MATHEMATISCHES FORSCHUNGSINSTITUT OBERWOLFACH

Tagungsbericht 25/1997

# Nonlinear Evolution Equations

*29.6. – 5.7.1997*

Die Tagung fand unter der Leitung von Herrn S. Klainerman (Princeton), und Herrn M. Struwe (Zürich) statt. Die Teilnehmer kamen aus Deutschland, Frankreich, Italien, Japan, USA, Schweiz und anderen Ländern. Sie vertraten einen breiten Themenkreis aus dem Gebiet der nichtlinearen Evolutionsgleichungen. Schwerpunkte der Tagung waren die drei folgenden Themenkreise, denen ausser etlichen Vorträgen auch je eine "Discussion & Problem session" gewidmet waren:

- Geometrische Evolutionsprobleme
- Wellengleichungen
- Dispersionsgleichungen

Dieses Programm gab viele Anregungen und viel Gelegenheit zu fruchtbaren informellen Diskussionen.

# Zusammenfassungen:

## The focussing problem for the porous medium equation

by Sigurd Angenent (Madison)

Reporting on joint work with D. G. Aronson I discussed the linear stability of the "Gravelau solution" for the porous medium equation $v_t = (m-1)v\Delta v + |\nabla v|^2$. The G-solution is a radially symmetric self-similar solution (of the form $v(x,t) = (T-t)^a V((T-t)^{-b}|x|)$), which describes "hole filling", i. e. how a solution whose initial support contains a circular hole will fill up that hole.

We found that depending on $m$ the G-solution is unstable for small non-symmetric perturbations, and that as $m$ decreases to 1, the G-solution becomes more and more unstable.

An infinite sequence of bifurcations occurs for some sequence $m_n \downarrow 1$: at each $m_n$ a branch of self-similar solutions with only discrete (but not full rotational) symmetry appears.

## Semi-linear wave equations with supercritical nonlinearities

by Philip Brenner (Göteborg)

We prove that the solution operator $\mathcal{E}_t(\phi, \psi)$ for the nonlinear Klein-Gordon (and wave-) equations are not Lipschitz mappings from (a subset) of the energy space $(H' \cap L_{\rho+1}) \times L_2$ to $H^s_{q'}$ for $t \neq 0, (n+1)(\frac{1}{2} - \frac{1}{q'}) \leq 1, 0 \leq s \leq 1$. This is in contrast with the subcritical case, where the corresponding mappings are Lipschitz.

Here $\mathcal{E}_t(\phi,\psi) = u(\cdot,t)$ , where $u$ is the solution of the NLKG

$$\begin{cases} \partial_t^2 u - \Delta_x u + m^2 u + |u|^{\rho-1} u = 0, \quad t > 0, \quad x \in \mathbb{R}^n \\ u|_{t=0}(x) = \phi(x), \quad \partial_t u|_{t=0}(x) = \psi(x), \end{cases}$$

and $\rho > \rho_* = (n+2)/(n-2)$ in the supercritical case, $n \geq 4$.

This result was an introduction to a discussion of supercritical nonlinear wave equations and their solutions!

## Global existence of solutions of Yang-Mills equations

by Piotr Chrusciel (Tours)

In this talk I review what the Yang-Mills equations are, and the history of the existence problem. I also present a new theorem, proved in collaboration with J. Shatah, that asserts global existence of solutions of the Cauchy problem for the Yang-Mills equations on globally hyperbolic Lorentzian four-dimensional manifolds.

## Mean curvature evolution of spacelike hypersurfaces in Lorentzian manifolds

by Klaus Ecker (Clayton, Victoria)

In this talk we will present the use of mean curvature type evolution in the construction of spacelike hypersurfaces of prescribed mean curvature in Lorentzian manifolds. The case of spacetimes which admit a compact Cauchy surface had been studied in joint work with G. Huisken.

Our most recent work considers mean curvature flow of noncompact spacelike hypersurfaces in asymptotically flat spacetimes. We show that in Minkowski space mean curvature flow admits a global smooth solution for *arbitrary* spacelike initial data. This result is based on some new interior estimates which also hold in general asymptotically flat spacetimes.

We also present solutions of the flow which move by translation and discuss their geometric properties and possible applications to general relativity.

## The surface diffusion for immersed hypersurfaces

by Joachim Escher (Basel)

(joint work with U.F. Mayer and G. Simonett, Vanderbilt University)

Let $\Gamma_0$ be a compact closed connected orientable immersed hypersurface in $\mathbb{R}^n$. Find a family $\Gamma = \{\Gamma(t); t \geq 0\}$ of hypersurfaces satisfying the following evolution equation:

$$V(t) = \Delta_{\Gamma(t)} H_{\Gamma(t)}, \Gamma(0) = \Gamma_0 , \qquad (*)$$

where $V$ denotes the normal velocity of $\Gamma$, while $\Delta_{\Gamma(t)}$ and $H_{\Gamma(t)}$ stand for the Laplace-Beltrami operator and the mean curvature of $\Gamma(t)$, respectively. We prove that problem $(*)$ is classically well-posed for initial data $\gamma_0$ belonging to the class $C^{2+\alpha}$. If $\Gamma_0$ is sufficiently $C^{2+\alpha}$-close to an Euclidean sphere we show that the solution exists globally and converges exponentially fast in $C^\infty$ to a sphere.

## Stability of motion of graphs by singular weighted curvature

by Mi-Ho Giga (Sapporo)

A general stability result is established for general solutions of a family of nonlinear evolutions with non-local diffusion in one space dimension.

Our motivation comes from material sciences and the "crystalline algorithm". Our results justify the crystalline algorithm, also.

**A level set method — revisited**

by Yoshikazu Giga (Sapporo)

The comparison principle is one of the fundamental tools in the level set method for surface evolution equations including the mean curvature flow equation. It turns out that there are a couple of ways to establish the comparison principle. Other than the standard method, a dimension reduction argument and a barrier argument are presented. These methods are very important to establish the level set method for motion by nonlocal curvature including crystalline flow. A dimension reduction argument reduces the situation for graph-like surfaces rather than a closed hypersurface. A barrier argument reduces the problem to short time existence of smooth solutions.

**The Cauchy problem for the Zakharov system**

by J. Ginibre (Orsay)

We study the local Cauchy problem in time for the Zakharov system

$$\begin{cases} i\partial_t u + \Delta u = nu \\ \qquad \Box n = \Delta |u|^2 \end{cases}$$

governing Langmuir turbulence, with initial data

$$(u(0), n(0), \partial_t n(0)) \in H^k \oplus H^\ell \oplus H^{\ell-1},$$

in arbitrary space dimension $\nu$. We define a natural notion of criticality according to which the critical values of $(k,\ell)$ are $(\nu/2-3/2, v/2-2)$. Using a method recently developed by Bourgain, we prove that the Zakharov system is locally well-posed for a variety of values of $(k,\ell)$. The results cover the whole subcritical range for $\nu \geq 4$. For $\nu \leq 3$, they cover only part of it and the lowest admissible values are $(k,\ell) = (1/2, 0)$ for $\nu = 2,3$ and $(k,\ell) = (0,-1/2)$ for $\nu = 1$. As a by-product of the one-dimensional result, we prove well-posedness of the Benney system governing the interaction of short and long waves for the same values of $(k,\ell)$.

## Scattering problem for the Hartree type equations with a long range potential

by Nakao Hayashi (Tokyo)

(joint work with Pavel I. Naumkin)

We study the scattering problem and asymptotics for large time of solutions to the Cauchy problem for the Hartree type equations

$$\begin{cases} iu_t = -\frac{1}{2}\Delta u + f(|u|^2)u & (t,x) \in \mathbb{R} \times \mathbb{R}^n, \\ u(0,x) = u_0(x), \quad x \in \mathbb{R}^n, & n \geq 2, \end{cases}$$

where the nonlinear interaction term is $f(|u|^2) = V * |u|^2, V(x) = \lambda |x|^{-\delta}, \lambda \in \mathbb{R}, 0 < \delta < 1$. In the case $n \geq 2$ we suppose that the initial data $u_0 \in H^{n+2,0} \cap H^{0,n+2}$ and the value $\epsilon = ||u_0||_{H^{n+2,0}} + ||u_0||_{H^{0,n+2}}$ is sufficiently small. Then we prove that the following decay estimate $||u(t)||_{L^p} \leq C\epsilon t^{\frac{n}{p}-\frac{n}{2}}$ is valid for all $t \geq 1$ and $2 \leq p \leq \infty$. Furthermore we show that for $\frac{1}{2} < \delta < 1$ there exists a unique final state $\hat{u}_+ \in H^{n+2,0}$ such that for all $t \geq 1$

$$||u(t) - \exp(-\frac{it^{1-\delta}}{1-\delta} f(|\hat{u}_+|^2)(\frac{x}{t}))U(t)u_+||_{L^2} = O(t^{1-2\delta}),$$

where $\hat{\phi}$ denotes the Fourier transform of the function $\phi$, $H^{m,s} = \{\phi \in \mathcal{S}'; \|\phi\|_{m,s} = \|(1+|x|^2)^{s/2}(1-\Delta)^{m/2}\phi\|_{L^2} < \infty\}, m, s \in \mathbb{R}$.

## Heat-kernels and maximal $L^p$-$L^q$-regularity for evolution equations

by Matthias Hieber (Karlsruhe)

In this talk, we consider a priori estimates for solutions of the equation

$$u' + \mathcal{A}u = f$$

of the form

$$\int_0^T \|u_t\|_p^q dt + \int_0^T \|\mathcal{A}u\|_p^q dt \leq C \int_0^T \|f\|_p^q dt,$$

where $0 < T < \infty$, $1 < p, q < \infty$ and $\mathcal{A}$ is an elliptic differential operator with non-smooth coefficients, e.g. $a\Delta$ or $\mathrm{div}(a\,\mathrm{grad})$ with $a \in L^\infty$. We prove such an estimate for operators for which the kernel of $e^{t\mathcal{A}}$ satisfies an upper Gaussian bound and in particular for the examples above.

## Relativistic membranes and time-harmonic flow

by Jens Hoppe (Zürich)

Hypersurface motions in Riemannian manifolds whose normal velocity is proportional to the induced volume-element on the surface are shown to have the property that the time $t(x)$ at which the hypersurface passes a point $x$ is a harmonic function. In a Hamiltonian formulation (either using parametrized surfaces or, after Hamiltonian reduction, a space of shapes) the non-linear evolution equations are shown to possess infinitely many Poisson-commuting conservation laws. These time-harmonic flows are also related to the problem of finding extremal 3-manifolds in 4-dimensional Minkowski space, and to 2+1 dimensional gas-dynamics.

## New estimates for the mean curvature flow

by Gerhard Huisken (Tübingen)

(joint work with C. Sinestrari)

When $M_t^n \subset \mathbb{R}^{n+1}$ is a solution of mean curvature flow such that on $M_0^n$ $S_k(\vec{\lambda}) \geq 0$, where $S_k(\vec{\lambda}) = S_k(\lambda_1, \ldots, \lambda_n)$ is the $k$-th symmetric polynomial of the principal curvatures, then for all $\eta > 0$ there exists a constant $C_\eta > 0$ such that

$$S_{k+1} \geq -\eta S_k S_1 - C_\eta \quad \text{on } M^n \times [0, T].$$

In particular, any rescaling near a singularity leads to a surface with $S_{k+1}(\vec{\lambda}) \geq 0$.

## Non-uniqueness for the $p$-harmonic flow

by Norbert Hungerbühler (Zürich)

If $f_0 : \Omega \subset \mathbb{R}^m \to S^n$ is a weakly $p$-harmonic map from a bounded smooth domain $\Omega$ in $\mathbb{R}^m$ (with $2 < p < m$) into a sphere and if $f_0$ is not stationary $p$-harmonic, then there exist infinitely many weak solutions of the $p$-harmonic flow with initial and boundary data $f_0$, i.e. there are infinitely many global weak solutions $f : \Omega \times \mathbb{R}_+ \to S^n$ of

$$\begin{aligned} \partial_t f - \operatorname{div}(|\nabla f|^{p-2} \nabla f) &= |\nabla f|^p f \quad \text{weakly on } \Omega \times \mathbb{R}_+ \\ f &= f_0 \qquad \text{on the parabolic boundary.} \end{aligned}$$

We also show that there exist non-stationary weakly $(m-1)$-harmonic maps $f_0 : B^m \to S^{m-1}$.

In the proof, we first construct a global weak solution using approximations obtained by a time-discrete scheme, and the special geometry of the target manifold to pass to the limit. Then, we prove that in case of initial data which are weakly $p$-harmonic but not stationary, the constructed solution cannot be constant in time.

**Penrose inequality and inverse mean curvature flow**

by Tom Ilmanen (Evanston)

(This is joint work with G. Huisken.) The Penrose conjecture of general relativity, in its purely Riemannian case, states the following: in an asymptotically flat 3-manifold of nonnegative scalar curvature, the ADM mass bounds the area of each outermost minimal surface. Using the inverse mean curvature flow put forward by Geroch and Jang-Wald, we succeed in proving this, even though the evolving surfaces jump around in the 4-manifold. A corollary is the positive mass theorem of Schoen and Yau.

**Some evolution questions and results in general relativity**

by Jim Isenberg (Potsdam)

Einstein's equation is a hyperbolic system, with a well-posed Cauchy problem. While global existence for Einstein's equation is a subtle issue—since there is no fixed a priori spacetime—the behaviour of solutions into the far future and far past is of intense interest. For cosmological solutions—those with spatially compact Cauchy surfaces—the Hawking-Penrose singularity theorems indicate that generically the spacetimes are not geodesically complete.

The strong cosmic censorship conjecture then suggests that generically it is unbounded curvature which causes this incompleteness, and that generically a maximal globally hyperbolic solution cannot be extended across a Cauchy horizon. We discuss a number of results which support this open conjecture. The most recent result concerns solutions with a spatially acting $T^2$ isometry group. We use global existence techniques to show that every such solution admits a global foliation by constant $T^2$ orbit area hypersurfaces. This result should be very helpful for studying strong cosmic censorship for this family of solutions.

## Does a quantum particle know the time?

by Lev Kapitanski (Manhatten)

(joint work with I. Rodnianski)

We study the regularity of the solution $E(t,x)$ of the Schrödinger equation

$$\frac{1}{i}\partial_t E + \frac{1}{4\pi}\partial_x^2 E = 0$$

on the circle $x \in \mathbb{T} = \mathbb{R}/\mathbb{Z}$ with the initial condition

$$E(0,x) = \sum_{\mathbb{Z}} \delta(x-n).$$

We prove that for rational $t$, $E(t,\cdot)$ belongs to the Besov space $B_\infty^{-1}$. For a generic irrational $t$, the regularity of $E(t,\cdot)$ is $1/2$ better: $E(t,\cdot) \in B_\infty^{-1/2}$. We show that for every $\sigma \in [0,\infty)$ there is a class of irrationals $I(\sigma)$ such that $E(t,\cdot) \in B_\infty^{-\frac{1+\sigma}{2+\sigma}}$ if $t \in I(\sigma)$.

## Instability of the Euler equation

by Herbert Koch (Heidelberg)

The 2-d Euler equations for an incompressible fluid have many stationary solutions. If $f$ is an arbitrary function and $\Delta\phi = f(\phi)$, $\phi = 0$ at the boundary, then $u = \nabla^{\perp}\phi$ is a stationary solution to the Euler equation. We show that any stationary solution $\overline{u}$ in $C^{1,\alpha}$ is Ljapunov unstable if the vector field $\overline{u}$ has a hyperbolic stationary point.

It has been shown by Friedlander and Vishik that the linearized flow is exponentially unstable. Since the map from the initial data to the solution is not differentiable there seems to be no easy way to derive nonlinear instability from linearized stability in general. The instability is due to compression in one direction which we directly study for the nonlinear equation.

## Solutions of semi linear Schrödinger equations in $H^s$

by Hartmut Pecher (Wuppertal)

The Cauchy problem

$$\begin{cases} u_t + \Delta u = c|u|^{\sigma}u & c \in \mathbb{C} \\ u(x,0) = \phi(x) \in H^{s,2}(\mathbb{R}^n) \end{cases}$$

has a solution $u \in C^o([0,T], H^{s,2}(\mathbb{R}^n))$ locally in $t$ if the following conditions are satisfied:

$$n \geq 3, 0 \leq s < \tfrac{n}{2}$$

and moreover

a) if $0 \leq s \leq 2$: $\quad 0 < \sigma < \frac{4}{n-2s}$

b) if $2 < s < 4 : s - 2 < \sigma < \frac{4}{n-2s}$

c) if $s \geq 4 : \quad s - 3 < \sigma < \frac{4}{n-2s}$.

If in addition $\sigma \geq \frac{4}{n}$ and $||\phi||_{H^{s,2}}$ is sufficiently small, the solution is global in $t$. This generalizes former results of Cazenave-Weissler, Ginibre-Ozawa-Velo and Kato, namely the lower bound on $\sigma$ is improved to include less regular nonlinearities.

## Nash-Moser methods for the solution of nonlinear evolution equations

by Markus Poppenberg (Dortmund)

A general new method for the proof of local well-posedness of nonlinear evolution equations is discussed. This technique is based on a combination of Nash-Moser-methods with semigroup theory. Two applications are considered: The first result is a proof of the local well-posedness in $H^\infty$ in the fully nonlinear parabolic case; the proof is based on a generalized Nash-Moser implicit function theorem and uses semigroup theory and elliptic theory. The second application is a joint work with H. Lange and H. Teismann; the local well-posedness in $H^\infty$ is proved for the nonlinear Schrödinger equation

$$\begin{aligned} i\,u_t &= -\Delta u + \alpha(\Delta |u|^2)u \\ u(0) &= \varphi \end{aligned}$$

(where $\alpha$ is a real constant). This equation appears in several applications in physics (e.g. theory of superfluids).

## Contact problems in thermoelasticity — existence and exponential stability

by Reinhard Racke (Konstanz)

After a review of nonlinear evolution equations arising for initial boundary value problems to the *nonlinear* equations of thermoelasticity with *linear* boundary conditions — in particular discussing the relation of possible decay of solutions and the geometry of the domain —, we discuss contact problems. Here, the *linearized* equations are considered together with *nonlinear* boundary conditions of contact type. We present results on the existence of solutions both to the fully dynamical (hyperbolic-parabolic) and to the quasistatic (elliptic-parabolic) systems, combined with a description of the exponential stability. Ingredients of the proofs and methods used: penalty ansatz, energy methods, compactness by compensation.

## On solutions for periodic generalized KdV equations

by Gigliola Staffilani (Stanford)

In the first part of this talk we consider the problem of local and global well-posedness for the periodic generalized KdV initial value problem

$$\begin{cases} \partial_t u + \partial_x^3 u + \lambda u^k \partial_x u = 0 & \lambda \in \mathbb{R} \\ u(x,0) = \phi(x) & x \in \mathbb{T},\ t \in \mathbb{R}, \end{cases}$$

with initial data $\phi$ in the energy space $H^1$. The proof we present uses a change of variable together with a generalization of an argument due to Bourgain. In the second part we show that if the energy norm $H^1$ of the solution $u$ is uniformly bounded, then the solution is global in time and for its Sobolev norms we have the polynomial bound $\|u(t)\|_{H^s} \leq C|t|^{2s}$, $s \geq 1$. To prove this last result we cannot use Kato's smoothing effect, a good tool to obtain similar bounds on the line. We use instead bilinear estimates for functions in Bourgain spaces $Y^{s,b}$, with $s < 0$.

### Relativistic and Nonrelativistic Elastodynamics with Small Shear Strains

by A. Shadi Tahvildar-Zadeh (Princeton)

We present a new variational formulation for relativistic dynamics of isotropic hyperelastic solids. We introduce the shear strain tensor and study the geometry of characteristics in the cotangent bundle for the relativistic equations, under the assumption of small shear strains, and obtain a result on the stability of the double characteristic manifold. We then focus on the nonrelativistic limit of the above formulation, and compare it to the classical formulation of elastodynamics via displacements. We obtain a global existence result for small-amplitude elastic waves in materials under a constant isotropic deformation and a result on the formation of singularities for large data.

### Local and global well-posedness for semi-linear hyperbolic equations

by Daniel Tataru (Princeton)

The aim of this talk is to give an overview of some older and some recent results on local and global well-posedness. We describe the $X^{s,\theta}$ spaces associated to the wave operators, which have been crucial in most of the new results. Their multiplicative properties are also discussed, together with the various special structures of nonlinearities called null-forms. As it turns out, these spaces work only up to a certain point, and some new methods are necessary. In this context we give some improved bilinear estimates of Strichartz type. These new estimates eventually lead to modifications of the $X^{s,\theta}$ spaces that are crucial to the study of most of the remaining substantial problems. In particular we discuss some new results (joint with S. Klainerman) on Yang-Mills equations in $4+1$ dimensions, and also some new results on the wave map equation at the critical level in 4+ dimensions.

## Isoperimetric inequalities and flow by mean curvature

by Peter Topping (Zürich)

We explore the link between the mean curvature flow and inequalities relating geometric quantities such as area, volume, diameter and Willmore energy. On one hand we observe how isoperimetric inequalities can be extracted from the theory of curve shortening on surfaces; in particular we give a new inequality which simultaneously generalises the inequalities of Alexandrov, Huber, Bol and others. On the other hand, we find geometric inequalities which must be satisfied for the mean curvature flow in higher dimensions to evolve smoothly before disappearing at a point; in particular we give a lower bound for the area of a dumbbell in terms of its length which must be satisfied for its neck not to pinch off.

## Well-posedness in the energy class for the Cauchy problem of the Zakharov-Klein-Gordon equations

by Yoshio Tsutsumi (Tokyo)

We consider the time local well-posedness in the energy class for the Cauchy problem of the Zakharov-Klein-Gordon equations, when the Klein-Gordon wave and the acoustic wave have different propagation speeds.

## Asymptotically self-similar solutions of the nonlinear Schrödinger equation

by Fred Weissler (Villetaneuse)

(joint work with Thierry Cazenave)

We consider the equation

$$i\,u_t + \Delta u = \gamma |u|^\alpha u,$$

where $u = u(t,x)$, $t \in \mathbb{R}$, $x \in \mathbb{R}^N$, $u \in \mathbb{C}$, and $\gamma \in \mathbb{R}$. The initial value $u(0,x)$ is denoted $\phi = \phi(x)$. Inspired by recent work of Cannone and Planekon on the Navier-Stokes system, we show that if $\phi \in \mathcal{S}'$ is such that $\sup_{t>0} t^\beta \|e^{it\Delta}\|_{\alpha+2}$ is small, where $\frac{\alpha+2}{\alpha+1} < \frac{N\alpha}{2} < \alpha+2$ and $\beta = \frac{4-(N+2)\alpha}{2\alpha(\alpha+2)}$, then there is a (positively) global solution $u(t)$ of the NLS equation such that $t^\beta \|u(t)\|_{\alpha+2} \leq M$ for all $t > 0$. For $\phi$ we can take $\phi(x) = c\frac{P_k(x)}{|x|^{\frac{2}{\alpha}+k}}$, where $P_k$ is a homogeneous polynomial of degree $k$, and $c$ is small. Such $\phi$ give rise to self-similar solutions (non-radial if $P_k$ is non-radial).

Writing $\phi = \phi_1 + \phi_2$ where $\phi_1$ has compact support and contains the singularity at the origin, and letting $u_2(t)$ be the solution with initial value $\phi_2$, we show that $\|u_2(t) - u(t)\|_{\alpha+2}$ decays more rapidly than $t^{-\beta}$, and so $u_2$ is asymptotically self-similar as $t \to \infty$. Note that $u_2 \in H^1$ if $\alpha < \frac{4}{N}$. Finally, if $\frac{4}{N} < \alpha < \frac{4}{N-2}$, we use the pseudo-conformal transformation to construct *locally* $H^1$ solutions which blow up in finite time with an asymptotically self-similar profile.

## Global Equivariant Yang-Mills Connections on the $1+4$ Dimensional Minkowski Space

by Lutz Wilhelmy (Zürich)

We construct global equivariant Yang-Mills fields on the $1+4$ dimensional Minkowski space for data with finite energy. The solution obtained is unique within a certain regularity class. Its positive Yang-Mills energy is conserved with the exception of finitely many times $t_i$. At these instants at least a certain amount of energy is absorbed in the spatial origin. While we cannot exclude that the Yang-Mills potential becomes singular also during time intervals between consecutive $t_i$, the Yang-Mills fields and the stress-energy-momentum tensor are at most singular at these instants and then only at the spatial origin. For regular data with small total energy the solution is globally regular.

The reduced equation is very similar to the equation for equivariant wave maps. The arguments carry over to this problem and provide an alternative approach to the global existence results for wave maps of Shatah and Tahvildar-Zadeh.

`Berichterstatter: Norbert Bollow/Norbert Hungerbühler`

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