

Dedicated to Carlo Maria Becchi

the Ricci flow
and
the Sausage

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Università di Parma and INFN

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MISSED OPPORTUNITIES¹

BY FREEMAN J. DYSON

It is important for him who wants to discover not to confine himself to one chapter of science, but to keep in touch with various others.

JACQUES HADAMARD

- ◆ A tale of two scientific quests - integrable QFT models and the classification of Riemannian manifolds, another chapter in Dyson's "MISSED OPPORTUNITIES" ?
- ◆ The renormalization of two-dim nonlinear "Sigma-model", integrable deformations and TBA (*Fateev and Al.B.Zamolodchikov*)
- ◆ The proof of Poincaré's conjecture after 100 years (*Grisha Perelman*)
- ◆ At the end, a personal recollection involving *Carlo Maria Becchi*.

The study of the “nonlinear sigma model” started in the ‘70s thanks to *Polyakov, Esker-Honenkamp*, and the Saclay school, *Brezin, Zinn-Justin, Le Grillou*.

Our story however starts with **Dan Friedan, 1980**:
“*Nonlinear Models in $2+\epsilon$ Dimensions*”, *PRL 45 (1980)*

$$S(\varphi) = \Lambda^\epsilon \int dx \frac{1}{2} T^{-1} g_{ij}(\varphi(x)) \partial_\mu \varphi^i(x) \partial_\mu \varphi^j(x)$$

The field φ takes values in the “target space M ”, a compact 2-dim Riemannian manifold. Path integral quantization leads to a regularized QFT. The “coupling” g_{ij} , under renormalization at two-loops evolves according to

$$\mu \frac{\partial}{\partial \mu} g_{ij} = -R_{ij} - \frac{1}{2} T R_{ikln} R_{jkl n} + O(T^2)$$

Full detail is found in Friedan's PhD Thesis, which appeared only in 1985 on Annals of Physics; this is the favorite quotation in the Math literature, probably because it appeared after Hamilton's paper? More later on ...

**THREE-MANIFOLDS WITH
POSITIVE RICCI CURVATURE**

RICHARD S. HAMILTON

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1. Introduction

Our goal in this paper is to prove the following result.

1.1 Main Theorem. *Let X be a compact 3-manifold which admits a Riemannian metric with strictly positive Ricci curvature. Then X also admits a metric of constant positive curvature.*

All manifolds of constant curvature have been completely classified by Wolf [6]. For positive curvature in dimension three there is a pleasant variety of examples, of which the best known are the lens spaces $L_{p,q}$. Wolf gives five

Received December 21, 1981.

- ◆ Developments: Fateev and Zamolodchikov analyzed the problem of quantizing the nonlinear sigma-model identifying it with a class of “Factorized Scattering Amplitudes” via Bethe Ansatz techniques. They introduced a class of exact solutions to the RG equation, the so-called “Sausage solutions” which are conjectured to act as “attractors” in the RG flow.
- ◆ Belardinelli, Destri and myself studied the RG equation numerically to find that the sausage solutions actually act as attractors in the space of metrics.

A numerical study of the RG equation for the deformed $O(3)$ nonlinear sigma model

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The numerical integration applies to a simplified form of the RG equation, obtained by specializing the metric to a conformal one, $g_{ij} = e^{\lambda(\phi)} \delta_{ij}$ which yields ($x \in S^2$) a sort of “dynamical Liouville equation”

$$\frac{\partial \lambda(x)}{\partial t} = -e^{-\lambda(x)} \Delta \lambda(x)$$

Deforming the sausage in an arbitrary way

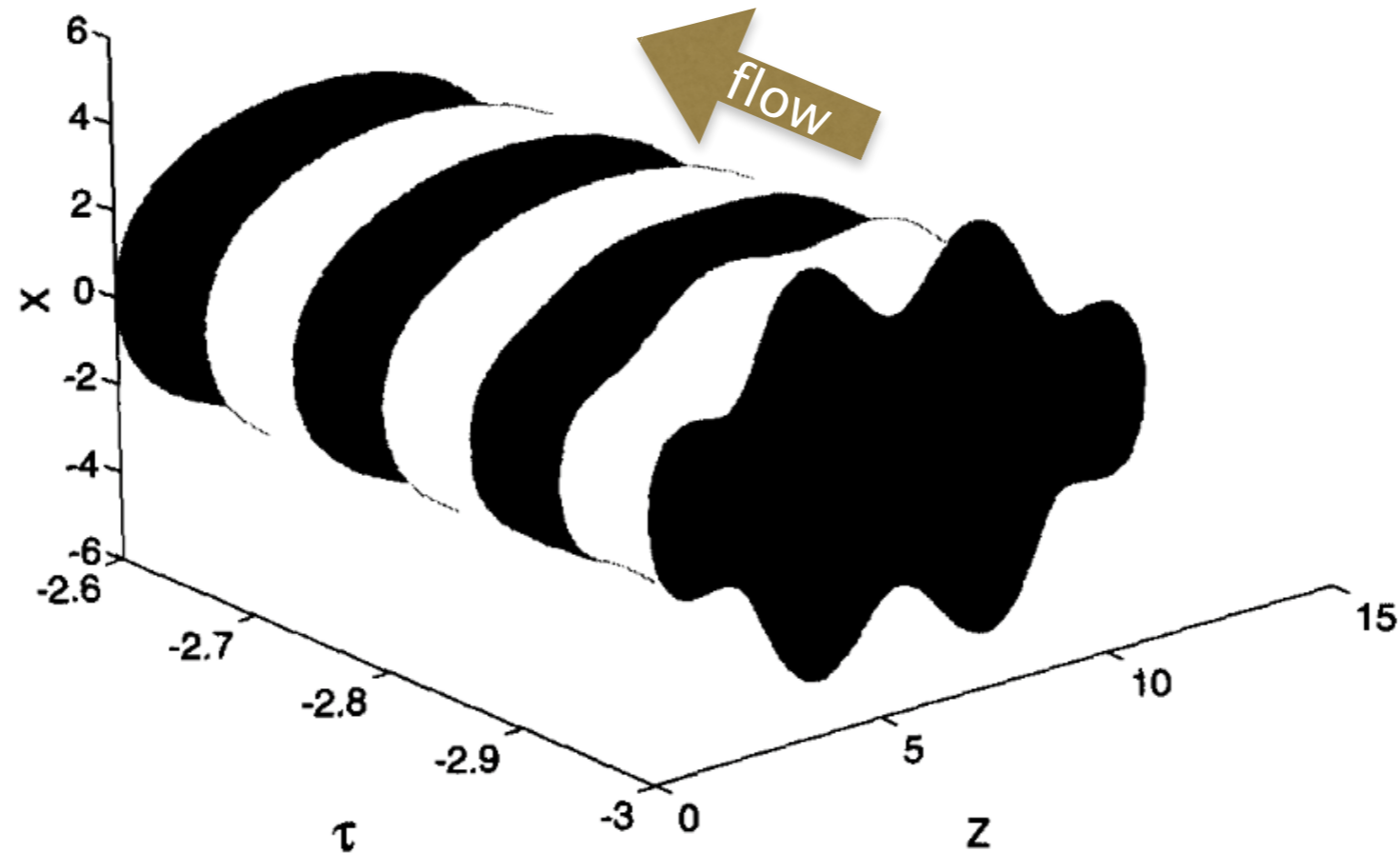


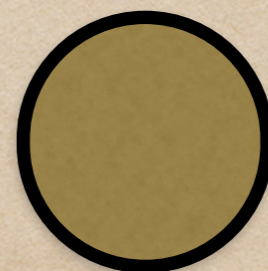
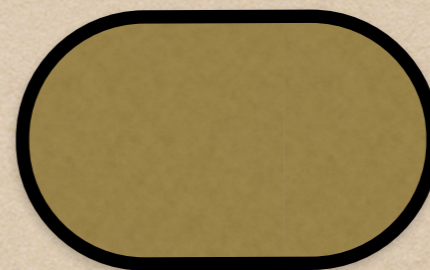
Fig. 4. A pictorial way of illustrating the attractive nature of the sausage solution.

$O(2)$ symmetric geometry evolves toward
 $O(3)$ symmetry through the sausage.

Our numerical code was inspired to the general idea of “spectral methods” in partial differential equations: the idea is to represent partial differential operators using spectral transforms, like Fourier, in such a way that one never uses finite differences approximations. This is particularly useful working on surfaces where Cartesian coordinates are not appropriate. The Laplace operator on S^2 is then represented algebraically by using a spherical harmonics transform. This made feasible also exploring two-loop RG equation with terms $(\Delta\lambda)^2$. The program was entirely realized in Matlab and it's still applicable.

FZ's "Sausage"

solutions were used
to test the correctness
of the code

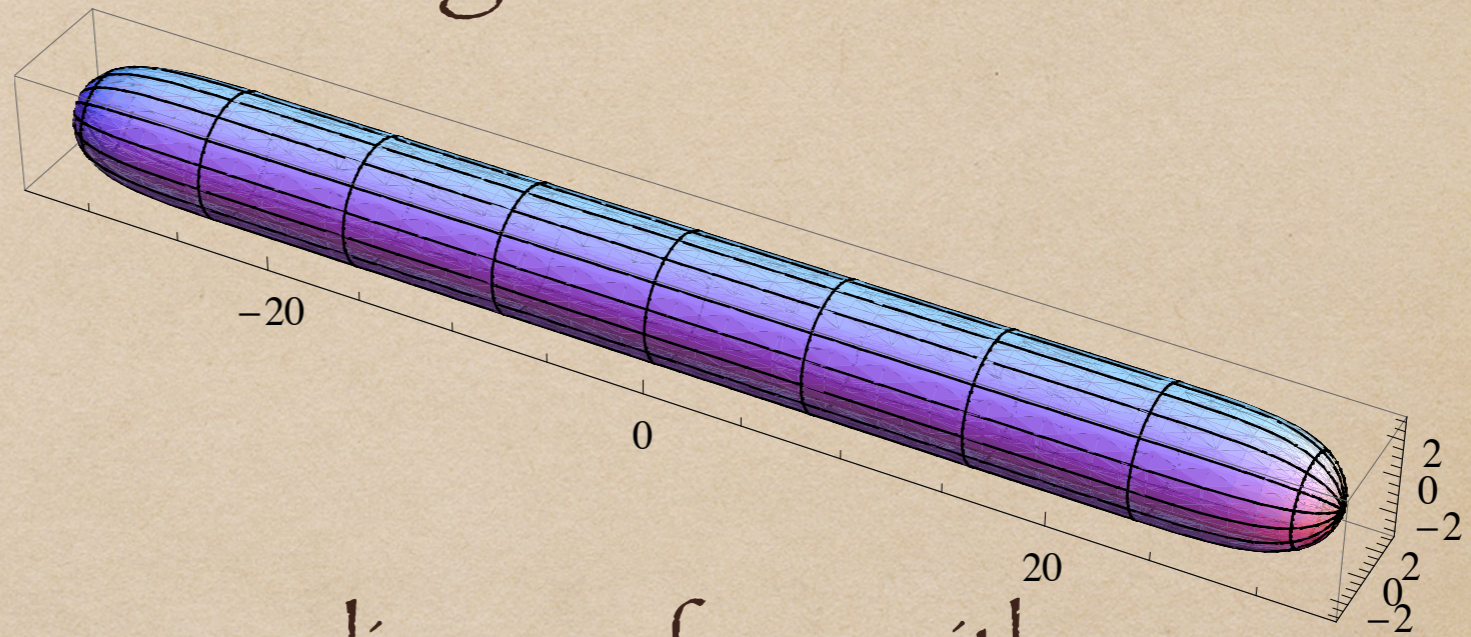


$$\lambda(y, \phi) = -\log(a(t) + b(t) \cosh(2y))$$

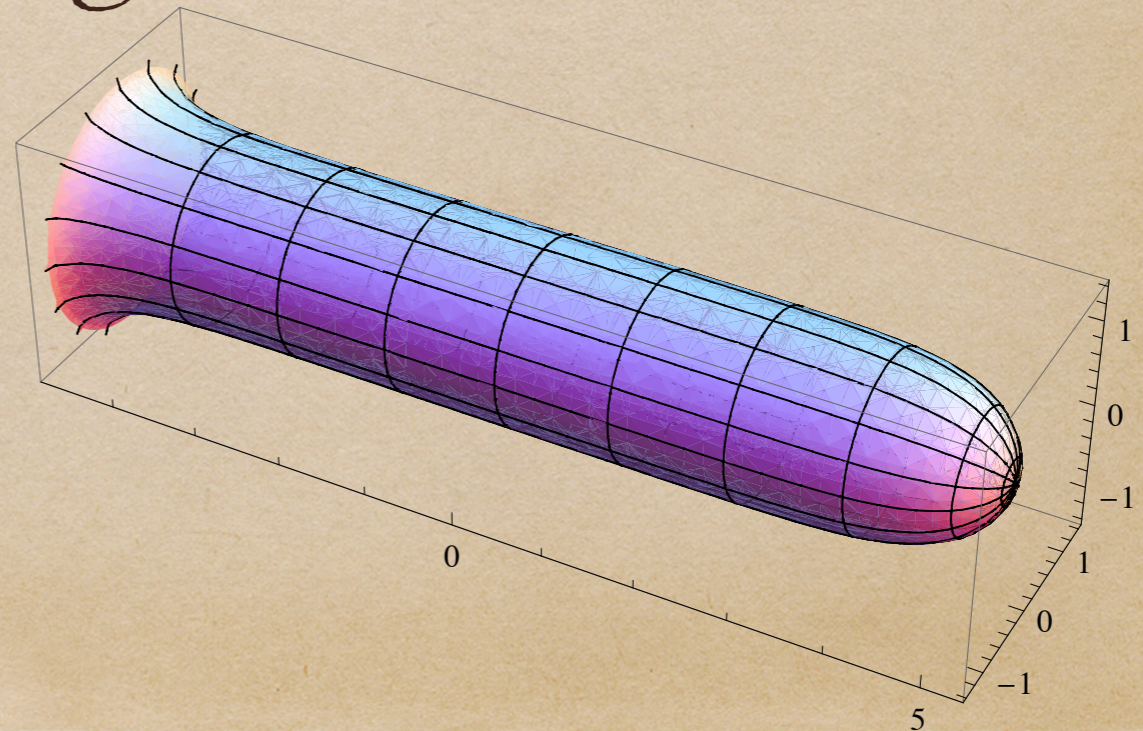
$$a(t) = \frac{1}{2}\nu \coth\left(\frac{1}{2\pi}\nu(t_0 - t)\right)$$

$$b(t) = \frac{1}{2}\nu / \sinh\left(\frac{1}{2\pi}\nu(t_0 - t)\right)$$

- ◆ another view of sausages



- ◆ and the corresponding surface with Minkowski metric:



...and meanwhile

- ◆ Hamilton's Ricci equation (1982)

Richard Hamilton starts a new chapter in Differential Geometry and Topology by introducing a flow in the space of all metrics generated by the equation

$$\frac{d g_{ij}}{d t} = -2R_{ij}$$

the so-called "Ricci equation"; this can be made a rigorous tool to explore the classification problem

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There followed an explosion of activities, documented in the mathematical literature - just try google, asking for “Ricci flow”, you will be overwhelmed by a massive amount of papers, difficult to master for a non-mathematician. This movement culminated in a rather unexpected way and in full glory with Perelman’s proof of Poincaré’s conjecture. Review papers, books both technical and expository appeared in recent times. Just see

B.Chow and D.Knopf, “The Ricci flow, an introduction”,

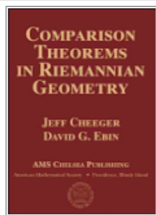
AMS, 2004

*D. O’Shea, “The Poincaré conjecture”,
W&Co, 2007*

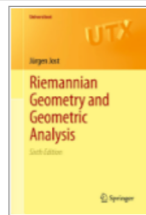




Comparison Geometry
Karsten Grove, Peter Petersen



Comparison Theorems in Riemannian Geometry
Jeff Cheeger, D. G. Ebin



Riemannian Geometry and Geometric Analysis
Jürgen Jost



Lectures on Harmonic Maps
Richard M. Schoen, Shing-Tung Yau



Three-dimensional Orbifolds and Their Geometric Structures
Michel Boileau, Sylvain Maillot



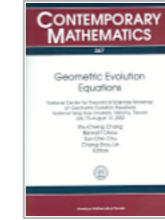
On the Extension Condition for Ricci Flow
Bing Wang



Ricci Flow and Geometrization of 3-Manifolds
John W. Morgan, Frederick R. Quinn



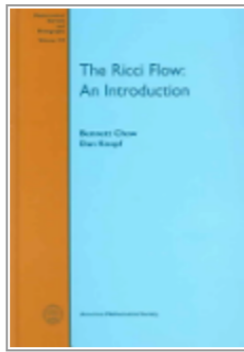
Sobolev Inequalities, Heat Kernels under Ricci Flow, and the Poincaré Conjecture
Qi S. Zhang



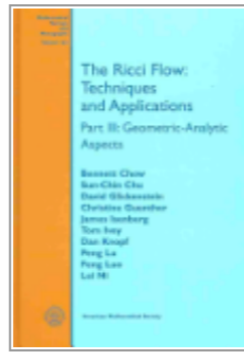
Geometric Evolution Equations
Shu-Cheng Chang



Comparison Geometry
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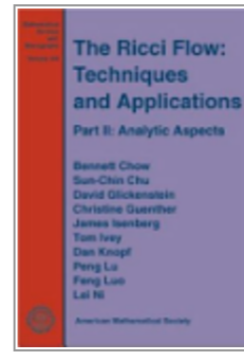
The Ricci Flow: An Introduction
Bennett Chow, Dan Knopf



The Ricci Flow: Techniques and Applications Part II: Geometric-Analytic Aspects
Bennett Chow, Sun-Chin Chu



Hamilton's Ricci Flow
Bennett Chow, Peng Lu, Lei Ni



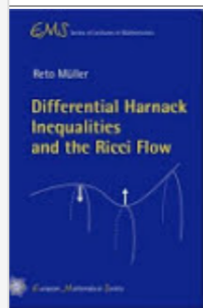
The Ricci Flow: Techniques and Applications Part II: Analytic Aspects
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Lectures on the Ricci Flow
Peter Topping



The Ricci Flow: Techniques and Applications Part I: Geometric Aspects
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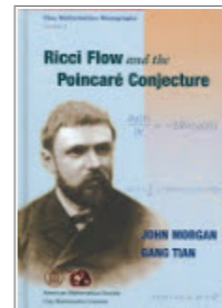
Differential Harnack Inequalities and the Ricci Flow
Reto Müller



The Ricci Flow in Riemannian Geometry
Ben Andrews, Christopher Bishop



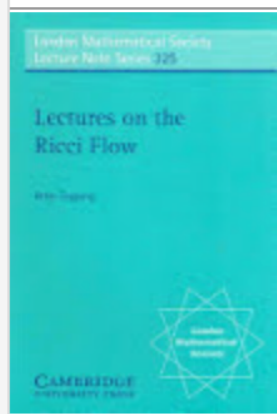
Precompactness of the Ricci Flow
David Alan Glickenstein



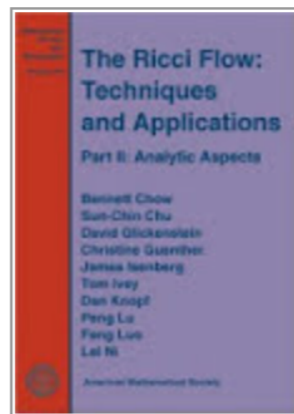
Ricci Flow and the Poincaré Conjecture
John W. Morgan, Gang Tian



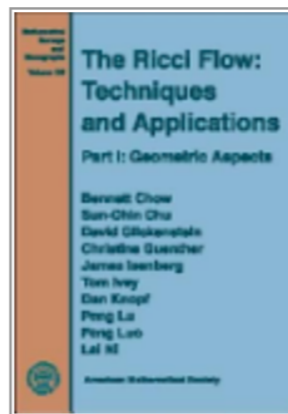
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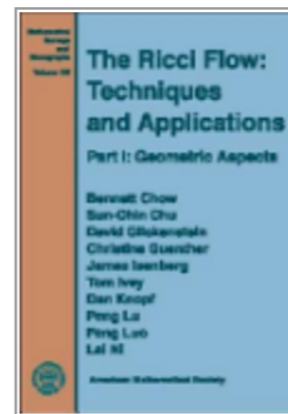
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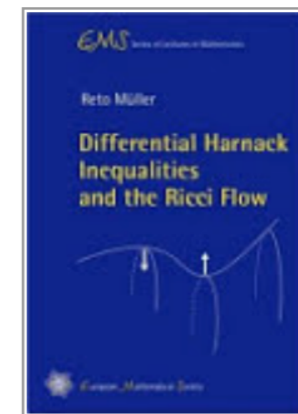
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- ◆ What I find rather astonishing is that in the era of internet with communication running at the speed of light Theoretical Physicists and Mathematicians have remained unaware for so long of each other efforts. For instance the convergence of any metric on S^2 to the constant curvature metric is contained as a special case in one of the theorems which you may find in Chow's papers. It's true, Mathematics produces very general results often too general for the sake of physics. FZ went a long way in deriving any single detail of the QFT of the nonlinear sigma-model, spectral results which are only qualitatively contained in Perelman's papers. This is what I regard as a candidate for a sequel of Dyson's "Missed Opportunities".

Now we can see some bridges laid down - for instance papers by **I. Bakas** and **G. Carfora**, to which I refer you for greater detail. In Chow-Knopf book reference is made to "Witten's black hole" or "cigar solution" to the **RE**. So some barriers are falling.

Let me end now with a personal recollection of a conversation I had long time ago with Carlo María.

- ◆ Carlo spent a couple of days in Trento, where I served as a newly appointed professor and spent some fruitful years in the late '80s. In a private conversation he expressed the idea that one should *study the evolution of the metric in the sigma model starting from deformed geometries, "something like potatoes"* ... I could not benefit much from Carlo suggestion, since I was totally ignorant at the time (and still now...) but I remembered his observation when I was involved in the "sausage" dynamics by Volodya Fateev. So, young men (and madams) listen to Carlo!
- ◆ "Potato physics" appeared in C. Becchi and C. Imbimbo, *Nucl.Phys.B462, 1996, 571, but beware: it's not light reading after dinner...*

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Thank you
for your patience