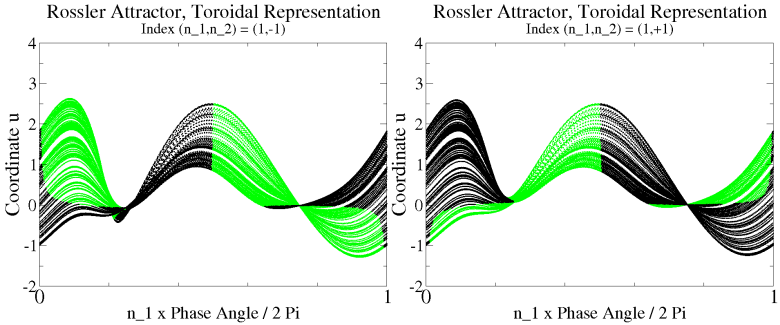
R^3 | $D^2 \times S^1$





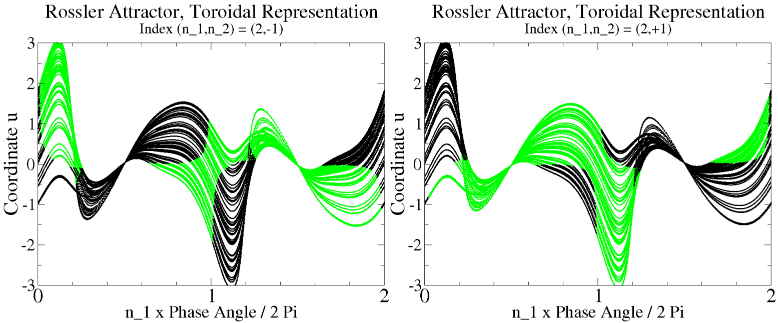
Rossler Attractor:

Two More Representations with $n = \pm 1$



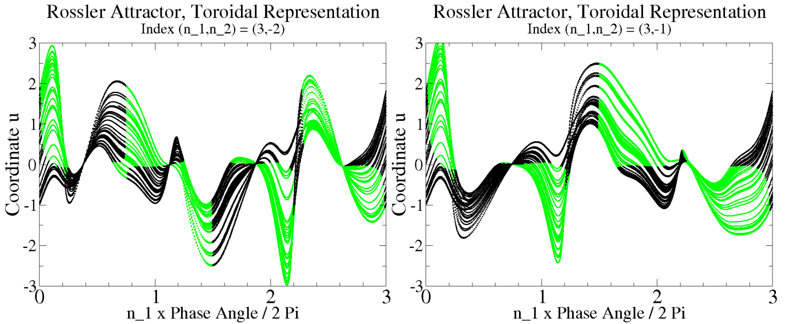
Rossler Attractor:

Two Two-Fold Covers with $p/q = \pm 1/2$



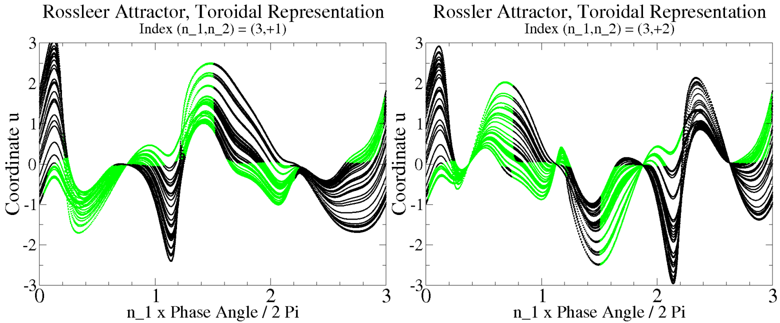
Rossler Attractor:

Two Three-Fold Covers with $p/q = -2/3, -1/3$



Rossler Attractor:

And Even More Covers (with $p/q = +1/3, +2/3$)



Angular Momentum and Energy

$$L(0) = \lim_{\tau\rightarrow\infty} \frac{1}{\tau} \int_0^\tau XdY - YdX \qquad K(0) = \lim_{\tau\rightarrow\infty} \frac{1}{\tau} \int_0^\tau \frac{1}{2}(\dot{X}^2 + \dot{Y}^2)dt$$

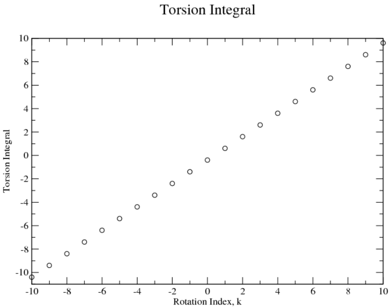
$$L(\Omega) = \langle u\dot{v} - v\dot{u} \rangle \qquad K(\Omega) = \langle \frac{1}{2}(\dot{u}^2 + \dot{v}^2) \rangle$$

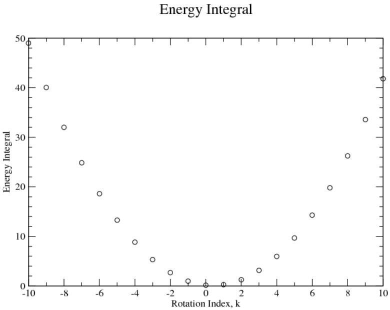
$$= L(0) + \Omega \langle R^2 \rangle \qquad = K(0) + \Omega L(0) + \frac{1}{2}\Omega^2 \langle R^2 \rangle$$

$$\langle R^2 \rangle = \lim_{\tau\rightarrow\infty} \frac{1}{\tau} \int_0^\tau (X^2 + Y^2)dt = \lim_{\tau\rightarrow\infty} \frac{1}{\tau} \int_0^\tau (u^2 + v^2)dt$$

Energy and Angular Momentum

Diffeomorphic, Quantum Number n





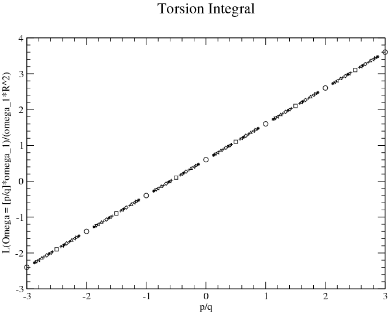
The Topology of Chaos

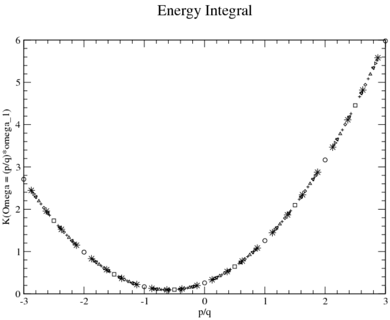
Robert Gilmore

Introduction-01
Introduction-02
Overview-01
Overview-02
Overview-03
Overview-04
Overview-05
Overview-06
Overview-07
Experimental-01
Experimental-02
Experimental-

Energy and Angular Momentum

Subharmonics, Quantum Numbers p/q





Embeddings

An embedding creates a diffeomorphism between an ('invisible') dynamics in someone's laboratory and a ('visible') attractor in somebody's computer.

Embeddings provide a *representation* of an attractor.

Equivalence is by Isotopy.

Irreducible is by Dimension

Inequivalent Irreducible Representations

Irreducible Representations of 3-dimensional Genus-one attractors are distinguished by three topological labels:

Parity	P
Global Torsion	N
Knot Type	KT

$$\Gamma^{P,N,KT}(\mathcal{SA})$$

Mechanism (stretch & fold, stretch & roll) is an invariant of embedding. It is independent of the representation labels.

Equivalent Reducible Representations

Topological indices (P,N,KT) are obstructions to isotopy for embeddings of minimum dimension (irreducible representations).

Are these obstructions removed by injections into higher dimensions (reducible representations)?

Systematically?

Equivalences by Injection

Obstructions to Isotopy

R^3	$\longrightarrow$	R^4	$\longrightarrow$	R^5
Global Torsion		Global Torsion		
Parity				
Knot Type				

There is one *Universal* reducible representation in R^N, $N \geq 5$. In R^N the only topological invariant is *mechanism*.

Summary

1 Question Answered $\Rightarrow$

2 Questions Raised

We must be on the right track !

Original Objectives Achieved

There is now a simple, algorithmic procedure for:

- Classifying strange attractors
- Extracting classification information

from experimental signals.

Result

There is now a classification theory for low-dimensional strange attractors.

1. It is topological
2. It has a hierarchy of 4 levels
3. Each is discrete
4. There is rigidity and degrees of freedom
5. It is applicable to R^3 only — for now

The Classification Theory has 4 Levels of Structure

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1. Basis Sets of Orbits

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2. Branched Manifolds

The Classification Theory has 4 Levels of Structure

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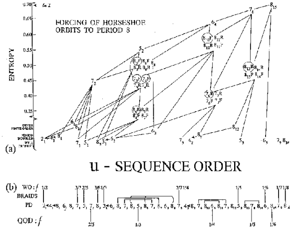
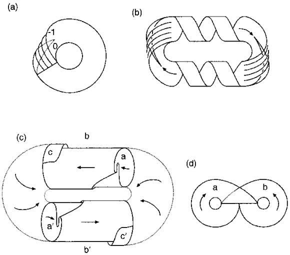
3. Bounding Tori

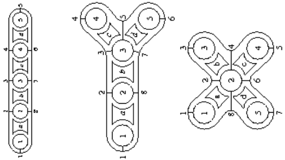
The Classification Theory has 4 Levels of Structure

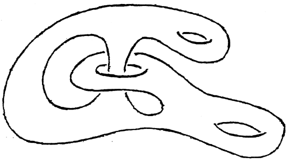
1. Basis Sets of Orbits
2. Branched Manifolds
3. Bounding Tori
4. Extrinsic Embeddings

Four Levels of Structure









Poetic Organization

LINKS OF PERIODIC ORBITS

organize

BOUNDING TORI

organize

BRANCHED MANIFOLDS

organize

LINKS OF PERIODIC ORBITS

Some Unexpected Results

- Perestroikas of orbits constrained by branched manifolds
- Routes to Chaos = Paths through orbit forcing diagram
- Perestroikas of branched manifolds constrained by bounding tori
- Global Poincaré section = union of $g-1$ disks
- Systematic methods for cover - image relations
- Existence of topological indices (cover/image)
- Universal image dynamical systems
- NLD version of Cartan's Theorem for Lie Groups
- Topological Continuation – Group Continuuation
- Cauchy-Riemann symmetries
- Quantizing Chaos
- Representation labels for inequivalent embeddings
- Representation Theory for Strange Attractors

We hope to find:

- Robust topological invariants for R^N, $N > 3$
- A Birman-Williams type theorem for higher dimensions
- An algorithm for irreducible embeddings
- Embeddings: better methods and tests
- Analog of χ^2 test for NLD
- Better forcing results: Smale horseshoe, $D^2 \rightarrow D^2$, $n \times D^2 \rightarrow n \times D^2$ (e.g., Lorenz), $D^N \rightarrow D^N$, $N > 2$
- Representation theory: complete
- Singularity Theory: Branched manifolds, splitting points (0 dim.), branch lines (1 dim).
- Singularities as obstructions to isotopy