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## Hyperbolic Techniques in Modelling, Analysis and Numerics

Organised by  
Rinaldo M. Colombo, Brescia  
Philippe G. LeFloch, Paris  
Christian Rohde, Stuttgart

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**ABSTRACT.** Several research areas are flourishing on the roots of the breakthroughs in conservation laws that took place in the last two decades. The meeting played a key role in providing contacts among the different branches that are currently developing. All the invitees shared the same common background that consists of the analytical and numerical techniques for nonlinear hyperbolic balance laws. However, their fields of applications and their levels of abstraction are very diverse.

The workshop was the unique opportunity to share ideas about analytical issues like the fine-structure of singular solutions or the validity of entropy solution concepts. It turned out that generalized hyperbolic techniques are able to handle the challenges posed by new applications. The design of efficient structure preserving methods turned out to be the major line of development in numerical analysis.

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### Introduction by the Organisers

The workshop *Hyperbolic Techniques in Modelling, Analysis and Numerics*, organized by Rinaldo M. Colombo (Brescia), Philippe G. LeFloch (Paris) and Christian Rohde (Stuttgart) welcomed 46 invitees from eight different countries. The group of attendants included besides internationally renowned researchers doctoral students and young postdocs. The program consisted of longer comprehensive lectures but also of a small number of short presentations given by young researchers. The general topic of the workshop circled around the mathematical theory of hyperbolic partial differential equations, in particular of balance laws, which has seen an astonishing development in the last two decades. The progress in analysis and

numerics was mainly driven by challenges from continuum mechanics, a prominent role being played by shock waves in gas dynamics. Modeling through hyperbolic partial differential equations has now become a cornerstone in many other branches of science, for instance wherever nonlinear transport phenomena occur. Many new models have been derived, which, in turn, pose completely new questions to the mathematical theory and to the numerical analysis of hyperbolic equations. Given this background, the meeting tried to exploit and foster all possible synergies. Apparently, new joint cooperations can be tracked back to the interaction during the workshop week.

An interesting new development in the field is the characterization of singularity development and transport in different instances of nonlinear wave equations by hyperbolic techniques. Alberto Bressan developed a program to describe the fine structure of sets of generic singularities in a wide class of wave equations. Stefano Bianchini presented new results on a detailed description of the entropy dissipation connected to the emergence of shock waves. Stefano Modena showed how a Lagrangian approach can be used to achieve a deeper insight in the behaviour and the structure of the solutions to hyperbolic conservation laws. Wave breaking in the Hunter-Saxton system was the topic of Anders Nordli. The understanding of the interaction of dispersive approximations and shock waves is far from being a settled problem. Michael Shearer reported on various phenomena related to Korteweg- and Boussinesq-type equations. Sylvie Benzoni demonstrated how modulation theory can help to understand discrete wave motion. Using variational time discretization Michael Westdickenberg gave an existence proof for measure valued solutions of the full Euler system including a characterization of the entropy dissipation. Eitan Tadmor showed how to derive new  $BV$ -estimates for the pressureless Euler equations in multiple space dimensions. The talk of Jan Giesselmann on relative entropies for Hamiltonian systems like Euler–Korteweg equations fitted also in this context. Christian Klingenberg broached the issue of the effect of different linearization levels in numerical schemes for multidimensional Euler equations. Even linear wave equations with rough coefficients can pose major difficulties to numerical discretisation methods as was shown by Franziska Weber. This applies even more for hyperbolic systems with uncertainty. Alina Chertock proposed a splitting method for the efficient stochastic Galerkin discretization of Euler systems. The challenges of low Mach number scenarios in astrophysical flows have also been discussed by Christian Klingenberg.

The analytical study of singular limits and associated numerical questions on the design of structure-preserving schemes for asymptotic regimes provided the joint chord for another block of contributions. The study of the zero-viscosity limit, i.e. the passage from a parabolic regularization towards a hyperbolic limit problem, is a seminal topic in the field. Driven by the needs of applied sciences, a much wider variety of asymptotic scenarios is analyzed currently. In this context, Andrea Corli gave a presentation on the study of nonlinear diffusion approximations. Within the workshop, Gianluca Crippa devoted his talk to the passage from non-local to local hyperbolic balance laws. Numerical aspects of non-local evolution equations

have been the topic of Elena Rossi. Graziano Guerra presented rigorous results for the compressible-incompressible passage covering discontinuous solutions. On the numerical side a novel class of asymptotic preserving finite-volume schemes that deal efficiently with weakly compressible low Mach number flows has been advocated by Mária Lukáčová-Medvidová. Manuel Torrilhon reviewed the analysis and numerics for the whole hierarchy of moment systems for the Boltzmann equations. The construction of new stable discretization schemes for moment equation was the topic of the lecture given by Philippe Helluy. Konstantina Trivisa discussed related model hierarchies to describe phenomena of collective self-organization.

As mentioned before, new applications have been always a driving force for the field. Phase transition in compressible two-phase flows has been studied by Ferdinand Thein generalizing the classical Riemann solver concept. Athanasios Tzavaras showed how mixed type models can help to understand shear band instabilities. The control of hyperbolic transport systems for population dynamics has been discussed by Mauro Garavello. The study of in particular hyperbolic evolutions on manifolds and networks is still an emerging research field. This has been addressed in the presentation of Raul Borsche on chemotactic movement on graphs and the lecture of Helge Holden about a hyperbolic transport equation which allows the numerical verification of the well-known Braess paradoxon in traffic flow. Francesca Marcellini showed how hyperbolic Riemann solver techniques can be used to understand the behavior of road traffic at junctions.

Finally the workshop was closed with an overview talk also given by Helge Holden who summarized the state of the art in the field and proposed a number of new challenges.

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## Workshop: Hyperbolic Techniques in Modelling, Analysis and Numerics

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## Abstracts

### On modulated equations for Hamiltonian PDEs

SYLVIE BENZONI-GAVAGE

(joint work with C. Mietka, L. Miguel Rodrigues)

The zero dispersion limit in dispersive perturbations of hyperbolic PDEs is a challenging topic, which is well understood only for the Korteweg-de Vries equation [9, 10, 11, 12], and, to some extent, the cubic Schrödinger equation [8]. For more general equations like the Euler–Korteweg (EK) system or even generalized KdV equations (gKdV), a preliminary route consists in investigating *modulated equations*.

We have undertaken to explore this route for a general class of *Hamiltonian PDEs* that contains EK and gKdV, the former itself containing the fluid formulation of nonlinear Schrödinger equations (NLS) and various other models of mathematical physics.

These Hamiltonian PDEs are of the form

$$(1) \quad \partial_t \mathbf{U} = \partial_x (\mathbf{B} \delta \mathcal{H}(\mathbf{U})),$$

where the unknown  $\mathbf{U}$  is (possibly) vector-valued,  $\mathbf{B}$  is a symmetric and nonsingular matrix, and  $\delta \mathcal{H}(\mathbf{U})$  denotes the variational derivative of an energy  $\mathcal{H} = \mathcal{H}(\mathbf{U}, \mathbf{U}_x)$  depending on  $\mathbf{U}$  and its spatial derivative  $\mathbf{U}_x$ . In practice, we restrict to a framework that is compatible with the examples mentioned here above, in which  $\mathbf{U}$  is either scalar-valued (*e.g.* for gKdV) or with values in  $\mathbb{R}^2$  (*e.g.* for EK), and the energy  $\mathcal{H}$  depends only on the first derivative of a single component of  $\mathbf{U}$ , in a quadratic manner.

Formally, the zero dispersion limit of the system (1) is obtained by substituting the ‘standard’ energy  $E(U) := \mathcal{H}(\mathbf{U}, 0)$  for  $\mathcal{H}(\mathbf{U}, \mathbf{U}_x)$ , which yields the first order system of conservation laws

$$(2) \quad \partial_t \mathbf{U} = \partial_x (\mathbf{B} \nabla_{\mathbf{U}} E(\mathbf{U})).$$

When linearized about a ‘stable’ constant state  $\mathbf{U}_0$  this system admits harmonic waves that propagate at a speed independent of their frequency, namely one of the characteristic speeds. By contrast, linear waves associated with (1) are dispersive, since the dispersion relation involves the differential operator  $\delta^2 \mathcal{H}(\mathbf{U}_0)$ , which is ‘generically’ of second order, instead of the matrix  $\nabla_{\mathbf{U}}^2 E(\mathbf{U}_0)$  for (2).

As far as nonlinear systems are concerned, the well-known shock waves propagated by (2) are expected to have dispersive counterparts that are oscillatory, unsteady solutions to (1). These dispersive patterns are referred to as *dispersive shocks*, and have been an active field of research for the last decades, especially from the physical point of view, see for instance [13].

Since the seminal work of Whitham in the late 1960s [14], *modulated equations* have been viewed as governing the propagation of oscillatory wave trains, and more precisely the evolution of averaged quantities associated with wave trains.

In particular, dispersive shocks were first interpreted in the light of modulated equations by Gurevich and Pitaevskii [7] in 1973. This was for KdV, and by extension we speak of the Gurevich–Pitaevskii problem for the determination of dispersive shocks associated with any dispersive equation.

However, there has been some fuzziness in the terminology, in that the term dispersive shock can be meant to describe either exact solutions to the original dispersive PDEs or some (supposedly) approximate solutions to these PDEs that are actually associated with exact, rarefaction wave solutions to modulated equations. The former are in most cases – meaning, apart from the KdV case, basically – far from being known to exist. As regards the latter, their understanding has been improved thanks to a breakthrough by El [4] and subsequent work by himself and co-authors. See for instance the review paper by El and Hoefer [5] and references therein. Nevertheless, there is not yet a rigorous proof of the existence of these idealized dispersive shocks as rarefaction wave solutions to modulated equations associated with dispersive PDEs that are not completely integrable.

We have been working on modulated equations associated with abstract systems of the form (1) with the aim of filling this gap. So far, we have pointed out a simple set of coordinates in which modulated equations are in closed form and that sheds new light on the Gurevich–Pitaevskii problem.

To explain briefly how these modulated equations look like, let us recall that the building blocks of modulated equations are *periodic travelling wave* solutions to (1). If (1) has  $N$  equations, a periodic travelling wave is ‘generically’ parametrized by  $(N + 2)$  parameters. A ‘slowly’ modulated wave train is a perturbation of a periodic travelling wave obtained by letting parameters vary on large time scales and large space scales. Modulated equations are partial differential equations for the slowly varying parameters, obtained by averaging over a period of the underlying wave.

In their basic form it is not obvious that modulated equations are in closed form. It turns out that a suitable set of coordinates is given by

- the local wave number, denoted by  $k$ ,
- the average value of the wave profile  $\underline{\mathbf{U}}$ , denoted by  $\mathbf{M}$ ,
- another scalar dependent variable that can be expressed in a simple manner in terms of  $k$ ,  $\mathbf{M}$ , and the average value of the *momentum*, or Benjamin’s impulse, along the wave.

To be more precise, this last variable reads

$$\alpha := \frac{1}{k} (\langle \mathcal{Q}(\underline{\mathbf{U}}) \rangle - \mathcal{Q}(\mathbf{M})),$$

where  $\mathcal{Q}(\underline{\mathbf{U}}) := \frac{1}{2} \underline{\mathbf{U}}^T \mathbf{B}^{-1} \underline{\mathbf{U}}$  is the momentum, and  $\langle \mathcal{Q}(\underline{\mathbf{U}}) \rangle$  denotes its average value along the wave. Introducing, in addition, the averaged energy  $H := \langle \mathcal{H}(\underline{\mathbf{U}}, \underline{\mathbf{U}}_x) \rangle$ , we have shown that it can be viewed as a function of  $(k, \alpha, \mathbf{M})$ , and



that the modulated equations associated with (1) read

$$(3) \quad \begin{cases} \partial_t k = \partial_x(\partial_\alpha H), \\ \partial_t \alpha = \partial_x(\partial_k H), \\ \partial_t \mathbf{M} = \partial_x(\mathbf{B} \nabla_{\mathbf{M}} H). \end{cases}$$

It is to be noted that this formulation was obtained in the special case of the Euler–Korteweg system in Lagrangian coordinates by Gavriluk and Serre in [6] (also see [1] for further explanations). The appealing form (3) of modulated equations has a number of implications investigated in the forthcoming paper [2]. Also see [3] for an earlier study of modulated equations associated with an abstract system of the form (1).

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# Concentration of entropy dissipation for $L^\infty$ -entropy solutions of scalar conservation laws in one-space dimension

STEFANO BIANCHINI

(joint work with Elio Marconi)

We consider the following problem: let  $u$  be a bounded entropy solution to the scalar conservation law

$$(1) \quad u_t + f(u)_x = 0, \quad u \in [-M, M], \quad f : \mathbb{R} \rightarrow \mathbb{R} \text{ smooth},$$

with initial datum  $u_0(x)$ . Being an entropy solution, by definition for all convex entropies  $\eta$  it holds in distributions

$$(2) \quad \eta(u)_t + q(u)_x \leq 0,$$

where  $q'(u) = f'(u)\eta'(u)$  is the entropy flux. In particular the r.h.s. of (2) is a negative locally bounded measure  $\mu_\eta$ , with the additional property that  $\mu_\eta(B) = 0$  for all Borel sets  $B$  such that  $\mathcal{H}^1(B) = 0$ : this last property is a consequence of being the divergence of an  $L^\infty$  vector field.

For BV solutions, Volpert's formula together with the definition of the entropy flux  $q$  gives that

$$\begin{aligned} & \eta(u)_t + q(u)_x \\ &= \eta'(u) \left( D_t^{\text{cont}} u + f'(u) D_x^{\text{cont}} u \right) \\ & \quad + \sum_{i \in \mathbb{N}} \left\{ -\dot{\gamma}_i(t) \left[ \eta(u(t, x+)) - \eta(u(t, x-)) \right] \right. \\ & \quad \quad \left. + \left[ q(u(t, x+)) - q(u(t, x-)) \right] \right\} g_i(t) \mathcal{H}^1 \llcorner_{\text{Graph}(\gamma_i)} \\ &= \sum_{i \in \mathbb{N}} \left\{ -\dot{\gamma}_i(t) \left[ \eta(u(t, x+)) - \eta(u(t, x-)) \right] \right. \\ & \quad \quad \left. + \left[ q(u(t, x+)) - q(u(t, x-)) \right] \right\} g_i(t) \mathcal{H}^1 \llcorner_{\text{Graph}(\gamma_i)}, \end{aligned}$$

where

- (1)  $D^{\text{cont}} u = (D_t^{\text{cont}} u, D_x^{\text{cont}} u)$  is the continuous part of the measure  $Du$ ,
- (2)  $u(t, x\pm)$  is the right/left limit of  $u(t)$  at the point  $x$ ,
- (3) the curves  $\gamma_i$  are such that

$$D^{\text{jump}} u = \sum_i (u(t, x+) - u(t, x-)) \begin{pmatrix} 1 \\ -\dot{\gamma}_i(t) \end{pmatrix} g_i(t) \mathcal{H}^1 \llcorner_{\text{Graph}(\gamma_i)}.$$

In short we will say that *the entropy dissipation is concentrated*, meaning that the measure  $\mu_\eta$  is concentrated on a  $\mathcal{H}^1$ -rectifiable set  $J$ . A simple superposition argument implies that  $J$  can be chosen to be independent on  $\eta$ .

For general  $L^\infty$ -entropy solutions, in the case the flux is uniformly convex, the solution is BV for all positive times due to Oleinik estimate [9]

$$D_x u(t) \leq \frac{\mathcal{L}^1}{ct},$$

and then the above computation applies.

For more general flux functions, in [8] it has been proved that under the assumption that  $f$  has finitely many inflection points (together with a regularity assumption on the local behavior of  $f$  about an inflection point), then again the entropy is concentrated: here the set  $J$  is the set where the characteristic speed  $f'(u(t, x))$  jumps, which has been proved to be a BV function in [4]. However for general flux  $f$  it can be shown that  $f'$  is not BV.

The main result is the following:

**Theorem.** *If  $u$  is a bounded entropy solution of a scalar conservation law, then the entropy dissipation is concentrated.*

No assumptions on the flux function  $f$  have been made, i.e. it can have flat parts of Cantor-like sets where  $f'' = 0$ . Such a statement is a corollary of a detailed description of the regularity of bounded entropy solutions, description which is at the core of this analysis.

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## Kinetic and macroscopic models for chemotaxis on networks

RAUL BORSCHÉ

We are interested in cell movement on networks. This can be described by different models along the edges of the network, which are supplemented by coupling conditions at the nodes. In this work we develop coupling conditions for different chemotaxis models. The starting point is the description of cell movement along the edges by a kinetic model. Since the equation is hyperbolic, it is sufficient to focus on a single junction from which arbitrary networks can be constructed. Consider for  $i \in \{1, \dots, N\}$

$$\partial_t f_i + \frac{1}{\epsilon} v \cdot \partial_x f_i = -\frac{\lambda}{\epsilon^2} \left( f_i - \frac{\rho}{2} \right) + \frac{1}{2\epsilon} \alpha v \overline{\partial_x m_i} \rho$$

$$\partial_t m_i - D(\partial_{xx}) m_i = \gamma_\rho \rho_i - \gamma_m m_i ,$$

where  $\overline{\partial_x m} = \frac{\partial_x m}{\sqrt{1+|\partial_x m|^2}}$  and  $\rho = \int_{-1}^1 f(t, x, v) dv$ .  $f(t, v, x)$  is the density of cells at time  $t \in [0, T]$ , location  $x \in \mathbb{R}^+$  and with velocity  $v \in [-1, 1]$ .  $m(t, x)$  is quantifying the chemoattractant emitted by the cells. At the boundary at  $x = 0$  the values of  $f(t, 0, v)$  for  $v > 0$  have to be prescribed. At a junction we determine these values from the outgoing quantities  $f(t, 0, v)$  for  $v < 0$  in the following way

$$(1) \quad f^+ = A f^- , \quad v > 0 ,$$

where  $f^+ = f(t, 0, v)$  and  $f^- = f(t, 0, -v)$ .

From the kinetic model different macroscopic models can be derived [1]. In the following we consider a model hierarchy as shown in figure 1.

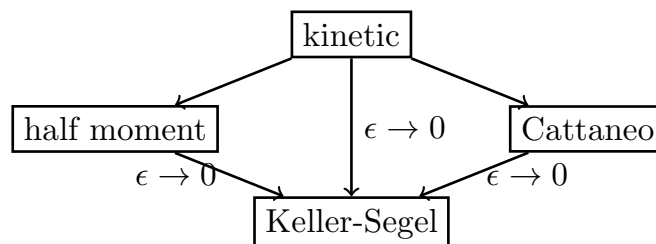


FIGURE 1. Hierarchy of models describing chemotaxis.

The half moment model is obtained by integrating the kinetic equation with respect to half spaces  $v > 0$  and  $v < 0$  and defining the macroscopic quantities

$$\rho^- = \int_{-1}^0 f(v) dv , \quad \rho^+ = \int_0^1 f(v) dv , \quad q^- = \int_{-1}^0 v f(v) dv , \quad q^+ = \int_0^1 v f(v) dv .$$

This set of equations can be closed using the ansatz functions  $f(v) = a^+ + vb^+$ ,  $v \geq 0$ ,  $f(v) = a^- + vb^-$ ,  $v \leq 0$ , which leads to a hyperbolic model system for four unknowns. The corresponding coupling conditions are obtained by integrating (1) for positive velocities, as well as their first moment.

For the Cattaneo model consider the integral over the full velocity space with

$$\rho(x, t) = \int_{-1}^1 f(x, t, v) dv, \quad q(x, t) = \frac{1}{\epsilon} \int_{-1}^1 v f(x, t, v) dv$$

and the linear closure ansatz  $f(x, t, v) = \frac{1}{2}\rho(x, t) + \epsilon \frac{3}{2}vq(x, t)$ . For the coupling conditions the closure is inserted into (1) and integrated over positive velocities. Thus the coupling conditions depend on the choice of the closure. The resulting equations are of the same form as the coupling conditions proposed by [2].

Finally the Keller-Segel model is obtained by considering the limit  $\epsilon \rightarrow 0$  in the above models. Also the coupling conditions converge in all three cases to those conditions investigated in [4]. In numerical examples this convergence is analyzed numerically on networks using asymptotic preserving schemes [3]. Properties like the conservation of mass or positivity at the node persist from the kinetic level to the Keller-Segel equation.

In a future work we plan to investigate models assuring positive values for the densities and to extend this procedure to other phenomena on networks.

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## Generic singularities of solutions to some nonlinear wave equations

ALBERTO BRESSAN

For a wide class of nonlinear hyperbolic PDEs, it is well known that solutions can develop singularities within finite time.

In general, the structure of the set where the solution is not smooth can be extremely complicated. However, at least in the case of one space dimension, it is reasonable to expect that for generic initial data the solution develops singularities only along a finite set of points or curves in  $t$ - $x$  space. Here “generic” should be understood in a topological sense, i.e., for all initial data in the intersection of countably many open dense sets in the space  $\mathcal{C}^k(\mathbb{R})$ , for a suitable  $k \geq 1$ . Three main settings will be considered here.

1) Hyperbolic systems of conservation laws:

$$u_t + f(u)_x = 0. \tag{1}$$

For a scalar conservation law, Schaeffer [13] has shown that, for an open dense set of initial data in  $\mathcal{C}^3$ , the solution contains finitely many shocks, on any bounded

region of the  $t$ - $x$  plane. This result has been extended in [9] to a particular class of hyperbolic systems, where shock and rarefaction curves coincide. On the other hand, for  $3 \times 3$  system, the recent analysis in [8] shows that a wide class of solutions can develop infinitely many jumps in finite time.

At the present time, the problem of generic regularity remains open for  $2 \times 2$  systems of conservation laws, such as isentropic gas dynamics. Indeed, for such systems one conjectures that, for a generic initial data in  $\mathcal{C}^3(\mathbb{R}, \mathbb{R}^2)$ , the solution remains smooth outside a locally finite family of shock curves. We recall that, for  $2 \times 2$  systems, a detailed description of the formation of new shocks was provided in [12].

2) The Burgers-Hilbert equation:

$$u_t + (u^2/2)_x = H[u], \quad (2)$$

where the right hand side contains the Hilbert transform of  $u$ . This equation was derived in [1] as a model of nonlinear waves with constant frequency. For initial data in  $H^2(\mathbb{R})$ , the local existence and uniqueness of the solution to (2) was proved in [11]. Global existence in the space  $\mathbf{L}^2(\mathbb{R})$  was recently proved in [5]. However, the uniqueness and continuous dependence of these general solutions remains an open problem. Here the main difficulty stems from the fact that Burgers' equation generates a semigroup which is contractive in the space  $\mathbf{L}^1(\mathbb{R})$ , but only Hölder continuous in  $\mathbf{L}^2(\mathbb{R})$ . On the other hand, the Hilbert transform is a linear isometry in  $\mathbf{L}^2$ , but it is not continuous as a map from  $\mathbf{L}^1$  into itself.

The detailed asymptotic structure of solutions of (2) near a shock has been studied in [6]. At the present time it remains to understand how new shocks are formed, and whether generic initial data yield solutions with finitely many shock curves in the  $t$ - $x$  plane.

3) Variational wave equations:

$$u_{tt} - c(u)(c(u)u_x)_x = 0. \quad (3)$$

Here the wave speed  $c(\cdot)$  is a smooth map, taking strictly positive values. As shown in [7], this equation can be rewritten as a first order semilinear system, by a suitable transformation of dependent and independent variables. This provides a method to construct global solutions to (3), for any initial data

$$(u(0, \cdot), u_t(0, \cdot)) = (u_0, u_1) \in H^1(\mathbb{R}) \times \mathbf{L}^2(\mathbb{R}).$$

Uniqueness of conservative solutions has recently been proved in [3].

For this equivalent semilinear system, smooth initial data yield globally smooth solutions. All singularities in the solution to the original wave equation arise from the change of variables.

The generic regularity of solutions to (3) is now well understood. Using Thom's transversality theorem and ideas from [10], it was shown in [2] that generic solutions of this wave equation are smooth outside a locally finite number of curves in the  $t$ - $x$  plane. An asymptotic description of all types of singularities that can occur in a generic solution is given in [4].

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## An operator splitting based stochastic Galerkin method for nonlinear systems of conservation laws with uncertainty

ALINA CHERTOCK

(joint work with Shi Jin, Alexander Kurganov)

We introduce a flux-splitting based stochastic Galerkin methods for nonlinear systems of hyperbolic conservation/ balance laws with random inputs. The method uses a generalized polynomial chaos approximation in the stochastic Galerkin framework (referred to as the gPC-SG method). It is well-known that such approximations for nonlinear system of hyperbolic conservation laws do not necessarily yield globally hyperbolic systems: the Jacobian may contain complex eigenvalues and thus trigger instabilities and ill-posedness.

In this talk, we present a systematic way to overcome this difficulty. The main idea is to split the underlying system of conservation laws into a linear hyperbolic system, and a nonlinear degenerated hyperbolic system which can be solved successively as scalar conservation laws with variable coefficients and source terms. The gPC-SG method, when applied to each of these subsystems, result in globally hyperbolic systems. The performance of the new gPC-SG method will be

illustrated on a number of numerical examples including the compressible Euler equations [1] and the Saint-Venant system of shallow water equations [2].

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### Semi-wavefronts in models of collective movements with density-dependent diffusivity

ANDREA CORLI

(joint work with Lorenzo di Ruvo and Luisa Malaguti)

We consider the scalar parabolic equation

$$(1) \quad \rho_t + f(\rho)_x = (D(\rho)\rho_x)_x + g(\rho), \quad (x, t) \in \mathbb{R} \times [0, +\infty),$$

where  $f \in C^1[0, \bar{\rho}]$ ,  $f(0) = 0$ ,  $g \in C[0, \bar{\rho}]$  and  $D \in C^1[0, \bar{\rho}]$ , for some  $\bar{\rho} > 0$ . On the diffusivity we assume that  $D(\rho) > 0$  for  $\rho \in (0, \bar{\rho})$ , allowing however that  $D$  can vanish at either 0 or  $\bar{\rho}$ , or even at both points. About the forcing term  $g$  we assume  $g(\rho) > 0$  for  $\rho \in [0, \bar{\rho})$  but  $g(\bar{\rho}) = 0$ .

The reaction-diffusion-convection equation (1), with  $D$  as above, models several physical and biological phenomena; probably the most known of them is the fluid flow through porous media. However, our main source of inspiration has been the appearance of (1) with  $g = 0$  in the framework of collective movements, namely, traffic flows and crowd dynamics [2]. As far as regards model (1), the source term  $g$  can be thought as modeling diffused entries [1].

We are concerned with traveling-wave solutions of (1), namely, special solutions of (1) of the form  $\rho(x, t) = \varphi(x - ct)$ . In this case the profile  $\varphi$  must satisfy the ordinary differential equation

$$(2) \quad (D(\varphi)\varphi')' + (c - f'(\varphi))\varphi' + g(\varphi) = 0.$$

Under the previous assumptions, one easily understands that we are faced to two main difficulties: the degeneracy of the diffusivity and the fact that equation (1) has only one equilibrium point. Indeed, we prove [3] that the latter excludes the possibility of traveling waves defined in the whole of  $\mathbb{R}$ .

In [3] we prove the existence of semi-wavefront solutions [5] for every wave speed  $c$ . We also give precise results about the slopes of the profiles when they reach 0 and characterize their strict monotony through suitable assumptions on the source term  $g$ . We fully discuss as well the singular case when  $D$  is no more differentiable at 0 but  $\dot{D}(0) = \pm\infty$ . Furthermore, in the case  $D(\bar{\rho}) = 0$  we also analyze the possibility of *sharp* (i.e., non smooth) semi-wavefront solutions [4] and completely characterize when this occurs.

The key remark we exploit in the proof is that every profile  $\varphi = \varphi(\xi)$  is strictly monotone in the region where  $0 \leq \varphi(\xi) < \bar{\rho}$ ; hence, it is invertible there, with



inverse function  $\xi = \xi(\varphi)$ ,  $\varphi \in [0, \bar{\rho})$ . This allows us to reduce the second-order equation (2) to a first-order equation by defining  $z(\varphi) := D(\varphi)\varphi'(\xi(\varphi))$ ,  $\varphi \in (0, \bar{\rho})$ . Then  $z$  satisfies the singular equation [5, 6]

$$(3) \quad \dot{z}(\varphi) = h(\varphi) - c - \frac{D(\varphi)g(\varphi)}{z(\varphi)}, \quad \varphi \in (0, \bar{\rho}).$$

We look for solutions of (3) vanishing at  $\bar{\rho}$ ; among them, the possibility that they also vanish at 0 (when also  $D$  does) provides informations about the slope of the profile at 0.

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## The nonlocal-to-local limit for conservation laws

GIANLUCA CRIPPA

(joint work with Maria Colombo, Laura V. Spinolo)

Nonlocal conservation laws appear in the modeling of a large number of phenomena, for instance in the study of traffic problems. Given a convolution kernel  $\rho_\varepsilon$  we focus on the following Cauchy problem:

$$(1) \quad \begin{cases} \partial_u u_\varepsilon + \partial_x((u_\varepsilon * \rho_\varepsilon) u_\varepsilon) = 0 \\ u_\varepsilon(t=0) = \bar{u}. \end{cases}$$

For any given  $\varepsilon > 0$  the Cauchy problem (1) is well posed, see for instance [3]. In fact, well posedness holds in much larger generality: instead of (1), it is possible to consider multidimensional systems, general nonlinearities in the second term, and measure solutions. However, for simplicity of exposition, we restrict our attention to the case of (1).

In [1] the question of the behavior of the solution  $u_\varepsilon$  of (1) when  $\varepsilon \downarrow 0$  was raised. Supported by some numerical experiments, the authors were led to conjecture that

the unique solution  $u_\varepsilon$  of (1) converges to the unique entropic solution  $u$  of Burgers' equation

$$(2) \quad \begin{cases} \partial_t u + \partial_x(u^2) = 0 \\ u(t=0) = \bar{u}. \end{cases}$$

From an analytical point of view this question is very challenging. In terms of a priori estimates, we easily see that (1) conserves the  $L^1$  norm uniformly with respect to  $\varepsilon$ , while the  $L^\infty$  norm and the  $BV$  norm may blow up when  $\varepsilon \downarrow 0$ . The uniform bound in  $L^1$  gives weak compactness of  $u_\varepsilon$  in the sense of measures. However this is not sufficient in order to pass to the limit in the nonlinearity.

A first result regarding the convergence was provided in [4]: if the solution  $u$  of (2) is sufficiently regular in  $[0, T[ \times \mathbb{R}$ , and if the kernel  $\rho_\varepsilon$  is even (i.e.,  $\rho_\varepsilon(-x) = \rho_\varepsilon(x)$  for all  $x$ ), then  $u_\varepsilon$  converges to  $u$  in  $[0, T[ \times \mathbb{R}$ .

In our work we investigate the question of the convergence in the case of non smooth solutions. We construct the following three counterexamples to the convergence of  $u_\varepsilon$  to  $u$ .

- (a) If  $\rho_\varepsilon$  is even and  $\bar{u}$  changes sign, then in general  $u_\varepsilon$  does not converge weakly to  $u$ . To show this, we consider

$$\bar{u} = \begin{cases} 1 & \text{for } x < 0 \\ -1 & \text{for } x > 0. \end{cases}$$

We can check that  $u_\varepsilon$  remains odd for any  $t > 0$ . This implies that  $(u_\varepsilon * \rho_\varepsilon)(0) = 0$  at any time. It follows that the total “mass” of  $u_\varepsilon$  on  $\{x < 0\}$  and on  $\{x > 0\}$  are conserved for all times, while the entropic solution  $u$  “loses mass” on the zero-speed shock placed at  $x = 0$ . This is incompatible with the weak convergence of  $u_\varepsilon$  to  $u$ .

- (b) If  $\bar{u}$  is nonnegative and  $\rho_\varepsilon$  is supported on  $\{x < 0\}$ , then in general  $u_\varepsilon$  does not converge weakly to  $u$ . We can consider

$$\bar{u} = \begin{cases} 1 & \text{for } x < 0 \\ 0 & \text{for } x > 0. \end{cases}$$

The entropic solution  $u$  of (2) consists of a shock with speed 1. On the other hand, for any  $\varepsilon > 0$ , we can check that  $u_\varepsilon \equiv 0$  on  $\{x > 0\}$  for any  $t > 0$ . This is incompatible with the weak convergence of  $u_\varepsilon$  to  $u$ .

- (c) If  $\bar{u}$  is nonnegative and  $\rho_\varepsilon$  is even, then in general  $u_\varepsilon$  does not converge strongly in  $L^{1+\nu}$  to  $u$  for any  $\nu > 0$ . The argument is based on the conservation in time, when  $\rho_\varepsilon$  is even, of the quantity

$$(3) \quad \int_{\mathbb{R}} u_\varepsilon \log u_\varepsilon \, dx$$

for any nonnegative solution  $u_\varepsilon$  of (1). Choosing

$$\bar{u} = \begin{cases} 0 & \text{for } x < 0 \\ 1 & \text{for } 0 < x < 1 \\ 0 & \text{for } x > 1, \end{cases}$$

we deduce from (3) that  $\int u_\varepsilon \log u_\varepsilon dx = 0$  for any  $t > 0$  and  $\varepsilon > 0$ . If one had  $u_\varepsilon \rightarrow u$  in  $L^{1+\nu}$ , it would follow that  $\int u \log u dx = 0$ . However, the entropic solution  $u$  of (2) consists of a rarefaction fan and an entropic shock, so that  $\int u \log u dx$  has to be strictly negative.

In addition, we study the nonlocal-to-local convergence in presence of viscosity in both (1) and (2). In detail, for  $\mu > 0$  we consider

$$(4) \quad \begin{cases} \partial_t u_{\varepsilon,\mu} + \partial_x((u_{\varepsilon,\mu} * \rho_\varepsilon) u_{\varepsilon,\mu}) = \mu \partial_{xx} u_{\varepsilon,\mu} \\ u_{\varepsilon,\mu}(t=0) = \bar{u} \end{cases}$$

and

$$(5) \quad \begin{cases} \partial_t u_\mu + \partial_x(u_\mu^2) = \mu \partial_{xx} u_\mu \\ u_\mu(t=0) = \bar{u}. \end{cases}$$

This is relevant both theoretically and in connection to the numerical experiments in [1] (which may be influenced by the presence of numerical viscosity). Extending a previous result in [2] (restricted to smooth solutions and specific to the viscous Burgers' equation) we show that the unique solution  $u_{\varepsilon,\mu}$  of (4) converges to the unique solution  $u_\mu$  of (5) strongly in  $L^2$ , for any  $\bar{u} \in L^2 \cap L^\infty$ . This result does not require assumptions neither on the sign of  $\bar{u}$  nor on the symmetry of  $\rho_\varepsilon$ .

We can summarize our results in the following convergence scheme:

$$\begin{array}{ccc} u_{\varepsilon,\mu} & \xrightarrow{(A)} & u_\mu \\ \downarrow (B) & & \downarrow (C) \\ u_\varepsilon & \xrightarrow{(D)} & u \end{array}$$

Regarding the two vanishing viscosity convergences (B) and (C), we observe that (C) is the classical result by Kružkov for scalar conservation laws, while (B) can be easily proved by establishing uniform (in  $\mu$ )  $L^\infty$  estimates on the solution  $u_{\varepsilon,\mu}$  of (4) and observing that the convolution with  $\rho_\varepsilon$  (with  $\varepsilon > 0$  fixed) improves the convergence as  $\mu \downarrow 0$  from weak to strong in the term  $u_{\varepsilon,\mu} * \rho_\varepsilon$ . Our results show that the convergence in (A) holds, while in general the convergence in (D) does not hold.

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## Control problems for structured population dynamics

MAURO GARAVELLO

(joint work with Rinaldo M. Colombo)

This note deals with control problems for a biological resource, breed in order to make a profit. More precisely, assume there is a population of *juveniles*, whose density is described by the function  $J = J(t, a)$ , and whose evolution is described by a renewable equation; see [1, 2, 3, 9, 10]. Here  $t$  is the time, while  $a$  denotes the biological age. At a certain age  $\bar{a} > 0$ , the individuals of the  $J$  population are selected either for reproduction purposes or directed to the market. The functions  $S = S(t, a)$  and  $R = R(t, a)$  denote the densities, respectively, of the population to be sold and of the population used for reproduction. The selling of the  $S$  individuals happen at the ages  $\bar{a}_1, \dots, \bar{a}_N$ , where  $N \in \mathbb{N} \setminus \{0\}$  and  $\bar{a} < \bar{a}_1 < \dots < \bar{a}_N$ . Thus, the dynamics of the structured  $(J, S, R)$  population is described by the following nonlocal system of renewal equations

$$(1) \quad \left\{ \begin{array}{ll} \partial_t J + \partial_a J = d_J(t, a) J & t \geq 0, a \in [0, \bar{a}] \\ \partial_t S + \partial_a S = d_S(t, a) S & t \geq 0, a \geq \bar{a}, a \notin \{\bar{a}_1, \dots, \bar{a}_N\} \\ \partial_t R + \partial_a R = d_R(t, a) R & t \geq 0, a \geq \bar{a} \\ \\ S(t, \bar{a}) = \eta J(t, \bar{a}) & t \geq 0 \\ R(t, \bar{a}) = (1 - \eta) J(t, \bar{a}) & t \geq 0 \\ J(t, 0) = \int_{\bar{a}}^{+\infty} w(\alpha) R(t, \alpha) d\alpha & t \geq 0 \\ S(t, \bar{a}_i+) = \theta_i S(t, \bar{a}_i-) & t \geq 0, i = 1, \dots, N \\ \\ J(0, a) = J_o(a) & a \in [0, \bar{a}] \\ S(0, a) = S_o(a) & a \in [\bar{a}, +\infty[ \\ R(0, a) = R_o(a) & a \in [\bar{a}, +\infty[ \end{array} \right.$$

where  $d_J$ ,  $d_S$ , and  $d_R$  are mortality functions,  $w = w(a)$  is a fertility function, and  $J_o$ ,  $S_o$ , and  $R_o$  are the initial conditions; see also [4, 5, 8]. For further structured population models, we refer for instance to [3, 6, 7, 10]. Moreover, we consider the maps  $\eta = \eta(t)$ , and  $\theta_i = \theta_i(t)$  ( $i \in \{1, \dots, N\}$ ) as control functions. Here  $\eta$  is responsible for the selection of the individuals at the age  $\bar{a}$ , while  $1 - \theta_i$  is the fraction of the  $S$  population which is sold at age  $\bar{a}_i$ . Note that the new juveniles individuals depend on the  $R$  population in a nonlocal way.

The profit  $\mathcal{P}$  of the biological resource is given by

$$(2) \quad \mathcal{P}(\eta, \theta; T) = \mathcal{I}(\eta, \theta; T) - \mathcal{C}(\eta, \theta; T),$$

where  $T > 0$  is the time horizon, while the income  $\mathcal{I}$  and the cost  $\mathcal{C}$  are defined as

$$(3) \quad \mathcal{I}(\eta, \theta; T) = \sum_{i=1}^N \int_0^T P_i(t, (1 - \theta_i(t)) S(t, \bar{a}_i-)) dt,$$

$$(4) \quad \begin{aligned} \mathcal{C}(\eta, \theta; T) = & \int_0^T \int_0^{\bar{a}} C_J(t, a, J(t, a)) \, da \, dt + \int_0^T \int_{\bar{a}}^{+\infty} C_S(t, a, S(t, a)) \, da \, dt \\ & + \int_0^T \int_{\bar{a}}^{+\infty} C_R(t, a, R(t, a)) \, da \, dt. \end{aligned}$$

As regards the income  $\mathcal{I}$ , each map  $P_i = P_i(t, s)$  is the price due to selling the individuals at age  $\bar{a}_i$ . The maps  $C_u(t, a, w)$  in (4), for  $u \in \{J, S, R\}$ , are the cost for maintaining the  $u$  population of age  $a$  at time  $t$ .

## 1. MAIN RESULTS

Fix  $T > 0$ ,  $\kappa \in \mathbb{N} \setminus \{0\}$ , and introduce the notation  $\mathbb{R}^+ = [0, +\infty[$ ,  $I_J = [0, \bar{a}]$ ,  $I_S = I_R = [\bar{a}, +\infty[$ ,  $I_T = [0, T]$ . Consider the following assumptions.

**(A):** For  $u = J, S, R$ , the mortality functions  $d_u$  satisfy

$$d_u \in (C^1 \cap L^\infty)(I_T \times I_u; \mathbb{R}) \quad \text{and} \quad \sup_{t \in \mathbb{R}^+} \tilde{v}(d_u(t, \cdot)) < +\infty,$$

while the fertility function  $w$  belongs to  $C_c^1([\bar{a}, +\infty[; \mathbb{R}^+)$ .

**(ID):**  $J_o \in \text{BV}(I_J; \mathbb{R}^+)$ ,  $S_o \in (L^1 \cap \text{BV})(I_S; \mathbb{R}^+)$ ,  $R_o \in (L^1 \cap \text{BV})(I_R; \mathbb{R}^+)$ .

**(P):**  $P \in L_{loc}^\infty([0, \bar{a}] \times \mathbb{R}^+; \mathbb{R})$  and  $P_i \in L_{loc}^\infty(I_T \times \mathbb{R}^+; \mathbb{R})$  for  $i = 1, \dots, N$ .

Moreover, the map  $j \rightarrow P(a, j)$ , respectively  $s \rightarrow P_i(t, s)$  for  $i = 1, \dots, N$ , is a polynomial of degree at most  $\kappa$  in  $j$  for all  $a \in [0, \bar{a}]$ , respectively in  $s$  for  $t \in \mathbb{R}^+$ .

**(C):**  $C_u \in L_{loc}^1(I_T \times I_u \times \mathbb{R}; \mathbb{R})$  and the map  $v \rightarrow C_u(t, a, v)$  is a polynomial of degree at most  $\kappa$  in  $v$ , for  $u = J, S, R$ .

The following results gives the well posedness of (1) in  $L^1$ .

**Theorem 1.1** ([5, Theorem 2.1]). *Assume (A) and (ID). For any  $\eta \in \text{BV}(I_T; [0, 1])$  and  $\theta \in \text{BV}(I_T; [0, 1]^N)$ , system (1) admits a unique solution such that, for every  $t \in I_T$ ,  $J(t, a) \geq 0$  for every  $a \in I_J$ , and  $S(t, a) \geq 0$ ,  $R(t, a) \geq 0$  for every  $a \geq \bar{a}$ . Moreover, there exists a function  $\mathcal{K} \in C^0(I_T; \mathbb{R}^+)$ , with  $\mathcal{K}(0) = 0$ , dependent only on  $g_J, g_S, g_R, d_J, d_S, d_R$  and  $w$  such that for all initial data  $(J'_o, S'_o, R'_o)$  and  $(J''_o, S''_o, R''_o)$  and for all controls  $\eta', \eta'', \theta'$  and  $\theta''$ , the corresponding solutions  $(J', S', R')$  and  $(J'', S'', R'')$  to (1) satisfy, for every  $t \in I_T$ , the stability estimate:*

$$\begin{aligned} & \|J'(t) - J''(t)\|_{L^1(I_J; \mathbb{R})} + \|S'(t) - S''(t)\|_{L^1(I_S; \mathbb{R})} + \|R'(t) - R''(t)\|_{L^1(I_R; \mathbb{R})} \\ & \leq \mathcal{K}(t) \left( \|J'_o - J''_o\|_{L^1(I_J; \mathbb{R})} + \|S'_o - S''_o\|_{L^1(I_S; \mathbb{R})} + \|R'_o - R''_o\|_{L^1(I_R; \mathbb{R})} \right) \\ & \quad + t \mathcal{K}(t) \left( \|J'_o - J''_o\|_{L^\infty(I_J; \mathbb{R})} + \|S'_o - S''_o\|_{L^\infty(I_S; \mathbb{R})} + \|R'_o - R''_o\|_{L^\infty(I_R; \mathbb{R})} \right) \\ & \quad + \mathcal{K}(t) \left( \|\eta' - \eta''\|_{L^\infty([0, t]; \mathbb{R})} + \|\theta' - \theta''\|_{L^\infty([0, t]; \mathbb{R}^N)} \right). \end{aligned}$$

The next result explains the dependence of the solution to (1) with respect to the controls.

**Theorem 1.2.** *Pose conditions (A), (ID). Let  $(J, S, R)$  be the solution to (1) corresponding to the piecewise controls*

$$(5) \quad \eta(t) = \sum_{k=1}^m \eta_k \chi_{[k-1, k[}(t), \quad \theta_i(t) = \sum_{k=1}^m \theta_i^k \chi_{[k-1, k[}(t)$$

for  $m \in \mathbb{N} \setminus \{0\}$ ,  $i = 1, \dots, N$ ,  $t \in [0, T]$ ,  $T = m$ , where the control parameters  $\eta_k$  and  $\theta_i^k$  belong to the real interval  $[0, 1]$ . Then, for all  $t$  and  $a$ ,

- (1) the quantities  $J(t, a)$ ,  $R(t, a)$  and  $S(t, a)$  are multiaffine in  $\eta_k$ ;
- (2) the quantities  $J(t, a)$ ,  $R(t, a)$  do not depend on  $\theta_i^k$ ;
- (3) the quantity  $S(t, a)$  is multiaffine in  $\theta_i^k$ .

The following result is a direct consequence of Theorem 1.2 and of assumptions (P) and (C).

**Corollary 1.3.** *Pose conditions (A), (ID), (P) and (C). Choose controls  $\eta$  and  $\theta_i$  as in (5). Then, the net profit  $\mathcal{P}$ , defined in (2), is polynomial in  $\eta$  and  $\theta_i$  of degree at most  $\kappa$  in each of the (scalar) variables  $\eta_1, \dots, \eta_m, \theta_1^k, \dots, \theta_N^k$  separately. Moreover, globally, it is a polynomial of degree at most  $\kappa m$  in  $\eta_1, \dots, \eta_m$  and of degree at most  $\kappa m N$  in  $\theta_1^k, \dots, \theta_N^k$ .*

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## Relative Entropy for Hamiltonian Flows in Gas Dynamics

JAN GIESSELMANN

(joint work with Corrado Lattanzio, Athanasios E. Tzavaras)

We study systems of partial differential equations having the form

$$(1) \quad \begin{aligned} \frac{\partial \rho}{\partial t} + \operatorname{div}_x(\rho u) &= 0 \\ \frac{\partial u}{\partial t} + (u \cdot \nabla_x)u &= -\nabla_x \frac{\delta \mathcal{E}}{\delta \rho}(\rho) \end{aligned} \quad x \in \mathbb{R}^d, \, t > 0,$$

where  $\rho \geq 0$  is a density obeying the conservation of mass,  $u$  is a velocity and  $m = \rho u$  a momentum flux. The evolution of  $u$  results from a functional  $\mathcal{E}(\rho)$  on the density and  $\frac{\delta \mathcal{E}}{\delta \rho}$  denotes the generator of the directional derivative of that functional. In case of irrotational flows the dynamics (1), indeed, have a Hamiltonian structure, i.e. defining  $\mathcal{H}(\rho, u) := \mathcal{E}(\rho) + \int \frac{1}{2} \rho |u|^2 dx$  equation (1) is equivalent to

$$\frac{\partial}{\partial t} \begin{pmatrix} \rho \\ u \end{pmatrix} = \begin{pmatrix} 0 & -\operatorname{div}_x \\ -\nabla_x & 0 \end{pmatrix} \begin{pmatrix} \frac{\delta \mathcal{H}}{\delta \rho} \\ \frac{\delta \mathcal{H}}{\delta u} \end{pmatrix} + \begin{pmatrix} 0 \\ u \times \operatorname{curl}_x u \end{pmatrix}.$$

In the non-irrotational case there is a discrepancy, but this discrepancy is compatible with conservation of energy. Solutions of (1) formally satisfy

$$\frac{d}{dt} \left( \int \frac{1}{2} \rho |u|^2 dx + \mathcal{E}(\rho) \right) = 0.$$

Depending on the selection of the functional  $\mathcal{E}(\rho)$  several models of interest fit under this framework. These include the equations of isentropic gas dynamics for

$$\mathcal{E}(\rho) = \int h(\rho) dx$$

with given energy density function  $h : [0, \infty) \rightarrow [0, \infty)$ ; the Euler-Poisson system (*e.g.* [6]) for

$$(2) \quad \begin{aligned} \mathcal{E}(\rho) &= \int \left( h(\rho) - \frac{1}{2} \rho c \right) dx, \\ \text{where } c &\text{ is the solution of } -\Delta_x c + \beta c = \rho - \langle \rho \rangle, \\ \beta &\geq 0 \text{ is a constant and } \langle \rho \rangle \text{ denotes the mean of } \rho; \end{aligned}$$

the system of quantum hydrodynamics (*e.g.* [1]) for

$$\mathcal{E}(\rho) = \int h(\rho) + \frac{1}{2\rho} |\nabla_x \rho|^2 dx;$$

and the Euler-Korteweg system (*e.g.* [5]), for

$$(3) \quad \mathcal{E}(\rho) = \int h(\rho) + \frac{C_\kappa}{2} |\nabla_x \rho|^2 dx \quad \text{where } C_\kappa > 0 \text{ is a constant.}$$

Our goal is to use the formal structure (1) in order to obtain a relative entropy identity. Depending on the choice of energy density  $h$ , most (but not all) of the

problems above are generated by convex functionals. Thus, it is natural to use the quadratic part of the Taylor expansion of the functional  $\mathcal{E}(\rho)$ ,

$$(4) \quad \mathcal{E}(\rho|\bar{\rho}) := \mathcal{E}(\rho) - \mathcal{E}(\bar{\rho}) - \left\langle \frac{\delta \mathcal{E}}{\delta \rho}(\bar{\rho}), \rho - \bar{\rho} \right\rangle,$$

for comparing two states  $\rho$  and  $\bar{\rho}$ . This definition involves the directional derivative of  $\mathcal{E}(\rho)$  in the direction  $(\rho - \bar{\rho})$  and provides a functional which we call *relative potential energy*. We combine it with the *relative kinetic energy*

$$(5) \quad K(\rho, m|\bar{\rho}, \bar{m}) = \int \frac{\rho}{2} \left| \frac{m}{\rho} - \frac{\bar{m}}{\bar{\rho}} \right|^2 dx$$

as a measure for the distance between two solutions  $(\rho, m)$  and  $(\bar{\rho}, \bar{m})$ .

In order to obtain a useful relative entropy identity we need to assume existence of a stress tensor (functional)  $S(\rho)$  satisfying

$$(6) \quad -\rho \nabla_x \frac{\delta \mathcal{E}}{\delta \rho} = \nabla_x \cdot S.$$

Hypothesis (6) holds for all the above examples. It gives a meaning to the notion of weak solution for (1) as it induces a conservative form.

Under this condition the structure (1) allows us to (formally) derive the following relative energy identity for solutions  $(\rho, m)$ ,  $(\bar{\rho}, \bar{m})$  of (1):

$$(7) \quad \begin{aligned} & \frac{d}{dt} (\mathcal{E}(\rho|\bar{\rho}) + K(\rho, m|\bar{\rho}, \bar{m})) \\ &= \int \nabla_x \bar{u} : S(\rho|\bar{\rho}) dx - \int \rho \nabla_x \bar{u} : (u - \bar{u}) \otimes (u - \bar{u}) dx, \end{aligned}$$

where the relative stress functional is defined by

$$(8) \quad S(\rho|\bar{\rho}) := S(\rho) - S(\bar{\rho}) - \left\langle \frac{\delta S}{\delta \rho}(\bar{\rho}), \rho - \bar{\rho} \right\rangle.$$

Formula (7) is similar to the well known relative entropy formulas first obtained in the works of Dafermos [2, 3] and DiPerna [4] which have been used successfully in many contexts. However, equation (7) has a different origin from all these calculations: it is based on the abstract Hamiltonian flow structure (1) while the latter are based on the thermodynamical structure induced by the Clausius-Duhem inequality. This difference notwithstanding, formula (7) and the formulas obtained in [3, 7] are similar in that they allow for a mechanical interpretation of the relative mechanical stress and the relative convective stress.

While formula (7) seems quite simple the actual formulas in specific examples are cumbersome. Moreover, (for pairs of weak solutions  $(\rho, m)$  and classical solutions  $(\bar{\rho}, \bar{m})$ ) the derivation of (7) needs to be justified in specific models (e.g. Euler-Korteweg) which is technically quite intricate. Details can be found in [8]. The framework described here can, in particular, be applied for obtaining weak-strong uniqueness for the models under consideration as long as the potential energy is strictly convex. We refer to [8] for the precise statements. In case of the Euler-Korteweg model (3) we even obtain weak-strong uniqueness for certain



non-convex energy densities  $h$ , since the gradient terms in the energy can be used to compensate for the lack of convexity, see [9] for details.

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### Uniqueness for a non-linear 1D compressible to incompressible limit in the non smooth case

GRAZIANO GUERRA

(joint work with Rinaldo M. Colombo)

The compressible to incompressible limit is widely studied in the literature, see for instance the review [9] and the references therein. The classical setting considers regular solutions, whose existence is proved only for a finite time, to the compressible equations. As the Mach number vanishes, these solutions are proved to converge to the solutions to the incompressible system. Here we are concerned with the isentropic 1D system of Euler equations and with its compressible to incompressible limit. In particular we want to study this limit for non smooth solutions defined for all times. In a 1D setting, an incompressible fluid behaves like a solid since its speed is constant in space. In [3] the full 1D non-isentropic Euler equations in all the real line are considered. The authors prove rigorously that the second order coefficients of the asymptotic expansion of the solution in the (small) Mach number satisfy the linear acoustic system. Here we consider instead two compressible immiscible fluids and let only one of the two become incompressible. More precisely we consider a 1D volume of a compressible inviscid fluid, say the *liquid*, that fills the segment of a tube  $[a(t), b(t)]$  and is surrounded by another compressible fluid, say the *gas*, filling the rest of the tube. We assume that the gas obeys a fixed pressure law  $\bar{P}(\rho)$ , while for the liquid we assume a one parameter family of pressure laws  $\bar{P}_\kappa(\rho)$  such that  $\bar{P}'_\kappa(\rho) \rightarrow +\infty$  as  $\kappa \rightarrow 0$ . The total mass of the liquid is

fixed:  $\int_{a(t)}^{b(t)} \rho(t, x) dx = m$ . Since the two fluids are immiscible, Lagrangian coordinates are a natural choice:  $z(t, x) = \int_{a(t)}^x \rho(t, \xi) d\xi$ ,  $\tau = \frac{1}{\rho}$ ,  $P(\tau) = \overline{P}(\frac{1}{\tau})$ , with  $\tau$  being the specific volume. In these coordinates, the liquid occupies the fixed region  $[0, m]$  and the interfaces at  $z = 0$  and  $z = m$  become stationary in time. For this problem it is also convenient to write the equations in terms of the pressure, so we introduce the inverses of the pressure laws, now seen as functions of the pressure:  $\mathcal{T}(p) = P^{-1}(p)$ ,  $\mathcal{T}_\kappa(p) = P_\kappa^{-1}(p)$ ,  $\mathcal{T}'_\kappa(p) \xrightarrow{\kappa \rightarrow 0} 0$ . The isentropic Euler equations for the two interacting fluids in these new variables become:

$$(1) \quad \begin{cases} \partial_t \mathcal{T}_\kappa(z, p) - \partial_z v = 0 \\ \partial_t v + \partial_z p = 0, \end{cases} \quad \mathcal{T}_\kappa(z, p) = \begin{cases} \mathcal{T}_\kappa(p) & \text{for } z \in ]0, m[ \\ \mathcal{T}(p) & \text{for } z \notin ]0, m[. \end{cases}$$

Given two functions  $(p, v) \in \mathbf{L}^1(\mathbb{R}, \mathbb{R}^2)$ , introduce now the weighted total variation:  $\text{TV}_\kappa(p, v) = \text{TV}(p, \mathbb{R}) + \text{TV}(v, \mathbb{R} \setminus ]0, m[) + \frac{1}{\kappa} \text{TV}(v, ]0, m[)$ . The following two theorems were proved in [8] with the assumption of a linear pressure in the liquid region and in [5] without this linearity assumption.

**Theorem 1.1.** *Given a positive constant  $c > 0$ , there exist  $\delta, \Delta, L > 0$  independent of  $\kappa$  such that if  $\text{TV}_\kappa(p_o^\kappa, v_o^\kappa) < \delta$  and  $p_o^\kappa \geq c$  hold, then the Cauchy problem for (1) with  $(p_o^\kappa, v_o^\kappa)$  as initial data has an entropy solution  $(p^\kappa, v^\kappa)$  defined for all times  $t \geq 0$ .*

**Theorem 1.2.** *Given a positive constant  $c > 0$ , fix an initial data  $(p_o, v_o)$  such that  $\text{TV}(p_o) + \text{TV}(v_o) \leq \delta$ ,  $p_o \geq c$ ,  $v_o(z) = \tilde{v}$  for all  $z \in ]0, m[$ , then for any  $\kappa \in ]0, 1[$  there exists an entropic solution  $(p_o^\kappa, v_o^\kappa)$  to the Cauchy problem for (1) with initial data  $(p_o, v_o)$ . Define the specific volume as  $\tau^\kappa(t, z) = \mathcal{T}_\kappa(z, p^\kappa(t, z))$ , then as  $\kappa \rightarrow 0$ , up to subsequences, we have the following convergence results.*

$$\begin{aligned} \tau^\kappa(t, \cdot) &\rightarrow \bar{\tau} & \tau^\kappa(t, \cdot) &\rightarrow \tau^*(t, \cdot) \\ v^\kappa(t, \cdot) &\rightarrow v_l(t) & v^\kappa(t, \cdot) &\rightarrow v^*(t, \cdot) \text{ in } \mathbf{L}^1(\mathbb{R} \setminus [0, m]) . \\ p^\kappa(\cdot, \cdot) &\xrightarrow{*} p_l(\cdot, \cdot) \text{ in } \mathbf{L}^\infty([0, m[ \times \mathbb{R}^+), & p^\kappa(t, \cdot) &\rightarrow p^*(t, \cdot) \end{aligned}$$

Moreover, the limits  $v_l(t)$ ,  $(p^*, v^*)(t, z)$  are entropy solutions [1] to

$$(2) \quad \begin{cases} \partial_t \mathcal{T}(p^*) - \partial_z v^* = 0 \\ \partial_t v^* + \partial_z p^* = 0 \\ m \frac{d}{dt} v_l(t) = p^*(t, 0-) - p^*(t, m+) \\ v_l(t) = v^*(t, 0-) = v^*(t, m+), \end{cases} \quad \begin{cases} p^*(0, z) = p_o(z) \\ v^*(0, z) = v_o(z) \\ v_l(0) = \tilde{v}. \end{cases} \quad z \notin [0, m]$$

The limit pressure is given by  $p_l(t, z) = (1 - \frac{z}{m}) p^*(t, 0-) + \frac{z}{m} p^*(t, m+)$  a.e.  $t \geq 0$ ,  $z \in [0, m]$ .

System (2) is a system of PDE and ODE coupled through the boundary values of the solutions to the PDE. The well posedness for this kind of systems was proved in [1] while a characterization of their solutions in terms of tangent vectors is given in [4]. This characterization is able to ensure the uniqueness of the compressible to incompressible limit obtained in Theorem 1.2. To show this,

we recall some definitions and results of [4] adapted to system (2). On the set  $Y = \mathbb{R} \times (\mathbf{L}^1 \cap \mathbf{BV}) (\mathbb{R} \setminus [0, m], \mathbb{R}^2)$  introduce the metric

$$d((v_{l,1}, (p_1, v_1)), (v_{l,2}, (p_2, v_2))) = |v_{l,1} - v_{l,2}| + \|(p_1, v_1) - (p_2, v_2)\|_{\mathbf{L}^1(\mathbb{R} \setminus [0, m], \mathbb{R}^2)}.$$

For any  $u_o = (v_{l,o}, (p_o, v_o)) \in Y$  with  $|v_{l,o}| + \text{TV}(p_o, v_o)$  sufficiently small, introduce the Lipschitz curve leaving  $u_o$ :

$$(3) \quad \mathcal{F}(h)(v_{l,o}, (p_o, v_o)) = \left( v_{l,o} + h(p^{\sigma^-} - p^{\sigma^+}), S_h(\tilde{p}, \tilde{v})|_{\mathbb{R} \setminus [0, m]} \right), \quad h \geq 0.$$

Here  $p^{\sigma^-}$  is the unique value of the pressure such that the state  $(p_o, v_o)(0-)$  can be connected to  $(p^{\sigma^-}, v_{l,o})$  with a wave of the first family, while  $p^{\sigma^+}$  is the unique value of the pressure such that the state  $(p^{\sigma^+}, v_{l,o})$  can be connected to  $(p_o, v_o)(m+)$  with a wave of the second family. The existence and uniqueness of these two states is ensured by [6, Lemma 4.1].  $S_h$  is the Standard Riemann Semigroup [2, Definition 9.1] on all the real line generated by  $\partial_t \mathcal{T}(p) - \partial_z v = 0$ ,  $\partial_t v + \partial_z p = 0$ . The initial data  $(\tilde{p}, \tilde{v})$  is given by  $(\tilde{p}, \tilde{v})(z) = (p_o, v_o)(z)$  for  $z \in \mathbb{R} \setminus [0, m]$ ;  $(\tilde{p}, \tilde{v})(z) = (p^{\sigma^-}, v_{l,o})$  for  $z \in [0, m/2[$ ;  $(\tilde{p}, \tilde{v})(z) = (p^{\sigma^+}, v_{l,o})$  for  $z \in [m/2, m]$ . With these definitions, [4, Theorem 3] applied to system (2) becomes:

**Theorem 1.3.** *There exists a positive  $\delta$ , a set of initial data*

$$X \supset \{u = (v_l, (p, v)) \in \mathbb{R} \times (\mathbf{L}^1 \cap \mathbf{BV}) (\mathbb{R} \setminus [0, m], \mathbb{R}^2) : |v_l| + \text{TV}(p, v) < \delta\}$$

*and a Lipschitz continuous local semigroup [4, Definition 2]  $\mathcal{S}$  on  $X$ , such that*

- (i)  $\forall u_o \in X$ , the map  $u(t) = \mathcal{S}_t u_o$  is a solution to (2) with initial datum  $u_o$ ;
- (ii)  $\forall u_o \in X$ , the map  $h \rightarrow \mathcal{S}_h u_o$  is first order tangent to  $h \rightarrow \mathcal{F}(h)u_o$  defined in (3) at  $u_o$ , in the sense that  $\lim_{h \rightarrow 0+} \frac{1}{h} d(\mathcal{S}_h u_o, \mathcal{F}(h)u_o) = 0$ ;
- (iii)  $\mathcal{S}$  is unique up to the domain;
- (iv) any Lipschitz curve  $u : [0, T] \rightarrow X$  first order tangent to  $\mathcal{F}$  at any point, coincides with the semigroup trajectories:  $u(t) = \mathcal{S}_t u(0)$ ,  $\forall t \in [0, T]$ .
- (v)  $\mathcal{S}_t u_o$  is defined as long as it does not leave the domain  $X$ , in particular if  $\mathcal{S}_t u_o \in X$  for any  $u_o \in X$  and any  $t \geq 0$ ,  $\mathcal{S}_t$  is a global semigroup.

Using this last result, we are able to show that the compressible to incompressible limit of Theorem 1.2 is unique. Indeed in [7] the following theorem is proved.

**Theorem 1.4.** *For any initial data  $u_o = (v_{l,o}, (p_o, v_o)) \in X$ , the compressible to incompressible limit  $u^*(t) = (v_l(t), (p^*, v^*)(t, \cdot))$ , satisfies  $\lim_{h \rightarrow 0} \frac{d(\mathcal{F}(h)u^*(t), u^*(t+h))}{h} = 0$ , and consequently it coincides with a trajectory of the semigroup in Theorem 1.3.*

Since from Theorem 1.2 we know that  $(v_l(t), (p^*, v^*)(t))$  is defined for all times  $t \geq 0$ , as a consequence we also have:

**Corollary 1.5.** *The trajectories of the local semigroup of Theorem 1.3 are defined for all times  $t \geq 0$ , hence  $\mathcal{S}_t$  is a global semigroup defined on  $X$ .*

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## Stability analysis of an implicit lattice Boltzmann scheme

PHILIPPE HELLUY

## 1. INTRODUCTION

Lattice kinetic models are essential in computational fluid dynamics. They are the key ingredient of the Lattice Boltzmann Method (LBM). The idea is to construct a kinetic interpretation of a hyperbolic system of conservation laws with a minimal set of velocities. In this report we analyze the D1Q3 lattice kinetic model, which is the simplest kinetic model representing the isothermal Euler equations. We show that it is unstable but that it can be made stable if the transport step is solved with an implicit scheme. The unknown of the D1Q3 model is a three-dimensional distribution function  $f(x, t) \in \mathbb{R}^3$ , where  $x \in \mathbb{R}$  and  $t \in [0, T]$  are respectively the space and time variable. The distribution function satisfies transport equations with a BGK relaxation source term [1]

$$(1) \quad f_t^i + v_i f_x^i = \frac{1}{\varepsilon} (M(f)^i - f^i), \quad i = 1 \dots 3,$$

where we have noted partial derivatives with indices ( $f_t = \partial_t f$  for instance). The kinetic velocity takes only three values

$$v = (-\lambda, 0, \lambda),$$

where  $\lambda$  is a positive real number. The fluid macroscopic variables are the density  $\rho(x, t)$ , the momentum  $q(x, t)$  and the momentum flux  $z(x, t)$ . As usual the fluid velocity is defined by

$$u = q/\rho.$$

The macroscopic variables are recovered by computing discrete moments of  $f$

$$\begin{pmatrix} \rho \\ q \\ z \end{pmatrix} = P \begin{pmatrix} f^1 \\ f^2 \\ f^3 \end{pmatrix}, \quad P = \begin{pmatrix} 1 & 1 & 1 \\ -\lambda & 0 & \lambda \\ \lambda^2 & 0 & \lambda^2 \end{pmatrix}.$$

The constant sound speed of the isothermal fluid is denoted by  $c > 0$ . The discrete Maxwellian state  $M(f)$  is then given by

$$(2) \quad M(f) = \frac{1}{\lambda^2} \begin{pmatrix} \rho u(u - \lambda)/2 + c^2 \rho/2 \\ \rho(\lambda^2 - u^2 - c^2) \\ \rho u(u + \lambda^2)/2 + c^2 \rho/2 \end{pmatrix}$$

in such a way that

$$PM(f) = \begin{pmatrix} \rho \\ q \\ \rho u^2 + c^2 \rho \end{pmatrix}.$$

Multiplying the kinetic equation (1) by  $P$  we obtain

$$(3) \quad \begin{aligned} \rho_t + q_x &= 0, \\ q_t + z_x &= 0, \\ z_t + \lambda^2 q_x &= \frac{1}{\varepsilon}(q^2/\rho + c^2 \rho - z). \end{aligned}$$

When  $\varepsilon \rightarrow 0$ , then formally  $f = M(f)$  and from (1) we see that  $\rho$  and  $u$  satisfy the isothermal Euler equations

$$(4) \quad \begin{aligned} \partial_t \rho + \partial_x(\rho u) &= 0, \\ \partial_t(\rho u) + \partial_x(\rho u^2 + c^2 \rho) &= 0. \end{aligned}$$

The model (1), (1) is thus a minimalistic abstract kinetic interpretation of the isothermal Euler equation. It is also denoted as the “D1Q3” model in the lattice-Boltzmann community [3]. It can be extended to higher dimensions. For instance, in two or three dimensions it becomes the D2Q9 or D3Q27 models.

## 2. NUMERICAL METHOD AND ASYMPTOTIC EXPANSION

A traditional method for solving numerically (1) is the first order Lie splitting algorithm. For applying one time step of the splitting algorithm, we start from a state that is close to equilibrium:  $f = M(f) + O(\varepsilon)$ . We first apply the free transport equation for a duration of  $\Delta t$

$$f_t + v \cdot f_x = 0.$$

Then in a second stage of the same duration  $\Delta t$  we apply the local BGK return to equilibrium

$$f_t = \frac{1}{\varepsilon}(M(f) - f).$$

In the case of the D1Q3 model, this approach can lead to instabilities that are sometimes observed in LBM simulations [2]. Therefore, we replace the exact transport

step by a first order implicit solver in time. Assuming high precision of the solver in the  $x$  variable the effect of the implicit solver can be modeled by

$$(5) \quad \frac{f(x, t) - f(x, t - \Delta t)}{\Delta t} + v f_x(x, t) = 0.$$

By a Taylor expansion, we find the equivalent equation of the implicit solver (5)

$$(6) \quad f_t + v f_x - \frac{\Delta t}{2} v^2 f_{xx} = O(\Delta t^2).$$

In a second step, we solve the differential equation exactly

$$f_t = \frac{1}{\varepsilon} (M(f) - f) = \frac{M - I}{\varepsilon} f.$$

This is easy because during the relaxation step  $\rho$ ,  $q$ , and thus  $M(f)$ , are constant.

In the following,  $\varepsilon$  is a small parameter, but we assume that the vector field  $M$  is restricted to a manifold of  $f$ 's on which

$$(7) \quad \frac{M - I}{\varepsilon} f = O(1).$$

In the literature this hypothesis is often formulated by saying that  $f$  remains close to a Maxwellian state and that the initial data are “well-prepared”. Hypothesis (7) is crucial because it will allow us to apply the Baker-Campbell-Hausdorff (BCH) formula with the good ordering for estimating the equivalent equation of the splitting algorithm. Let us also point out that we assume that (7) remains true even if  $\varepsilon \sim \Delta t$  or  $\varepsilon \sim \Delta t^2$  for instance. For a more precise analysis of this hypothesis, we refer to [4] (Section VI.3 pages 388–392).

In the Lie formalism, one time-step of the splitting scheme can be written

$$\varphi(\tau) = \exp\left(\tau \frac{M - I}{\varepsilon}\right) \exp\left(\tau(-v\partial_x + \frac{1}{2}\tau v^2 \partial_{xx})\right) + O(\tau^3).$$

Now we apply the BCH formula

$$\exp(A) \exp(B) = \exp\left(A + B + \frac{1}{2} [A, B] + \frac{1}{12} ([A, [A, B]] + [B, [B, A]]) + \dots\right).$$

We obtain

$$\varphi(\tau) = \exp(\tau L) + O(\tau^3),$$

with

$$L = -v\partial_x + \frac{1}{2}\tau v^2 \partial_{xx} + \frac{M - I}{\varepsilon} + \frac{1}{2}\tau \left[ \frac{M - I}{\varepsilon}, -v\partial_x \right].$$

Therefore at second order in time, the equivalent equation of the scheme is

$$f_t + v f_x - \frac{\Delta t}{2} v^2 f_{xx} - \frac{1}{2} \Delta t \left[ \frac{M - I}{\varepsilon}, -v\partial_x \right] f = \frac{M(f) - f}{\varepsilon}.$$

For expressing the Lie bracket in a more convenient way, we introduce the matrix

$$V = \begin{bmatrix} -\lambda & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \lambda \end{bmatrix}.$$

Then the Lie bracket becomes

$$\begin{aligned}[M - I, -v\partial_x]f &= -V\partial_x M(f) + M'(f)V\partial_x f \\ &= (M'V - VM')\partial_x f\end{aligned}$$

Now we go back to variables  $(\rho, q, z)$ . After some computations, we find that

$$P[M - I, -v\partial_x]P^{-1} \begin{bmatrix} \rho \\ q \\ z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ -c^2 + u^2 & -2u & 1 \\ 0 & c^2 - \lambda^2 - u^2 & 2u \end{bmatrix} \partial_x \begin{bmatrix} \rho \\ q \\ z \end{bmatrix}.$$

We obtain the equivalent equations solved by the splitting algorithm at order 2 in  $\Delta t$

$$\begin{aligned}(8) \quad & \rho_t + q_x - \frac{\Delta t}{2} z_{xx} = 0, \\ & q_t + z_x - \frac{\Delta t}{2} \lambda^2 q_{xx} = \frac{\Delta t}{2\varepsilon} ((u^2 - c^2)\rho_x - 2uq_x + z_x), \\ & \partial_t z + \lambda^2 \partial_x q - \frac{\Delta t}{2} \lambda^2 z_{xx} = \frac{1}{\varepsilon} (q^2/\rho + c^2\rho - z) + \frac{\Delta t}{2\varepsilon} ((c^2 - \lambda^2 - u^2)q_x + 2uz_x).\end{aligned}$$

On this equation we will now assume that  $1 \gg \Delta t > \varepsilon$ . We freeze  $\Delta t$  and perform a Chapman-Enskog expansion when  $\varepsilon \rightarrow 0$ . The second equation implies that when  $\varepsilon \rightarrow 0$

$$z_x = (c^2 - u^2)\rho_x + 2uq_x = (q^2/\rho + c^2\rho)_x + O(\varepsilon)$$

and is thus redundant with

$$z = q^2/\rho + c^2\rho + O(\varepsilon).$$

The third equation in (8) gives

$$z = q^2/\rho + c^2\rho - \varepsilon (\partial_t z + \lambda^2 \partial_x q) + \frac{\Delta t}{2} ((c^2 - \lambda^2 - u^2)q_x + 2uz_x) + O(\varepsilon \Delta t).$$

We need to rewrite the factor in  $\varepsilon$ :

$$\partial_t z + \lambda^2 \partial_x q,$$

with only spatial derivatives. At leading order we have

$$\begin{aligned}\partial_t z &= \partial_t (q^2/\rho + c^2\rho) + O(\varepsilon + \Delta t) \\ &= \frac{2q}{\rho} q_t - \frac{q^2}{\rho^2} \rho_t + c^2 \rho_t + O(\varepsilon + \Delta t).\end{aligned}$$

But  $q_t = -z_x + O(\varepsilon + \Delta t)$  and  $\rho_t = -q_x + O(\varepsilon + \Delta t)$  thus

$$z_t = -2uz_x + u^2 q_x - c^2 q_x + O(\varepsilon + \Delta t).$$

Then

$$z_t = -2u (2uq_x + (c^2 - u^2)\rho_x) + (u^2 - c^2)q_x + O(\varepsilon + \Delta t).$$

Finally

$$z_t + \lambda^2 q_x = (-3u^2 + \lambda^2 - c^2) q_x - 2u (c^2 - u^2) \rho_x + O(\varepsilon + \Delta t).$$

We then obtain the equivalent viscous equation of the splitting method

$$\begin{aligned}\rho_t + (\rho u)_x &= \kappa \frac{\Delta t}{2} z_{xx}, \\ (\rho u)_t + (\rho u^2 + c^2 \rho)_x &= \kappa \frac{\Delta t}{2} \lambda^2 q_{xx} + D_x,\end{aligned}$$

with  $\kappa = 1$  (effect of the implicit solver) or  $\kappa = 0$  (exact transport solver) and

$$D = \left(\varepsilon + \frac{\Delta t}{2}\right) \left((\lambda^2 - c^2 - 3u^2) q_x + 2u (u^2 - c^2) \rho_x\right).$$

### 3. STABILITY ANALYSIS

Now we want to analyze the entropy stability of the second order term when  $\varepsilon \rightarrow 0$ . For this, we define

$$\begin{aligned}w &= \begin{pmatrix} \rho \\ q \end{pmatrix}, \quad F(w) = \begin{pmatrix} q \\ \frac{q^2}{\rho} + c^2 \rho \end{pmatrix}, \\ A(w) &= \begin{pmatrix} \kappa(c^2 - u^2) & 2\kappa u \\ 2u(u^2 - c^2) & (1 + \kappa)\lambda^2 - c^2 - 3u^2 \end{pmatrix},\end{aligned}$$

and thus second order equivalent equations become

$$(9) \quad w_t + F(w)_x = \frac{\Delta t}{2} (A(w)w_x)_x$$

An entropy of the Euler equations is

$$S(w) = \frac{q^2}{2\rho} + c^2 \rho \ln \rho.$$

We know that with this choice there exists an entropy flux  $G(w)$  such that

$$S'F' = G'.$$

Multiplying (9) on the left by  $S'(w)$ , integrating by part in  $x$  and neglecting boundary terms, we obtain the entropy dissipation balance

$$\frac{d}{dt} \int_x S = -\frac{\Delta t}{2} \int_x w_x \cdot S''(w) A(w) w_x.$$

A sufficient condition for entropy dissipation is thus that  $E(w) = S''(w)A(w)$  is a positive matrix. The D1Q3 model is generally used for subsonic flows. When  $\kappa = 0$  (no numerical viscosity)  $E(w)$  has always a negative eigenvalue and the scheme is thus unstable. The negative eigenvalue has a minimal modulus if  $\lambda = \sqrt{3}c$  and is then of order  $O(u^6)$ . It justifies the fact that the scheme can, however, be applied in practice on relatively coarse meshes for low Mach number flows. When  $\kappa \neq 0$  Taylors expansions in  $u$  give

$$\begin{aligned}\rho^2 \det(E(w)^T + E(w)) &= -4c^6 + 8\lambda^2 c^4 + O(u^2), \\ \rho \text{Tr}(E(w)^T + E(w)) &= 2c^4 - 2c^2 + 4\lambda^2 + O(u^2).\end{aligned}$$

If  $\lambda$  is large enough, the scheme is thus stable for low Mach flows.



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**Burgers meets Braess**

HELGE HOLDEN

(joint work with Rinaldo M. Colombo)

The talk is based on the recent paper [2] where we introduce a framework to study the possible occurrence of the Braess paradox on a traffic network, where the flow on each road is described using so-called traffic hydrodynamics [5, 6].

The Braess paradox was introduced by D. Braess in 1968 in [1], where he described a simple network with traffic flow in which one had the paradoxical situation that the addition of a new road to the network, could make the travel times worse for all. The paradox has been studied extensively, and turns up not only in traffic flow, but also in mesoscopic electron systems, and in mechanical springs. Real-world examples include Seoul, Stuttgart, and New York City. The list of relevant literature is too vast to be included here; see [2] and the references therein.

The modeling of dense traffic flow by a hydrodynamic approach where cars are represented by their density, and the dynamics is described by the conservation of the number of cars, was introduced by Lighthill and Whitham [5] and Richards [6] in 1955–56. It has been studied extensively, and was extended to a network of traffic in [4], see also [3].

Let us briefly describe the model we study. We consider unidirectional traffic flow on a network of roads. The traffic dynamics on each road is given by  $\rho_t + (\rho v(\rho))_x = 0$  where  $\rho$  is the density of vehicles and  $v = v(\rho)$  is the velocity, which is considered to be a decreasing function of the density. The resulting flux function  $f(\rho) = \rho v(\rho)$  is a concave function which satisfies  $f(0) = f(\rho_{\max}) = 0$  where  $\rho_{\max}$  denotes the maximum capacity of the road. There is a maximum of the flow at a point  $\rho_m$  with  $\rho_m \in (0, \rho_{\max})$ . We only study stationary flow in the uncongested phase, i.e.,  $\rho \in (0, \rho_m)$ . These assumptions vastly simplify the analysis.

Instead of giving the general formulation, we will here only present a simple example. Consider the roads given on Figure 1. The network is given by two routes, denoted  $\alpha$  and  $\beta$ , connecting  $A$  and  $B$ . The route  $\alpha$  consists of roads  $a$  and  $b$ , the route  $\beta$  consists of roads  $c$  and  $d$ . Roads  $a$  and  $d$  are identical, and similarly for roads  $b$  and  $c$ . The velocity of roads  $a$  and  $d$  is given by  $\ln(1 + \rho)/\rho$ , while

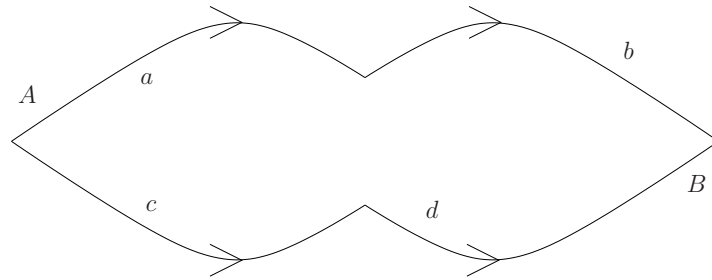


FIGURE 1. Network consisting of two routes connecting  $A$  to  $B$ .

on roads  $b$  and  $c$  the velocity is constant, denoted  $V$ . All roads have unit length. Let there be a constant inflow at  $A$  of cars given by  $\phi$ . We need to determine the fraction  $\theta \in [0, 1]$  of cars that choose route  $\alpha$  (which clearly implies that the fraction  $1 - \theta$  follows route  $\beta$ ). The total travel times read

$$\tau_\alpha(\theta) = \tau_a(\theta) + \tau_b(\theta) \quad \text{and} \quad \tau_\beta(1 - \theta) = \tau_c(1 - \theta) + \tau_d(1 - \theta).$$

in obvious notation, and the mean travel time of the network equals

$$T(\theta) = \theta\tau_\alpha(\theta) + (1 - \theta)\tau_\beta(1 - \theta),$$

and the name of the game is to determine the minimum of  $T$ . The symmetry of the problem clearly implies that the equilibrium, i.e., when the travel time along  $\alpha$  equals that of  $\beta$ , occurs when  $\theta = 1/2$ , which is a global minimum as well as a local Pareto optimum (i.e., no perturbation will reduce all travel times) and Nash equilibrium (no driver would benefit for making any local change).

Now add a new road  $e$  of unit length, see Figure 2. We denote by  $\gamma$  the route

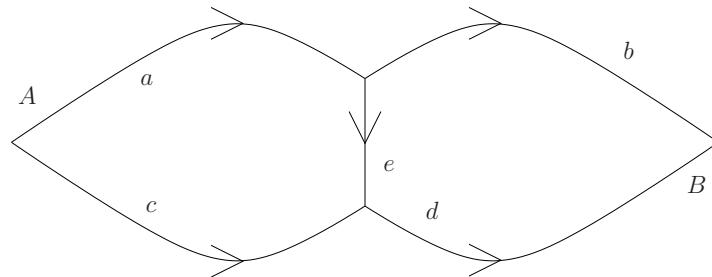


FIGURE 2. A network consisting of three routes  $\alpha$ ,  $\beta$ , and  $\gamma$  connecting  $A$  to  $B$ .

connecting  $a$ ,  $e$ , and  $d$ , and assume that the velocity along road  $c$  is given by another constant  $v$ . Denote by  $\theta_1$  and  $\theta_2$  the fraction of cars taking routes  $\alpha$  and  $\beta$ , respectively. The fraction that uses route  $\gamma$  is  $1 - (\theta_1 + \theta_2)$ . Naturally  $\theta_1, \theta_2, (\theta_1 + \theta_2) \in [0, 1]$ . Now the travel times read

$$\tau_\alpha(\theta_1, \theta_2) = \tau_a(1 - \theta_2) + \tau_b(\theta_1),$$

$$\tau_\beta(\theta_1, \theta_2) = \tau_b(\theta_2) + \tau_a(1 - \theta_1),$$

$$\tau_\gamma(\theta_1, \theta_2) = \tau_a(1 - \theta_2) + \tau_e(1 - \theta_1 - \theta_2) + \tau_d(1 - \theta_1),$$

and the average total travel time

$$T(\theta_1, \theta_2) = \theta_1 \tau_\alpha(\theta_1, \theta_2) + \theta_2 \tau_\beta(\theta_1, \theta_2) + (1 - \theta_1 - \theta_2) \tau_\gamma(\theta_1, \theta_2).$$

Then, one can show, see [2, Theorem 2.7], that provided

$$\frac{e^\phi - 1}{\phi} < \frac{1}{V} - \frac{1}{v} < \frac{2}{\phi}(e^\phi - e^{\phi/2}),$$

the above network example will display the Braess paradox, that is, the addition of road  $e$  will make travel times worse than in the case without road  $e$ . More precisely, the point with  $\theta_1 = \theta_2 = 0$  is the unique Nash point for the network with five roads. At the same time the corresponding travel time  $\tau_\gamma(0, 0)$  is worse than the global optimal configuration for the network with four roads.

Clearly, the occurrence of the Braess paradox is unwanted, and a natural question is to inquire if one can enforce a *control* on road  $e$  that removes the paradox. We show in [2, Theorem 3.1] that by enforcing a suitable speed limit on road  $e$ , the Braess paradox does not occur.

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## Towards a numerical solver for the multi-dimensional Euler equations

CHRISTIAN KLINGENBERG

(joint work with Wasilij Barsukow)

Our goal is to develop a numerical method for the two dimensional compressible inviscid Euler equations. To that end we consider the linearized Euler equations:

$$\begin{aligned} v_t + \nabla p &= 0 \\ p_t + \nabla \cdot v &= 0 \end{aligned}.$$

The motivation for studying this is that for the multi-dimensional Euler equations acoustics and advection are different. Here we begin by studying acoustics via the linearized Euler equations.

To solve these equations we can represent the solution via a closed formula for any given initial value problem. Note that these equations can be written as

$$\begin{aligned} p_{tt} - \Delta p &= 0 \\ v_{tt} - \nabla \nabla \cdot v &= 0 \quad , \end{aligned}$$

in other words even though the pressure satisfies a wave equations the velocity satisfies a more complicated equation. The closed form solution for  $v$  uses a Green's function and is more complicated than Kirchhoff's or Hadamard's formula.

This closed form solution can now be used to study the evolution of piecewise constant initial data on a rectangular mesh in two space dimensions. This will ensure that there are no numerical artifacts in the evolution that falsify the solution. So our two-dimensional algorithm consists of projecting the data to piecewise constants on rectangles, followed by the exact evolution of this data for a sufficiently small time step and finally projecting it back to piecewise constants. This leads to a poor algorithm, whose poor quality can not be attributed to an approximation of the evolution. The poor quality is seen by the smearing out of shocks that depend on their orientation with respect to the grid and also that this algorithm lacks the ability to solve low Mach number flow. Note that even for these linearized equations it is possible to have a notion of a Mach number. As this number goes to zero one obtains an incompressible equation.

We conclude that a two dimensional algorithm can not be based on reconstructing the data as piecewise discontinuous data. Our next step will be to base a new algorithm on the reconstruction to piecewise continuous elements.

We acknowledge helpful discussions on this topic with Phil Roe.

### **Asymptotic preserving IMEX finite volume schemes for singular limits of weakly compressible flows**

MÁRIA LUKÁČOVÁ-MEDVIĐOVÁ

(joint work with G. Bispen, L. Yelash)

In the case of weakly compressible flows the magnitude of flow velocity  $\mathbf{u}$  is much smaller than the sound speed  $c$ , which results in the so-called low Mach number flows. Here the Mach number is a reference number defined as  $M = \frac{|\mathbf{u}|}{c}$ . Such flows arise in many applications, such as meteorology, combustion or astrophysics. Since the resulting problem is stiff, it is a well-known fact that a naive discretization would require that the spatial and the temporal steps,  $\Delta x$  and  $\Delta t$ , need to be reduced simultaneously as the Mach number  $M \rightarrow 0$ . Clearly, this is non-affordable computationally.

In our talk we have presented new IMEX finite volume schemes for the Euler equations with the gravity source term that are based on the so-called acoustic/advection splitting strategy. More precisely, we split the whole nonlinear system of the Euler equations into a stiff linear part governing fast acoustic and gravity waves and a non-stiff nonlinear part that models slow nonlinear advection effects, see also our recent papers [2, 3, 4, 11]. For time discretization we have

used higher order globally stiffly accurate IMEX schemes and approximate stiff linear operator implicitly and the non-stiff nonlinear operator explicitly, see, e.g. ASR(2,2,2) [1]. Consequently, we can efficiently resolve slow nonlinear dynamics due to advection effects.

Our main goal is to analyse the asymptotic preserving properties of these methods and show that a suitable splitting into the linear stiff subsystem for acoustic/gravity waves and the nonlinear non-stiff subsystem for the advection combined with the IMEX FV discretization yields asymptotic preserving schemes. The concept of the *asymptotic preserving schemes* has been firstly introduced by Jin et al., see [8], [9] and the references therein: a numerical scheme is called asymptotic preserving if it is uniformly consistent as a singular limit parameter, e.g. the Mach number, approaches its limit. In particular, the scheme reduces to a consistent approximation of the limit equation. In our recent paper [5] we have analysed both the *asymptotic consistency* as well as *asymptotic stability* of our IMEX FV schemes.

In particular, using the theory of circulant matrices we are able to investigate the matrix properties of the resulting discrete system. We show that its inverse acts as an orthogonal projection on null spaces of the corresponding discrete operators appearing at the right hand side of the discrete system. Consequently, we obtain that new solution at the time step  $t_{n+1}$  satisfy the expected asymptotic properties. More precisely, they are of order  $\mathcal{O}(M^2)$ . This leads to the consistency result: *Numerical solution yields a consistent approximation of the limiting incompressible Euler equations in the singular limit as  $M \rightarrow 0$ .* Furthermore, using the energy method and the equivalence of discrete norms we are also able to prove that the numerical solution is uniformly stable with respect to  $M$ , if a fixed mesh is used.

We also refer to a recent work of Kaiser et al. [10], where asymptotic consistency of the so-called RS IMEX schemes for the isentropic Euler equations has been studied. Note that RS IMEX schemes are strongly related to our IMEX FV schemes; both IMEX methods use analogous splitting and may differ in the choice of a reference solution or an equilibrium solution. In [2, 3] we have analysed asymptotic consistency and accuracy of the IMEX FV for the shallow water equations with a bottom topography source term, which are mathematically equivalent to the isentropic Euler equations used in [10].

In order to preserve equilibria of the underlying hyperbolic balance laws on the discrete level a special treatment of zero-order source terms is required, which yields the well-balanced schemes, see, e.g., [6], [7] and the references therein. Our schemes are *well-balanced* as well. Indeed, they preserve a particular underlying equilibrium by the construction, since time update is realized only for perturbations of the underlying equilibrium state.

Our numerical experiments presented at the end of the talk clearly demonstrated the uniform order of convergence with respect to  $M$ , as far as advective effects are dominant. If acoustic waves are also present in the solution, the scheme is convergent uniformly with respect to  $M$ , but the order of convergence is recovered

only if the space discretization parameter is small enough to resolve fast acoustic waves.

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## A traffic model with phase transitions at a junction

FRANCESCA MARCELLINI

(joint work with Mauro Garavello)

We consider the Phase Transition traffic model in [6], based on a non-smooth  $2 \times 2$  system of conservation laws,

$$(1) \quad \begin{cases} \partial_t \rho + \partial_x (\rho v(\rho, w)) = 0 \\ \partial_t (\rho w) + \partial_x (\rho w v(\rho, w)) = 0 \end{cases} \quad \text{with} \quad v = \min \{V_{\max}, w \psi(\rho)\},$$

where  $\rho$  is the traffic density,  $w = w(t, x)$  is the maximal speed of each driver,  $\psi$  is a  $\mathbf{C}^2$  function and  $V_{\max}$  is a uniform bound on the speed. This is a macroscopic description displaying 2 phases, the *Free* phase  $F$  and *Congested* phase  $C$ , described by the sets

$$\begin{aligned} F &= \{(\rho, w) \in [0, R] \times [\check{w}, \hat{w}]: v(\rho, \rho w) = V_{\max}\}, \\ C &= \{(\rho, w) \in [0, R] \times [\check{w}, \hat{w}]: v(\rho, \rho w) = w \psi(\rho)\}, \end{aligned}$$

where  $R$  is the maximal traffic density. This model is an extension of the classical Lighthill-Whitham [12] and Richards [14] model and it falls into the class of second order traffic models introduced by Aw and Rascle in [1] and independently by

Zhang in [15]. In 2002, Colombo proposed the first second order model with two different phases in [4, 5]. See also the phase transition models in [2, 10, 13].

### 1. THE RIEMANN PROBLEM AT A JUNCTION

We propose a Riemann solver at a junction for the model in (1) which conserves the number of cars and also the maximal speed  $w$  of each vehicle, see [8]. Note that  $w$  is a peculiar characteristic of (1), being a specific feature of every single driver.

We consider a junction with  $n$  incoming arcs  $I_1, \dots, I_n$  and  $m$  outgoing arcs  $I_{n+1}, \dots, I_{n+m}$ , where each incoming arc is given by  $I_i = ]-\infty, 0]$  and each outgoing arc is  $I_j = [0, +\infty[$ , see [3, 7, 9, 11]. On each arc we consider the phase transition model in (1) with the change of variable  $\eta = \rho w$ ; we get a system where the conserved variables are  $\rho$  and  $\eta$  and the speed is  $v(\rho, \eta) = \min \left\{ V_{\max}, \frac{\eta}{\rho} \psi(\rho) \right\}$ .

We consider the following Riemann problem

$$(2) \quad \begin{cases} \begin{cases} \partial_t \rho + \partial_x (\rho v(\rho, \eta)) = 0 \\ \partial_t \eta + \partial_x (\eta v(\rho, \eta)) = 0 \end{cases} & (\rho, \eta) \in I_i \\ \begin{cases} \partial_t \rho + \partial_x (\rho v(\rho, \eta)) = 0 \\ \partial_t \eta + \partial_x (\eta v(\rho, \eta)) = 0 \end{cases} & (\rho, \eta) \in I_j \\ (\rho_i, \eta_i)(0, x) = (\bar{\rho}_i, \bar{\eta}_i) \\ (\rho_j, \eta_j)(0, x) = (\bar{\rho}_j, \bar{\eta}_j), \end{cases}$$

where  $(\bar{\rho}_i, \bar{\eta}_i) \in F \cup C$  are the initial data in each incoming arc  $I_i$ ,  $i = 1, \dots, n$ , and  $(\bar{\rho}_j, \bar{\eta}_j) \in F \cup C$  are the initial data in each outgoing arc  $I_j$ ,  $j = 1, \dots, m$ .

We define the concept of Riemann solver at a generic junction.

**Definition 1.1.** *A Riemann solver at a junction is a function*

$$\begin{aligned} \mathcal{RS}_J : \prod_{i=1}^{n+m} (F \cup C) &\longrightarrow \prod_{i=1}^{n+m} (F \cup C) \\ ((\rho_1, \eta_1), \dots, (\rho_{n+m}, \eta_{n+m})) &\longmapsto ((\rho_1^*, \eta_1^*), \dots, (\rho_{n+m}^*, \eta_{n+m}^*)) \end{aligned}$$

satisfying the following properties.

(1) *The consistency condition holds, i.e.:*

$$\mathcal{RS}_J((\rho_1^*, \eta_1^*), \dots, (\rho_{n+m}^*, \eta_{n+m}^*)) = ((\rho_1^*, \eta_1^*), \dots, (\rho_{n+m}^*, \eta_{n+m}^*)).$$

(2) *For every  $i \in \{1, \dots, n\}$ , the Riemann problem in (2) with initial data  $(\rho, \eta)(0, x) = (\rho_i, \eta_i)$ , with  $x < 0$ , is solved with waves with negative speed.*

(3) *For every  $i \in \{n+1, \dots, n+m\}$ , the Riemann problem in (2) with initial data  $(\rho, \eta)(0, x) = (\rho_i, \eta_i)$ , with  $x > 0$ , is solved with waves with positive speed.*

(4) *The traffic distribution*

$$A \begin{bmatrix} \rho_1^* v(\rho_1^*, \eta_1^*) \\ \vdots \\ \rho_n^* v(\rho_n^*, \eta_n^*) \end{bmatrix} = \begin{bmatrix} \rho_{n+1}^* v(\rho_{n+1}^*, \eta_{n+1}^*) \\ \vdots \\ \rho_{n+m}^* v(\rho_{n+m}^*, \eta_{n+m}^*) \end{bmatrix}$$

holds, where  $A = (\alpha_{i,j})_{i=1,\dots,n; j=n+1,\dots,n+m}$ , whose coefficients indicate the percentage of traffic that passes from  $I_i$  to  $I_j$ , with  $\sum_{j=n+1}^{n+m} \alpha_{ij} = 1$ .

(5) The mass conservation holds, i.e.  $\sum_{i=1}^n \rho_i^* v(\rho_i^*, \eta_i^*) = \sum_{i=n+1}^{n+m} \rho_i^* v(\rho_i^*, \eta_i^*)$ .

(6) The distribution of the maximal speed holds, i.e.:

$$w_{n+1}^* = \frac{1}{\sum_{i=1}^n \alpha_{i,n+1} \gamma_i^*} [\alpha_{1,n+1} \gamma_1^* w_1^* + \dots + \alpha_{n,n+1} \gamma_n^* w_n^*],$$

$$\vdots$$

$$w_{n+m}^* = \frac{1}{\sum_{i=1}^n \alpha_{i,n+m} \gamma_i^*} [\alpha_{1,n+m} \gamma_1^* w_1^* + \dots + \alpha_{n,n+m} \gamma_n^* w_n^*],$$

where  $w_i^* = \frac{\eta_i^*}{\rho_i^*}$  and  $\gamma_i^* = \rho_i^* v(\rho_i^*, \eta_i^*)$  for every  $i \in \{1, \dots, n+m\}$ .

For special junctions, the cases of  $1 \times m$  and  $2 \times 1$  junctions, we prove that the Riemann solver is well defined. The following result holds (see [8] for the proof).

**Theorem 1.2.** *Under the assumptions*

**(H-1):**  $R, \tilde{w}, \hat{w}, V_{\max}$  are positive constants, with  $\tilde{w} < \hat{w}$ ;  $\tilde{w}$  and  $\hat{w}$  are the minimum, respectively, maximum, of the maximal speeds of each vehicle;

**(H-2):**  $\psi \in \mathbf{C}^2([0, R]; [0, 1])$  with  $\psi(0) = 1$ ,  $\psi(R) = 0$ ,  $\psi'(\rho) \leq 0$  and  $\frac{d^2}{d\rho^2}(\rho \psi(\rho)) \leq 0$ , for all  $\rho \in [0, R]$ ;

**(H-3):**  $\tilde{w} > V_{\max}$ ;

**(H-4):** the waves of the first family in  $C$  have negative speed,

the Riemann solver  $\mathcal{RS}_J$  for the cases of  $1 \times m$  and  $2 \times 1$  junctions, constructed as in [8, Section 4, Section 5], satisfies all the conditions of Definition 1.1 and produces a solution to the Riemann problem (2).

**Remark 1.3.** We note that the distribution of the maximal speed in (6) of Definition 1.1 is given by

$$w_2^* = \dots = w_{1+m}^* = \bar{w}_1,$$

in the case of  $1 \times m$  junction and is given by

$$w_3 = \frac{\gamma_1}{\gamma_1 + \gamma_2} \bar{w}_1 + \frac{\gamma_2}{\gamma_1 + \gamma_2} \bar{w}_2,$$

where  $\gamma_1 = \rho_1 v(\rho_1, \eta_1)$  and  $\gamma_2 = \rho_2 v(\rho_2, \eta_2)$ , in the case of  $2 \times 1$  junction, see [8].

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## Lagrangian structure of BV solutions for hyperbolic systems of conservation laws

STEFANO MODENA

(joint work with Stefano Bianchini)

One of the key observations in Fluid Dynamics is that the fluid flow can be described from two different (and in some sense complementary) points of view: the Lagrangian point of view (in which the trajectory in space-time of each single fluid particle is tracked) and the Eulerian point of view (in which one looks at fluid motion focusing on fixed locations in the space through which the fluid flows as time passes). Such key observation has been successfully applied to the analysis of some particular partial differential equations (among all, the transport equation and the Euler equation), leading to important theoretical results. For instance, in the linear transport equation

$$(1) \quad \begin{cases} \partial_t v(t, x) + b(t, x) \cdot \nabla_x v(t, x) &= 0, \\ v(t, 0) &= \bar{v}(x), \end{cases}$$

where

$v : [0, \infty) \times \mathbb{R}^d \rightarrow \mathbb{R}$ , is the unknown,

$b : [0, \infty) \times \mathbb{R}^d \rightarrow \mathbb{R}^d$  is a given, incompressible vector field,  $\operatorname{div}_x b(t, x) = 0$ ,

the solution to (1) presents a strong connection with the Lagrangian flow  $\mathbf{x} : [0, \infty) \times \mathbb{R}^d \rightarrow \mathbb{R}^d$  generated by the ODE

$$(2) \quad \begin{cases} \frac{\partial \mathbf{x}}{\partial t}(t, y) &= b(t, \mathbf{x}(t, y)), \\ \mathbf{x}(0, y) &= y. \end{cases}$$

Indeed, under suitable regularity assumptions, it can be proved that the function  $v(t, x)$  implicitly defined by

$$(3) \quad v(t, \mathbf{x}(t, y)) = v(0, y) = \bar{v}(y)$$

provides the unique solution to the Cauchy problem (1).

In a joint work [2] in preparation with Stefano Bianchini (see also [7]) we show that also the hyperbolic system of conservation laws in one space variable in its most general form

$$(4) \quad \begin{cases} \partial_t u + \partial_x F(u) = 0, \\ u(0, x) = \bar{u}(x), \end{cases} \quad u = u(t, x) \in \mathbb{R}^N, \quad t \geq 0, \quad x \in \mathbb{R}, \quad \text{Tot.Var.}(\bar{u}) \ll 1,$$

can be analyzed from a Lagrangian point of view. Here  $F : \mathbb{R}^N \rightarrow \mathbb{R}^N$  is a generic smooth function, which is only assumed to be *strictly hyperbolic*, i.e. its differential  $DF(u)$  has  $N$  distinct real eigenvalues in each point of its domain. No convexity assumption on  $F$  is made. We also consider small initial data ( $\text{Tot.Var.}(\bar{u}) \ll 1$ ), because this is the setting where the well-posedness of the Cauchy problem (4) is established (see for instance [1, 3, 5] and the references therein).

There are basically two different motivations for studying hyperbolic systems of conservation laws from a Lagrangian point of view. On one side there is a purely theoretical motivation: our theory provides a suitable extension in a more general setting to two well known theories developed in the past years. In [6] Tai-Ping Liu proposed a *wave-tracing* algorithm for tracing the trajectory in time of each wavefront present in a Glimm approximate solution to (4). Our Lagrangian approach provides the counterpart of Liu's wave-tracing for an exact (and not approximate) solution to (4). In [4] Constantine Dafermos introduced the notion of generalized characteristics. His theory works when the flux  $F$  is genuinely non linear; our approach is a generalization of Dafermos' theory in the case when  $F$  is only strictly hyperbolic, without any convexity assumption.

On the other side, there is a more applicative reason. We think that our Lagrangian approach can lead to a deeper understanding of the behavior and of the structure of the solutions to (4). In particular we aim to use our Lagrangian approach to study the fine structure of the solution (its regularity, its behavior near a point of "strong interaction", the stability of the shocks and so on).

The introduction of the precise notion of *Lagrangian representation* for the solution to the general system (4) is beyond the scope of this paper. For this reason we prefer here to give such definition in the context of a single scalar conservation law (i.e.  $N = 1$ ). In such simplified setting, the definition reads as follows.

**Definition 1.1.** A Lagrangian representation of the solution of (4) in the case  $N = 1$  is a 3-tuple  $(\mathcal{W}, \mathbf{x}, \rho)$  where

$\mathcal{W} \subseteq \mathbb{R}$  is an interval, called the set of waves or set of particles,

$\mathbf{x} : [0, \infty) \times \mathcal{W} \rightarrow \mathbb{R}$  is the position function,

$\rho : [0, \infty) \times \mathcal{W} \rightarrow [-1, 1]$  is the density function,

such that

(a) some regularity assumptions on  $\mathbf{x}$ ,  $\rho$  hold; more precisely

- the map  $t \mapsto \mathbf{x}(t, w)$  is Lipschitz for each fixed  $w$ ; the map  $w \mapsto \mathbf{x}(t, w)$  is increasing for each fixed  $t$ ;
- the distributional derivative  $D_t \rho$  of  $\rho$  with respect to the time is a finite Radon measure;

(b) for a.e. wave  $w$  and a.e. time  $t$ , it holds  $\frac{\partial \mathbf{x}}{\partial t}(t, w) = \lambda(t, \mathbf{x}(t, w))$ , where

$$\lambda(t, x) = \begin{cases} f'(u(t, x)) & \text{if } x \mapsto u(t, x) \text{ is continuous at } x, \\ \frac{f(u(t, x+)) - f(u(t, x-))}{u(t, x+) - u(t, x-)} & \text{if } u \text{ has a jump at } x; \end{cases}$$

(c) for a.e. time  $t$ , it holds  $D_x u(t) = \mathbf{x}(t)_\#(\rho(t)\mathcal{L}^1)$ .

The main theorem we prove in [2], [7] is the following.

**Theorem 1.2.** There exists (at least) one Lagrangian representation for the solution to the general strictly hyperbolic system (4).

We would like to stress once again that, even if we gave above the definition of Lagrangian representation only for a scalar conservation law, in [2], [7] we provide the correct definition and prove Theorem 1.2 for a general system of  $N$  conservation laws.

Instead of presenting a sketch of the proof of Theorem 1.2, we prefer to conclude this extended abstract trying to give an “interpretation” of Definition 1.1.

First of all there is a set of (infinitesimal) waves (or particles)  $\mathcal{W}$ . Each particle  $w \in \mathcal{W}$  moves along a Lipschitz trajectory  $\mathbf{x}(\cdot, w)$ , which satisfies a suitable ODE, see Property (b) above. The monotonicity of  $w \mapsto \mathbf{x}(t, w)$  for fixed time  $t$  implies that two different particles can have the same position at a given time, but they can not cross each other. Finally Property (c) means that, at each fixed time  $t$ , starting from  $\mathbf{x}$  and  $\rho$  we are able to reconstruct the (distributional derivative of the) solution  $u(t, \cdot)$ , so that  $\mathbf{x}$  and  $\rho$  are enough to determine  $u$ .

It is instructive to make a comparison with the analysis made at the beginning about the transport equation (1). Exactly as in (1), also for the system of conservation laws (4) we are able to construct a flow  $\mathbf{x}(t, w)$ , which satisfies the “correct” ODE (compare Property (b) in Definition 1.1 with equation (2)) and along which the initial datum is transported. However, differently from the transport equation where the vector field  $b$  is incompressible, the system of conservation laws (4) is far from satisfying any “incompressibility” property: this is clear even when one tries to solve a scalar conservation law through the method of characteristics and sees that two distinct characteristics can collide in a finite time. In our Lagrangian

framework, this reflects on the fact that, as we have already pointed out, two waves can have the same position at the same time (i.e. they can *interact*), and such interactions can create or cancel waves. This is a well known behavior of conservation laws and a main source of difficulties in their analysis. The map  $\rho$  is exactly the tool we introduce in order to keep track of all these phenomena: in our setting, equation (3) (where, roughly speaking, all the particles have the same density) is substituted by Property (c) above, (where each particle is counted with its density  $\rho(t, w)$ ).

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## On $\alpha$ -dissipative solutions of the two-component Hunter–Saxton equation

ANDERS NORDLI

(joint work with Katrin Grunert)

The two-component Hunter–Saxton system is a generalization of the Hunter–Saxton equation, given by

$$(1a) \quad u_t(x, t) + u(x, t)u_x(x, t) = \frac{1}{4} \left( \int_{-\infty}^x (u_x(z, t)^2 + \rho(z, t)^2) \, dz - \int_x^{\infty} (u_x(z, t)^2 + \rho(z, t)^2) \, dz \right),$$

$$(1b) \quad \rho_t(x, t) + (u(x, t)\rho(x, t))_x = 0.$$

Solutions of (1) experience wave breaking which means that  $u_x$  tends pointwise to  $-\infty$  in finite time while  $u$  stays continuous. At wave breaking the energy density,  $u_x(x, t)^2 + \rho(x, t)^2$ , concentrates into a measure. What amount of the concentrated energy to keep can be chosen freely, and hence there is no uniqueness of weak solutions. To select a solution we let  $\alpha$  be a Lipschitz continuous function,  $\alpha : \mathbb{R} \rightarrow [0, 1]$ , and choose to retain an  $(1 - \alpha)$ -fraction of the energy concentrated at the point of wave breaking.

The method of characteristics can be applied to obtain an equivalent system in Lagrangian coordinates. The new system is given by

$$\begin{aligned}y_t(\xi, t) &= U(\xi, t), \\U_t(\xi, t) &= \frac{1}{2}V(\xi, t) - \frac{1}{4} \lim_{\xi \rightarrow \infty} V_\infty(\xi, t), \\H_t(\xi, t) &= 0, \\r_t(\xi, t) &= 0,\end{aligned}$$

where the definition of  $V$  determines which weak solution we get. The choice of  $\alpha$  gives

$$V_\xi(\xi, t) = \begin{cases} H_\xi(\xi, 0), & \text{if there has been no wave breaking,} \\ (1 - \alpha(\bar{y})H_\xi(\xi, 0), & \text{if there was wavebreaking at } \bar{y}. \end{cases}$$

Existence and uniqueness of solutions of the equivalent system can be shown by a contraction argument. The solution of the equivalent system can be mapped back to Eulerian coordinates to prove existence of  $\alpha$ -dissipative weak solutions of (1).

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### Non local mixed systems and IBVPs for balance laws

ELENA ROSSI

(joint work with Rinaldo M. Colombo, Veronika Schleper)

We couple a non local balance law with a parabolic equation, obtaining the following new class of mixed hyperbolic–parabolic systems:

$$(1) \quad \begin{cases} \partial_t u + \nabla \cdot (u v(w)) = (\alpha w - \beta)u \\ \partial_t w - \mu \Delta w = (\gamma - \delta u)w \end{cases}$$

The idea behind is to describe two competing populations, predators and prey, characterised by their density, called respectively  $u$  and  $w$ : the first evolves according to the balance law, the second diffuses according to the parabolic equation. The source terms of this system, motivated by Lotka–Volterra equations, describe the feeding.

The main feature of the mixed system (1) lies in the drift term  $v$  in the balance law:  $v$  is chosen to be a non local function of the prey density  $w$ . This allows to

model the fact that predators can feel the presence of prey also from far away. A possible choice of the functional  $v$  is the following

$$(2) \quad v(w) = \kappa \frac{\nabla(w * \eta)}{\sqrt{1 + \|\nabla(w * \eta)\|^2}},$$

where  $\kappa > 0$  and  $\eta$  is a positive smooth mollifier. When  $v$  is chosen as in (2), predators direct their movement towards the regions where the concentration of prey is higher.

Solutions  $(u, w)$  to system (1) are sought in the space  $(\mathbf{L}^1 \cap \mathbf{L}^\infty \cap \mathbf{BV})(\mathbb{R}^n; \mathbb{R}) \times (\mathbf{L}^1 \cap \mathbf{L}^\infty)(\mathbb{R}^n; \mathbb{R})$ , thus in a space different from that considered usually for parabolic equations. In [3] the basic well posedness results for the mixed system (1) are proven: in particular [3, Theorem 2.2] ensures existence, uniqueness, continuous dependence of the solution on the initial data,  $\mathbf{L}^1$  and  $\mathbf{L}^\infty$  estimates.

The analytic structure suggests that a reliable numerical procedure should be devised to study qualitatively the solutions to (1). In [6] we derive an algorithm to numerically solve the coupled system: the parabolic part is approximated by an explicit finite-difference method, while an *ad hoc* adaptation of Lax–Friedrichs method with dimensional splitting is used for the hyperbolic part. Both source terms are treated by operator splitting, using a second order Runge–Kutta method.

The convergence of the numerical algorithm is proven in [6, Theorem 4.1]: the hyperbolic variable  $u$  converges strongly in  $\mathbf{L}^1$ , the parabolic one  $w$  converges weakly\* in  $\mathbf{L}^\infty$ . The proof relies on a careful tuning between the integration methods and it exploits strongly the non locality of the convective part in the balance law.

The algorithm has been implemented in a series of **Python** scripts. Using them, qualitative properties of the solutions are investigated. We observe the formation of a discrete, quite regular pattern: while prey diffuse, predators accumulate on the vertices of a regular lattice, see [3, Figure 3.3] and [6, Figure 5]. In [2, Section 2] we try to change some parameters of the system and see how this influences the pattern.

The analytic study of system (1) is on all  $\mathbb{R}^n$ . However, both numerical integrations and possible biological applications suggest that the boundary plays a relevant role. It would then be interesting to study the mixed system (1) in a bounded domain. As far as parabolic equations in bounded domain are concerned, in the literature many results can be found. However, known results for balance laws in bounded domains lack some estimates needed to deal with the coupling. Therefore, in [4] the focus is shifted to the following Initial Boundary Value Problem (IBVP) for a general balance law

$$(3) \quad \begin{cases} \partial_t u + \nabla \cdot f(t, x, u) = F(t, x, u) & (t, x) \in \mathbf{I} \times \Omega \\ u(0, x) = u_o(x) & x \in \Omega \\ u(t, \xi) = u_b(t, \xi) & (t, \xi) \in \mathbf{I} \times \partial\Omega, \end{cases}$$

where  $\Omega \subseteq \mathbb{R}^n$  is a bounded domain and  $\mathbf{I} = [0, T]$ .

The key reference for the study of this IBVP is the fundamental paper [1]. However, there detailed estimates are given explicitly only in the case of homogeneous boundary conditions, that is  $u_b = 0$ . In [4] we go over this case, providing rigorous hypotheses and estimates and paying particular attention to the regularity and compatibility conditions. Then, we study also the general IBVP, with possibly non homogeneous boundary condition, and prove its well posedness: in [4, Theorem 2.7 and Theorem 4.3] we show the existence and uniqueness of an entropy solution to (3),  $\mathbf{L}^\infty$  and TV estimates, and  $\mathbf{L}^1$  Lipschitz continuity of the solution as a function of time, of the initial datum and of the boundary datum. Parabolic, hyperbolic and also elliptic techniques have been used to deal with (3).

What is now missing is the stability of the solution with respect to the flux and the source. As far as the latter is concerned, it might result from a careful use of the doubling of variables technique. However, the stability with respect to the flux appears to be a challenging problem. A first step in this direction has been made in [5]. Here, we consider the one dimensional IBVP for a conservation law with flux  $f$  that does not depend explicitly on the space variable:

$$(4) \quad \begin{cases} \partial_t u + \partial_x f(t, u) = 0 & (t, x) \in \mathbb{R}^+ \times \mathbb{R}^+ \\ u(0, x) = u_o(x) & x \in \mathbb{R}^+ \\ u(t, 0) = u_b(t) & t \in \mathbb{R}^+ \end{cases}$$

Note that also the case of an unbounded domain, such as the half line, is now included. We prove the existence of a solution, exploiting the wave front tracking technique, and the stability of the solution with respect to the flux function.

This stability result is necessary to deal with the coupling of a balance law with a parabolic equation. However, its extension to the multidimensional case, but even to the one dimensional case with space dependent flux, is still an open problem.

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## Shock waves in the presence of dispersion

MICHAEL SHEARER

(joint work with Gennady El and Mark Hoefer)

Dispersive shock waves (DSW) of the KdV equation have a well-defined structure [3] that includes a modulated periodic wave train, led by a solitary wave. This structure is also seen in the modified KdV equation,

$$(1) \quad u_t + (u^3)_x = \mu u_{xxx},$$

in which the flux  $f(u) = u^3$  is non-convex [1]. Due to the non-convex (cubic) flux in the modified equation, the sign of the dispersion coefficient,  $\mu$ , is important and there is a richer set of DSW for equation (1), including contact DSW (if  $\mu < 0$ ) and kinks (if  $\mu > 0$ ). We investigate the structure of these waves using the approach of Gurevich and Pitaevskii [3, 4] in which the analysis is simplified by the use of Riemann invariants for the Whitham modulation equations.

It is also instructive to compare solutions of (1) with those of the modified KdV-Burgers equation, which includes a diffusive term,

$$(2) \quad u_t + (u^3)_x = \nu u_{xx} + \mu u_{xxx}, \quad \nu > 0.$$

The structure of shock waves for (2) is quite different, and fits the classical conservation laws description of Lax and Oleinik if  $\mu < 0$ . However, for  $\mu > 0$ , there are undercompressive shocks, which are diffusive equivalents of the kink solutions of (1).

We are in the process of extending results to equations like the BBM equation, in which the dispersion has an evolutionary quality. In this analysis, we discovered a new phenomenon, that of stationary expansion shocks, for both the BBM equation, and for the Boussinesq system of equations.

Stationary shock solutions  $u(x, t) = \text{sgn}(x)A$  of the BBM equation

$$(3) \quad u_t + uu_x = \mu u_{xxt},$$

are *expansive* if  $A > 0$ . When such a shock is approximated by a smooth initial function  $u(x, 0) = u_0(x) = \tanh(x/\epsilon)$  with  $0 < \epsilon \ll 1$ , and allowed to evolve in time, we observe numerically that the smoothed discontinuity persists. The magnitude decays like  $1/t$  and a rarefaction wave develops. This structure is explained in [2] using matched asymptotic expansions in which the stationary shock is treated as an inner layer and the rarefaction is a simple wave attaching to the constants  $\pm A$  in the far field.

A similar surprising phenomenon is observed in stationary solutions of a version of the Boussinesq equations of shallow water flow,

$$(4) \quad \begin{aligned} h_t + (uh)_x &= 0 \\ u_t + uu_x + h_x - \frac{1}{3}u_{xxt} &= 0. \end{aligned}$$

Smooth initial data approximating an expansion shock persists in time, weakening to give way to a rarefaction wave only algebraically in time. This structure is explained using the Riemann invariants, with the observation that one invariant is



close to constant throughout, while the other invariant satisfies the BBM equation (3) to leading order.

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### On the two-dimensional pressure-less equations

EITAN TADMOR

We prove the existence of weak solutions for the two-dimensional pressure-less Euler equations. To this end we develop an  $L^1$  framework of dual solutions for such equations. Their existence is realized as vanishing viscosity limits,

$$u_t^\epsilon + u^\epsilon \cdot \nabla_x u^\epsilon = \epsilon \Delta u^\epsilon.$$

The limit  $\bar{u} := \lim_{\epsilon \downarrow 0} u^\epsilon$  follows from new BV estimates,

$$\|u^\epsilon(\cdot, t)\|_{BV} \leq \text{Const.} \|u_0(\cdot)\|_{BV},$$

derived by tracing the *spectral gap* of the velocity gradient matrix,  $\nabla u = (\partial_{x_i} u_j)$

$$\|\eta(\cdot, t)\|_{L^1} \leq \|\eta_0(\cdot)\|_{L^1}, \quad \eta(\cdot, t) := \lambda_2(\nabla u) - \lambda_1(\nabla u).$$

## Analytical results for isothermal & adiabatic two phase flow with phase transition

FERDINAND THEIN

(joint work with Maren Hantke)

We study compressible two phase flow governed by the Euler equations for a liquid and a vapor phase and allow for phase transition. In the work by Hantke et al. [1], existence and uniqueness results to the Riemann problem for the compressible isothermal Euler equations were shown. They considered two phase flows for a liquid and a vapor phase with and without phase transition. To close the system two (specific) linear equations of state were chosen to relate density and pressure inside the phases. In order to clearly distinguish their approach from other models for two phase flows which are currently studied, we shortly summarize important points of their model:

- *one* set of Euler equations for both phases and the two phase are distinguished by the equation of state
- the *sharp* interface between the phases is a non-classical shock
- the mass transfer across the interface is modeled via a kinetic relation which is consistent with the second law of thermodynamics

Based on this several questions arise. The first one considers the equations of state linking the pressure and the density. We want to generalize the result of [1] in the spirit of [2] to arbitrary (yet thermodynamically consistent) equations of state. The basic assumption for the equations of state is that they are suitable to solve the single phase Riemann problem. For the isothermal Euler equations

$$(*) \quad \begin{aligned} \frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} &= 0, \\ \frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2 + p)}{\partial x} &= 0. \end{aligned}$$

we have the following jump conditions at the interface, see [3],

$$\begin{aligned} (1) \quad & 0 = \llbracket \rho(u - w) \rrbracket, \\ (2) \quad & 0 = \rho(u - w) \llbracket u \rrbracket + \llbracket p \rrbracket \end{aligned}$$

and the entropy inequality for isothermal processes

$$(3) \quad 0 \leq z \llbracket g + e_{kin} \rrbracket.$$

We use the following notation

- $\rho$  denotes the mass density,  $u$  the velocity
- $w$  denotes the speed of the phase boundary
- $z = -\rho(u - w)$  is the mass flux across the interface
- $g$  is the Gibbs free energy and  $e_{kin}$  the kinetic energy

To complete the system one additional equation is needed. The missing equation is given by the kinetic relation and has to be chosen such that (3) is fulfilled. Hence

we choose

$$(4) \quad z = \tau p_V \llbracket g + e_{kin} \rrbracket$$

with  $p_V$  being the pressure in the vapor phase and  $\tau \in \mathbb{R}$  a strictly positive constant. Using standard thermodynamical properties of the Gibbs free energy and some (sufficient) assumptions we can prove that there exists a unique solution of the equations at the interface. Additionally we show that if the Riemann problem has a solution this solution is also unique. Furthermore we have for the solution that the phase boundary is subsonic and thus always lies between the two classical waves.

The second question that the work in [1] raises is how this result extends in the adiabatic (i.e. no heat flux) case. Therefore we consider the full system of Euler equations

$$\begin{aligned}
 (**) \quad & \frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} = 0, \\
 & \frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2 + p)}{\partial x} = 0, \\
 & \frac{\partial(E)}{\partial t} + \frac{\partial(u(E + p))}{\partial x} = 0, \\
 & E = \rho(e + \frac{1}{2}u^2).
 \end{aligned}$$

Now we consider the following conditions at the interface (cf. [4])

$$\begin{aligned}
 (5) \quad & 0 = \llbracket \rho(u - w) \rrbracket, \\
 (6) \quad & 0 = \rho(u - w) \llbracket u \rrbracket + \llbracket p \rrbracket, \\
 (7) \quad & 0 = \rho(u - w) \llbracket e + \frac{p}{\rho} + \frac{1}{2}(u - w)^2 \rrbracket, \\
 (8) \quad & 0 \leq \zeta_{PB} = \rho(u - w) \llbracket s \rrbracket.
 \end{aligned}$$

Here  $s$  denotes the (specific) entropy. Now the kinetic relation is given by

$$(9) \quad z = -\rho(u - w) = -\tau p_V \llbracket s \rrbracket.$$

Here  $\tau$  may depend on the Temperature and thus is in general not constant anymore. In order to solve the problem we first discuss the phase boundary. Therefore we prescribe the vapor phase on one side and show that there is a unique solution for the liquid phase on the other side of the phase boundary. The same must be done again for a prescribed liquid phase. In the case of evaporation, i.e.  $z > 0$  we can show that under certain assumptions the interface conditions (5) - (7) connect two states uniquely if a solution exists. As in [1] we can only have subsonic solutions in the liquid phase. Hence we have two classical acoustic waves (one in each phase), a contact wave in the vapor phase and the phase boundary between the contact wave and the acoustic wave in the liquid phase.

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**Model reduction through tangent spaces in kinetic gas theory**

MANUEL TORRILHON

We consider a kinetic transport equation in the form

$$(1) \quad \partial_t f + c_i \partial_{x_i} f = S(f)$$

for the probability density  $f : \Omega \times \mathbb{R}^+ \times \mathbb{R}^d \rightarrow \mathbb{R}$ ,  $(x, t, c) \mapsto f(x, t, c)$  with a spatial domain  $\Omega \subset \mathbb{R}^d$ ,  $d \in \{1, 2, 3\}$  and  $i = 1, \dots, d$ . In the kinetic theory of monatomic gases the probability density describes the distribution of particle velocities such that  $f(x, t, c) dc dx$  represents the number of particle in the phase space volume element  $[x, x + dx] \times [c, c + dc]$ . The operator  $S(f)$  may be given by the Boltzmann collision integral or a kinetic model like the BGK-approximation. We assume that there is an equilibrium given by the Maxwell distribution  $f_M(c; \rho, v, \theta)$ , an isotropic Gaussian with density  $\rho$ , velocity  $v$ , temperature  $\theta$  and particle mass  $m$  that satisfies  $S(f_M) = 0$ .

A model reduction approach aims at the replacement

$$(2) \quad f(x, t, c) \quad c \in \mathbb{R}^d \quad \longleftrightarrow \quad W(x, t) = \{w_\alpha(x, t)\}_{|\alpha|=1,2,\dots,N}$$

that is, at  $(x, t)$  the description of the gas by a velocity distribution function defined on a 3-dimensional space is replaced by a finite set of field variables  $w_\alpha(x, t)$  where  $\alpha$  is a multiindex. This set may contain variables related to the fluid dynamic fields density, velocity and temperature, but could also contain further internal variables that describe the state of the gas. If we decide for such a reduced description it is necessary to formulate a reconstruction or prolongation operator  $f^{(*)}$  that computes a distribution function from  $w_\alpha$  in the form

$$(3) \quad f(x, t, c) = f^{(*)}(W(x, t), c).$$

The function  $f^{(*)}$  is also called *model* or *closure relation*. To obtain evolution equations for the variables  $W(x, t)$  we use a variational formulation of the kinetic equation (1) with test functions  $\varphi_\alpha$

$$(4) \quad \int_{\mathbb{R}^d} \varphi_\alpha(x, t, c) \left( \partial_t f^{(*)}(W(x, t), c) + c_i \partial_{x_i} f^{(*)}(W(x, t), c) \right) dc = \\ \int_{\mathbb{R}^d} \varphi_\alpha(x, t, c) S\left(f^{(*)}(W(x, t), c)\right) dc, \quad |\alpha| = 1, 2, \dots, N$$

where for generality the test function can depend on space and time as well. The general questions are now: What is a good model to choose for  $f^{(*)}$ ? Ideally, it should contain Maxwellians, but also approximates more general distributions with few parameters. What should be used as test functions  $\varphi_\alpha$ ? Ideally, these contain the monomials  $1, c, c^2$  such that the physical conservation laws are part of the reduced equations. What can be said about the final evolution equations for  $W(x, t)$ ? Ideally, we expect symmetric hyperbolic balance laws with an entropy as a natural nonlinear approximation for kinetic transport (1).

The model  $f^{(*)}(W(x, t), c)$  can be interpreted as a manifold to which the evolution of  $f$  is constraint due to the dimensional reduction. The tangent space of this manifold is given by the gradients

$$(5) \quad v_\beta(W(x, t), c) = \frac{\partial f^{(*)}(W(x, t), c)}{\partial w_\beta}$$

and the differential is  $df^{(*)} = \sum_{\beta=1}^N v_\beta(W(x, t), c) dw_\beta$ . With this the variational formulation simplifies to a first order, quasi-linear system of partial differential equations in the form

$$(6) \quad A_{\alpha\beta}^{(0)}(W) \partial_t w_\beta(x, t) + A_{\alpha\beta}^{(i)}(W) \partial_{x_i} w_\beta(x, t) = P_\alpha(W), \quad |\alpha| = 1, 2, \dots, N$$

with summation convention for  $\beta$  and coefficients ( $c_0 = 1$ )

$$(7) \quad A_{\alpha\beta}^{(i)}(W; x, t) = \int_{\mathbb{R}^d} c_i \varphi_\alpha(x, t, c) v_\beta(W, c) dc,$$

$$(8) \quad P_\alpha(W; x, t) = \int_{\mathbb{R}^d} \varphi_\alpha(x, t, c) S(f^{(*)}(W, c)) dc.$$

With *tangent space reduction* the gradients are used as test functions  $\varphi_\alpha(x, t, c) = v_\alpha(W(x, t), c)$ , so that the matrices  $A_{\alpha\beta}^{(i)}$  become symmetric and moreover  $A_{\alpha\beta}^{(0)}$  is positive definite. Consequently, for any model the system is of Friedrichs type and indeed symmetric hyperbolic. However, due to the nonlinearity of the matrices  $A_{\alpha\beta}^{(i)}$  the system can not be written in balance law form with a flux function in general. The existence of an entropy remains unclear and also the conservation laws may not be part of the system.

For the *linear model*  $f^{(*)}(W, c) = \sum_{\alpha=1}^N w_\alpha(x, t) \varphi_\alpha(c)$  with functions  $\varphi_\alpha$  independent of physical space and time, the tangent space reduction leads to the usual Galerkin formulation where  $\varphi_\alpha(c)$  are test and ansatz functions. In this case the matrices  $A_{\alpha\beta}^{(i)}$  become constant and the system can be written in balance form, thus possesses an entropy which is equivalent to the  $L^2$ -norm of  $W$ . However, the linear model does not contain Maxwell distributions in a natural way and typically requires large  $N$  to achieve accurate approximations.

A typical choice for a model that contains Maxwellians is the *Hermite or Grad expansion* [2]

$$(9) \quad f^{(*)}(W, c) = \sum_{\alpha=1}^N w_\alpha \psi_\alpha((c - v)/\theta) f_M(c; \rho, v, \theta)$$

with  $\psi_\alpha$  chosen as  $d$ -variate polynomials and density, velocity and temperature are considered part of the variable set  $W$ . Polynomials are also used as test functions  $\varphi_\alpha(W, c) = \psi_\alpha((c - v)/\theta)$  such that the reduced equations (4) represent moment equations including the conservation laws. Unfortunately, this model leads to a complicated expression for the gradients  $v_\beta(W, c)$  and the system is not hyperbolic in general. However, the gradient can be artificially projected onto the model space by requiring

$$(10) \quad \frac{\partial f^{(*)}(W, c)}{\partial w_\beta} \stackrel{!}{=} \sum_{\gamma=1}^N \psi_\gamma((c - v)/\theta) T_{\gamma\beta}(W) f_M(c; \rho, v, \theta)$$

with a regular matrix  $T_{\gamma\beta}(W)$ . This approach yields system matrices of the form

$$(11) \quad A_{\alpha\beta}^{(i)}(W) = \int_{\mathbb{R}^d} c_i \psi_\alpha((c - v)/\theta) \psi_\gamma((c - v)/\theta) f_M dc T_{\gamma\beta}(W)$$

which can be symmetrized by multiplying with the transpose of  $T_{\gamma\beta}(W)$  from the left. Consequently, the system is hyperbolic and contains the conservation laws, but as for the tangent space reduction it can not be written in balance law form and does not possess an entropy in general. The various projection approaches in [1] can be recast into the form (10).

In order to achieve a more tractable expression for the gradients  $v_\beta$  it is possible to use

$$(12) \quad \frac{\partial f^{(*)}(W, c)}{\partial w_\beta} \stackrel{!}{=} \sum_{\gamma=1}^N \psi_\gamma(c) T_{\gamma\beta}(W) f^{(*)}(W, c)$$

as an equation to determine the model  $f^{(*)}$ . For simplicity we can set  $T_{\gamma\beta} = \delta_{\gamma\beta}$  and find  $f^{(*)}(W(x, t), c) = \exp\left(\sum_{\alpha=1}^N w_\alpha(x, t) \psi_\alpha(c)\right)$  for the model. Similar to the Grad expansion polynomials are chosen for  $\psi_\alpha(c)$ , so that the model corresponds to the well-known *maximum-entropy distribution* [4, 5]. Using test functions  $\varphi_\alpha(c) = \psi_\alpha(c)$  the system matrices have the form

$$(13) \quad A_{\alpha\beta}^{(i)}(W) = \int_{\mathbb{R}^d} c_i \varphi_\alpha(c) \varphi_\beta(c) f^{(*)}(W(x, t), c) dc$$

which yield a symmetric hyperbolic system. This system can be written in balance law form and the Boltzmann entropy  $\eta(W) = \int f^{(*)}(W, c) \log f^{(*)}(W, c) dc$  is also an entropy for the partial differential equation.

In [3] it was demonstrated that within the maximum-entropy approach the mapping between the coefficients  $W$  and the evolved moments is ill-posed even arbitrary close to a Maxwellian. As a result the approach yields a singular flux function for the moment equations. We show in [7] that this singularity leads to the existence of fast and small shock waves that allow to compute smooth shock profiles without violating the characteristic condition of [6].

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**On kinetic models for the collective self-organization of agents**

KONSTANTINA TRIVISA

## 1. MATHEMATICAL MODELING, WELLPOSEDNESS RESULTS, AND INVESTIGATION OF HYDRODYNAMIC LIMITS FOR KINETIC FLOCKING MODELS.

Models describing collective self-organization of biological agents are currently receiving considerable attention. In this line of research we investigate a class of such models. The novel idea in (cf. Karper, Mellet and Trivisa [9, 10]) is the creation of a new model by combining the kinetic Cucker-Smale model with the strong local alignment term  $\{\beta \operatorname{div}_v(f(u - v))\}$  which is obtained as the singular limit of a non-symmetric alignment term in [12]. That leads to a new kinetic flocking model able to treat both long range interactions (Cucker-Smale model) and short-range interactions (due to the strong local alignment term):

$$(1) \quad f_t + v \cdot \nabla_x f + \operatorname{div}_v(fL|f|) + \beta \operatorname{div}_v(f(u - v)) = 0 \quad \text{in } \mathbb{R}^d \times \mathbb{R}^d \times (0, T)$$

where  $f := f(t, x, v)$  is the scalar unknown,  $d \geq 1$  is the spatial dimension, and  $\beta \geq 0$  is a constant.

The first two terms describe the free transport of the individuals, and the last two terms take into account the interactions between individuals, who try to align with their neighbors. The alignment operator  $L$  and the average local velocity  $u$  have the form

$$(2) \quad L[f] = \int_{\mathbb{R}^d} \int_{\mathbb{R}^d} K_f(x, y) f(y, w) (w - v) dw dy, \quad u(t, x) = \frac{\int_{\mathbb{R}^d} f v dv}{\int_{\mathbb{R}^d} f dv}$$

where the kernel  $K_f$  may depend on  $f$  and may not be symmetric in  $x$  and  $y$ . This model is endowed with some very desirable features: it has symmetry, it preserves the total *momentum* and has the advantage that it captures both *the*

*long ranged dynamics and short ranged dynamics.* Thus it provides a correction of some earlier models in the literature [1, 2, 12].

**1.1. On strong local alignment in the kinetic Cucker-Smale model.** In this work [9] Trivisa et al. justify rigorously the model (1) by proving that “the correction term” proposed in [12]  $\{f^r \tilde{L}^r[f^r]\}$  as correction to the kinetic Cucker-Smale model [1, 2] converges weakly to the strong local alignment term  $\{f(u - v)\}$  when the radius of interaction goes to zero,  $f^r \tilde{L}^r[f^r] \rightharpoonup f(u - v)$  as  $r \rightarrow 0$ . The analysis relies on a new velocity averaging lemma, delicate estimates and a refined covering lemma (cf. Lemma 2.5, [10]).

**1.2. Existence of solutions to kinetic flocking models.** This research establishes the global existence of weak solutions to a class of kinetic flocking equations. The models under consideration include the kinetic Cucker-Smale equation [1, 2] with possibly non-symmetric flocking potential, the Cucker-Smale equation with additional strong local alignment, and a model proposed by Motsch and Tadmor in [12] as correction to the Cucker-Smale model (cf. Ha and Tadmor [6]). The investigation of Trivisa et al. [9] provides the first rigorous existence result for a large class of kinetic flocking models. The main tools employed in the analysis are a new velocity averaging lemma (cf. Lemma 2.6, [9]) and the Schauder fixed point theorem.

**1.3. Hydrodynamic limit of the kinetic Cucker-Smale flocking model.** The starting point is the model (1) considered by Trivisa et al. [9, 10] significantly enhanced to include possible random effects, noise, and a confinement potential. The objective of this work is the rigorous investigation of the singular limit corresponding to strong noise and strong local alignment. The proof relies on the construction of a new relative entropy functional with suitable dissipation properties and the establishment of entropy inequalities which yield the appropriate convergence results. The resulting limiting system (cf. Section 3, Theorem 3.1 [12]), is an Euler-type flocking system.

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## Emergence of localizing solutions out of the competition of Hadamard instability and viscosity in plasticity

ATHANASIOS E. TZAVARAS

(joint work with Theodoros Katsaounis, Min-Gi Lee, Julien Olivier)

Shear bands are narrow zones of intense shear observed during plastic deformations of metals at high strain rates. As they often precede rupture their study has attracted attention as a mechanism of material failure [1]. We aim to reveal the onset of localization into shear bands using a simple model from viscoplasticity. We consider the system of partial differential equations

$$(1) \quad \begin{aligned} \gamma_t &= v_x, \\ v_t &= (\gamma^{-m} v_x^n)_x, \end{aligned}$$

which describes shear motions of a viscoplastic material and in terms of classification belongs to the class of hyperbolic-parabolic systems.  $\gamma$  is the plastic strain,  $v$  is the velocity in the shearing direction, and  $m, n > 0$  are material parameters. The yield relation  $\sigma = \gamma^{-m} \gamma_t^n$  characterizes the viscoplastic nature of materials:  $\gamma^{-m}$  accounts for plastic (net) strain softening and  $\gamma_t^n$  for strain-rate hardening.

For  $n = 0$ , the system (1) is elliptic in the  $t$ -direction and exhibits *Hadamard instability* - the catastrophic growth of oscillations for the linearized initial value problem - induced by the (net) strain-softening response. But when  $n > 0$ , the viscosity competes against this ill-posedness. The combination of the destabilizing effect of strain softening and the stabilizing effect of strain-rate hardening is conjectured to lead to localization of the strain in narrow zones called shear bands. It is at the core of a destabilizing mechanism proposed for more general models in the mechanics literature [5, 1] for the explanation of shear band formation.

To set the localization problem in the language of mathematical analysis, observe that (1) admits a class of solutions, that are valid for any values of the parameters  $m$  and  $n$  and describe uniform shearing

$$(2) \quad v_s(x) = x, \quad \gamma_s(t) = t + \gamma_0, \quad \sigma_s(t) = (t + \gamma_0)^{-m}.$$

The issue then becomes to examine whether small perturbations of the uniform shearing solutions develop nonuniformities that go astray or whether nonuniformities get suppressed resulting into stable response. Due to their time-dependent nature, the study of stability generally involves the behavior of non-autonomous systems. In the regime  $n > m$ , both linearized and nonlinear analyses indicate that

the uniform shearing solutions are stable. On the complementary region  $m > n$ , an analysis of the linearized system of relative perturbations indicates instability of the uniform shearing solutions. Such results can be easily explained in the special case  $\varphi(\gamma) = \frac{1}{\gamma}$  but retaining the dependence in  $n$ , by studying

$$(3) \quad v_t = \left( \frac{v_x^n}{\gamma} \right)_x, \quad \gamma_t = v_x.$$

This model has a special property: after considering a transformation to relative perturbations and a rescaling of variables,

$$(4) \quad \begin{aligned} v_x(x, t) &=: u(x, t) = U(x, \tau(t)), & \gamma(x, t) &= \gamma_s(t) \Gamma(x, \tau(t)), \\ \sigma(x, t) &= \sigma_s(t) \Sigma(x, \tau(t)) & \text{where } \tau(t) &= \log\left(1 + \frac{t}{\gamma_0}\right), \end{aligned}$$

the problem of stability of the time-dependent uniform shearing solution is transformed into the problem of stability of the equilibrium  $(\bar{U}, \bar{\Gamma}) = (1, 1)$  for the nonlinear but autonomous parabolic system

$$(5) \quad U_\tau = \Sigma_{xx} = \left( \frac{U^n}{\Gamma} \right)_{xx}, \quad \Gamma_\tau = U - \Gamma.$$

The following heuristic argument leads to a conjecture regarding the effect of rate sensitivity  $n$  on the dynamics: As time proceeds the second equation in (5), which is of relaxation type, relaxes to the equilibrium manifold  $\{U = \Gamma\}$ . Accordingly, the stability of (5) is determined by the equation describing the effective equation

$$U_\tau = (U^{n-1})_{xx},$$

which is parabolic for  $n > 1$  and backward parabolic for  $n < 1$ . This heuristic argument suggests instability in the regime  $n < 1$ .

In [3] we study the dynamics of (5) and provide an analysis of linearized stability. The linearized system around the equilibrium  $(1, 1)$  reads

$$(6) \quad \begin{aligned} \tilde{U}_\tau &= n\tilde{U}_{xx} - \tilde{\Gamma}_{xx}, \\ \tilde{\Gamma}_\tau &= \tilde{U} - \tilde{\Gamma}, \end{aligned}$$

and its dynamics can be analyzed via Fourier analysis. A complete picture emerges:

- (a) For  $n = 0$ , high-frequency modes grow exponentially fast and indicate catastrophic growth and Hadamard instability.
- (b) For  $0 < n < 1$ , the modes still grow and are unstable but at a tame growth rate; in this regime the behavior is that of Turing instability, familiar from problems in morphogenesis.
- (c) For  $n > 1$  strain-rate dependence is strong and stabilizes the motion.

In [4], we study the subtle mechanism of shear band formation in the nonlinear regime. We construct a class of self-similar solutions that exhibit localization in the regime  $m > n$ . We exploit the invariance properties of the system (1) and seek

(following [2]) self-similar solutions of the form

$$(7) \quad \begin{aligned} \bar{\gamma}(t, x) &= (t+1)^a \bar{\Gamma}((t+1)^\lambda x), \\ \bar{v}(t, x) &= (t+1)^b \bar{V}((t+1)^\lambda x), \end{aligned}$$

where  $\xi = (t+1)^\lambda x$  is the similarity variable and  $\lambda > 0$  is a parameter. The usual form of self-similar solutions for parabolic problems are generated for values of the parameter  $\lambda < 0$  and capture the spreading effect associated with parabolic behavior. By contrast, we insist here on  $\lambda > 0$  and study the existence of solutions focusing around the line  $x = 0$  as time proceeds.

Parameters  $a$  and  $b$  are selected by

$$(8) \quad a^{\lambda, m, n} = \frac{2-n}{1+m-n} + \frac{2\lambda}{1+m-n}, \quad b^{\lambda, m, n} = \frac{1-m}{1+m-n} + \frac{1-m+n}{1+m-n} \lambda$$

and  $(\bar{\Gamma}, \bar{V})$  is constructed by solving the initial value problem for the singular system of ordinary differential equations

$$(9) \quad \begin{aligned} a^{\lambda, m, n} \bar{\Gamma} + \lambda \xi \bar{\Gamma}_\xi &= \bar{V}_\xi, \\ b^{\lambda, m, n} \bar{V} + \lambda \xi \bar{V}_\xi &= (\bar{\Gamma}^{-m} \bar{V}_\xi^n)_\xi, \end{aligned}$$

$$(10) \quad \bar{\Gamma}|_{\xi=0} = \bar{\Gamma}(0) > 0, \quad \bar{V}|_{\xi=0} = \bar{U}(0) > 0,$$

where  $\bar{\Gamma}(0)$  and  $\bar{U}(0)$  are positive parameters.

The invariance properties of the system (9) allows to de-singularize (9) and together with a nonlinear change of variables leads to reformulating the problem into an autonomous system of three first-order equations

$$(11) \quad \begin{aligned} \dot{p} &= p \left( \frac{1}{\lambda} \left( r - \frac{2-n}{1+m-n} \right) - \frac{1-m+n}{1+m-n} + 1 - q - \lambda pr \right), \\ \dot{q} &= q \left( + 1 - q - \lambda pr \right) + b^{\lambda, m, n} pr, \\ n\dot{r} &= r \left( \frac{m-n}{\lambda} \left( r - \frac{2-n}{1+m-n} \right) + \frac{1-m+n}{1+m-n} - 1 + q + \lambda pr \right). \end{aligned}$$

The question of existence of a solution  $(\bar{V}, \bar{\Gamma})$  to (9) is reformulated to that of the construction of a suitable heteroclinic orbit for (11). In [3], we considered a system related to the case  $m = 1$  and numerically constructed the heteroclinic orbit. In [4], we exploit the geometric theory of nonlinear perturbations, we construct a normally hyperbolic invariant manifold, and analyze the dynamics on that manifold to construct a suitable heteroclinic orbit. This provides a profile for the localizing solution of the form (7). As  $n$  is a small parameter, the system (11) admits both fast and slow time scales. Problems with multiple time scales are habitually found in multiple contexts, and one gets a clear geometric picture of the problem by analyzing the geometric picture in the phase space via the geometric singular perturbation theory. In [4] we present a novel application of the method to analyze the nonlinear competition of Hadamard instability with viscosity effected by strain-rate hardening in dynamic plasticity.

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## Convergence rates of finite difference schemes for the linear transport and wave equation with rough coefficient

FRANZISKA WEBER

Propagation of acoustic waves in a heterogeneous medium plays an important role in many applications, for instance in seismic imaging in geophysics and in the exploration of hydrocarbons [1, 4]. This wave propagation can be modeled by the linear wave equation:

$$(1a) \quad \frac{1}{c^2(x)} \partial_{tt} p(t, x) - \Delta p(t, x) = 0, \quad (t, x) \in D_T,$$

$$(1b) \quad p(0, x) = p_0(x), \quad x \in D,$$

$$(1c) \quad \partial_t p(0, x) = p_1(x), \quad x \in D,$$

where  $D_T := [0, T] \times D$ ,  $D \subset \mathbb{R}^d$ , augmented with boundary conditions. Here,  $p$  is the acoustic pressure and the wave speed is determined by the coefficient  $c^2 = c^2(x) > 0$ . The coefficient  $c$  encodes information about the material properties of the medium. As an example, the coefficient  $c$  represents various geological properties when seismic waves propagate in a rock formation.

Under the assumption that the coefficient  $c^2 \in C^{0,\alpha} \cap L^\infty(D)$  for some  $\alpha > 0$  and that it is uniformly positive and bounded on  $D$ , and that the initial data  $p_0 \in H^1(D)$  and  $p_1 \in L^2(D)$ , one can prove existence of a unique weak solution  $p \in C^0([0, T]; H^1(D))$  with  $\partial_t p \in C^0([0, T]; L^2(D))$  following classical energy arguments for linear partial differential equations. See for instance [11, Chapter III, Thm. 8.1, 8.2]. A smoother coefficient  $c$  and more regular initial data  $p_0, p_1$  result in a more regular solution [11]. Many numerical methods are available for the approximation of the linear wave equation with inhomogeneous coefficient  $c$ , see for example [3, 8, 10], but the error estimates are often based on the assumption that the coefficient has sufficiently much regularity. Some exceptions are the works [5, 7, 6]. However, this regularity assumption is not always realized in practice, since, as mentioned before, the coefficient represents properties of the possibly very heterogeneous material in which the waves propagate. Moreover, the material properties can often only be determined by measurements. Such measurements are inherently uncertain. This uncertainty is modeled in a statistical manner by

representing the material properties (such as rock permeability) as random fields. In particular, log-normal random fields are heavily used to model porous and other geophysically relevant media [4, 2]. Thus, the coefficient  $c$  is not smooth, not even continuously differentiable, see Figure 1, on the left, for an illustration of the coefficient  $c$  where the rock permeability is modeled by a log-normal random field (the figure represents a single realization of the field).

Closer inspection of the coefficients obtained in practice reveals that the material coefficient  $c$  is at most a Hölder continuous function, that is,  $c \in C^{0,\alpha}$  for some  $0 < \alpha < 1$ .

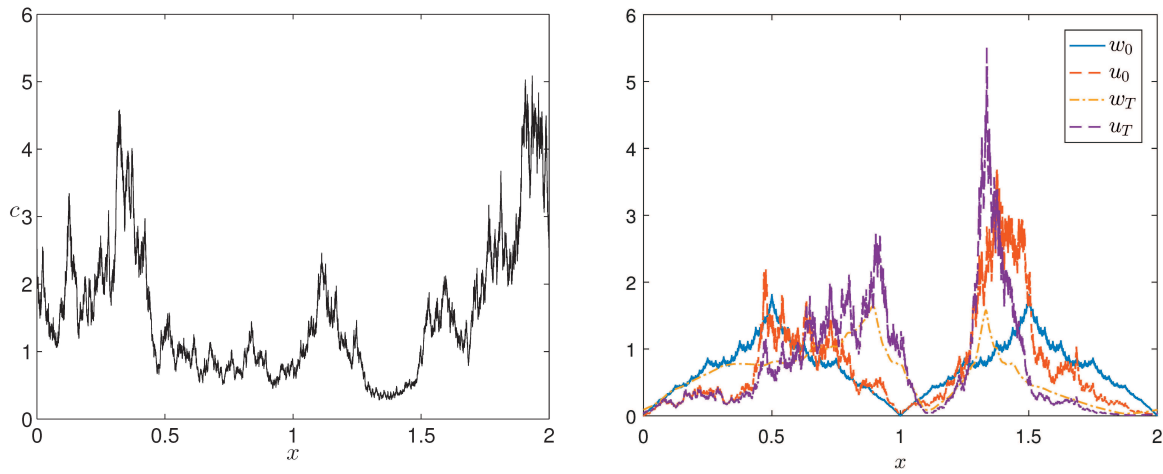


FIGURE 1. Left: A sample of a log-normally distributed random coefficient  $c$  ( $\alpha = 1/2$ ). Right: Approximation of (2) by scheme (3) at time  $T = 0$  and  $T = 1$ , number of grid points  $N_x = 2^{14}$ ,  $\gamma = 1/2$ .

Given these facts, it makes sense to study (1) and its numerical approximation under the assumption that the coefficient  $c$  is only Hölder continuous.

In the talk, we therefore discussed the numerical approximation of the simpler model of the one dimensional transport equation

$$(2) \quad \partial_t u(t, x) + \partial_x(a(x)u(t, x)) = 0, \quad (t, x) \in [0, T] \times D,$$

for  $a \in C^{0,\alpha}(D)$  positive, by a simple upwind finite difference scheme,

$$(3) \quad \frac{u_j^{n+1} - u_j^n}{\Delta t} + \frac{a_j u_j^n - a_{j-1} u_{j-1}^n}{\Delta x} = 0, \quad 1 \leq j \leq N_x, \quad 0 \leq n \leq N_T,$$

$\Delta t, \Delta x > 0$  are the discretization parameters. This scheme is stable and it is possible to show that the approximations are approximately Hölder continuous in time. Using an adaption of Kružkov's doubling of variables technique [9], one can then show the following convergence rate of the scheme:

**Theorem 1.1.** *Let  $a \in C^{0,\alpha}(D)$  strictly positive. Denote  $w := au$ , where  $u$  is the solution of (2) and  $w_{\Delta x} := a_{\Delta x} u_{\Delta x}$ , where  $u_{\Delta x}$  is the piecewise constant*

interpolation of the solutions  $u_j$  of (3) and  $a_{\Delta x}$  the piecewise constant interpolation of  $a_j$ . Assume that the initial data  $w_0 := au_0 \in L^p(D)$  and is Hölder continuous with exponent  $\gamma_\infty \in (0, 1]$ . Then  $w_{\Delta x}(t, \cdot)$  converges to  $w(t, \cdot)$  at (at least) the rate

$$(4) \quad \|(w - w_{\Delta x})(t, \cdot)\|_{L^p(D)} \leq C \Delta x^{(\gamma_\infty \alpha)/(\gamma_\infty \alpha + 2 - \gamma_\infty)},$$

where  $C$  is a constant not depending on  $\Delta x$ , and where  $p \in \{1, 2\}$ .

The details of the proof can be found in [12]. The techniques used to prove the convergence rate can also be extended to prove a rate of convergence for a finite difference scheme for the linear wave equation (1) in one space dimension. We note that the rate (4) depends explicitly on the Hölder regularity of the initial data and the coefficient  $a$ . Numerical experiments confirm that the rates of convergence are indeed quite low. However, we have not found an example yet that shows that (4) is sharp.

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## A Variational Time Discretization for Compressible Euler Equations

MICHAEL WESTDICKENBERG

(joint work with Fabio Cavalletti, Marc Sedjro)

The compressible Euler equations model the dynamics of compressible fluids such as gases. They form a system of hyperbolic conservation laws

$$(1) \quad \left. \begin{aligned} \partial_t \varrho + \nabla \cdot (\varrho \mathbf{u}) &= 0 \\ \partial_t (\varrho \mathbf{u}) + \nabla \cdot (\varrho \mathbf{u} \otimes \mathbf{u}) + \nabla \pi &= 0 \\ \partial_t \varepsilon + \nabla \cdot ((\varepsilon + \pi) \mathbf{u}) &= 0 \end{aligned} \right\} \quad \text{in } [0, \infty) \times \mathbf{R}^d.$$

The unknowns  $(\varrho, \mathbf{u}, \varepsilon)$  depend on time  $t \in [0, \infty)$  and space  $x \in \mathbf{R}^d$  and we assume that suitable initial data  $(\varrho, \mathbf{u}, \varepsilon)(t=0, \cdot) =: (\bar{\varrho}, \bar{\mathbf{u}}, \bar{\varepsilon})$  is given. We will consider  $\varrho$  as a map from  $[0, \infty)$  into the space of nonnegative, finite Borel measures, which we denote by  $\mathcal{M}_+(\mathbf{R}^d)$ . The quantity  $\varrho$  is called the density and it represents the distribution of mass in time and space. The first equation in (1) (the continuity equation) expresses the local conservation of mass, where

$$(2) \quad \mathbf{u}(t, \cdot) \in \mathcal{L}^2(\mathbf{R}^d, \varrho(t, \cdot)) \quad \text{for all } t \in [0, \infty)$$

is the Eulerian velocity field taking values on  $\mathbf{R}^d$ . The second equation in (1) (the momentum equation) expresses the local conservation of momentum  $\mathbf{m} := \varrho \mathbf{u}$ . The quantity  $\varepsilon$  is the total energy of the fluid and  $\varepsilon(t, \cdot)$  is a measure in  $\mathcal{M}_+(\mathbf{R}^d)$ . The third equation in (1) expresses the local conservation of energy.

The quantity  $\pi$  in the momentum equation is the pressure. It is determined by the thermodynamic properties of the fluid. Three cases are of interest:

- The pressure vanishes (the pressureless gas case). Then the total energy of the fluid is simply the kinetic energy, and the third equation in (1) follows *formally* from the first two, by the chain rule.
- The pressure is a function of the density  $\varrho$  only because the thermodynamical entropy is constant throughout time and space (the isentropic case). Again the conservation of total energy follows formally from the continuity and the momentum equation.
- The pressure is a function of the density  $\varrho$  and total energy  $\varepsilon$  (the full Euler case). In this case, there is again an additional conservation law since the thermodynamical entropy *formally* satisfies a transport equation.

Even though system (1) formally conserves the total energy (being a Hamiltonian system), there actually is a dissipation of energy due to the nonsmoothness of the solutions: In the pressureless case, the modeling suggests a concentration of mass (sticky particle dynamics) by which the kinetic energy decreases. In the cases with pressure, solutions may form jump singularities along codimension-one manifolds, which are called shocks. Again total energy is dissipated in the process.

We consider a variational time discretization for the system of conservation laws (1) in the spirit of minimizing movements for curves of maximal slopes on metric spaces. We recall that for certain (possibly degenerate) parabolic equations, such

as the porous medium equations, the solutions are curves on the space of nonnegative measures characterized by the requirement that at each time an energy (or entropy) functional is decreased at maximal rate (which also characterizes gradient flows). This comes with a natural time discretization, where in each timestep one tries to find the right balance between minimizing this energy functional and keeping the step short. For the porous medium equation the update length is measured using the Wasserstein distance. For the variational time discretization of (1) we proceed analogously: In each timestep we minimize the sum of the internal energy and of a new functional measuring the deviation of material point trajectories from straight paths. This functional thus measures the work required to accelerate material points. The minimization then boils down to maximizing the difference between a change in internal energy and work done, which in formal analogy to the fundamental laws of thermodynamics we interpret as maximizing the (suitably defined) entropy production. Since the internal energy only depends on some negative power of the determinant of the deformation gradient, it does not suggest any natural function space setting in which one can hope for compactness. To circumvent this problem, we minimize over the closed convex cone of *monotone* transport maps, which in particular guarantees the non-interpenetration of matter. Notice that for the porous medium equation, the relevant transport maps are *cyclically monotone* because those are the maps that solve the optimal transport problem that underlies the Wasserstein distance. In this case, the (cyclical) monotonicity follows implicitly from the choice of metric, whereas for (1) we make monotonicity an explicit constraint. This can be justified by the fact that in each timestep the transport maps are perturbations of the identity map, which is monotone.

Since monotone maps enjoy very good properties (they are of bounded variation locally, for example) one can prove the existence of a minimizer for each timestep. By a suitable interpolation in time, we obtain a family of approximate solutions to (1), parametrized by the timestep  $\tau > 0$ . We establish that as  $\tau \rightarrow 0$ , these approximate solutions converge (along a subsequence) to a measure-valued solution of (1). One crucial ingredient to the proof is a characterization of the polar cone of the cone of monotone maps: every element in the polar cone can be represented by the distributional divergence of a matrix field taking values in symmetric positive semidefinite matrices. This matrix field, which we call a stress tensor, therefore has exactly the same structure as the matrix field  $\rho \mathbf{u} \otimes \mathbf{u} + \pi \mathbf{1}$ , which appears in the momentum equation (1). The momentum can be shown to be Lipschitz continuous with respect to a suitable Kantorovich norm. We show that measure-valued solutions obtained from this variational time discretization satisfy an energy inequality pointwise: energy can only be dissipated at each point in space and time; there is no spontaneous generation of energy. Energy dissipation is given explicitly and consists of two parts: the first is related to the dissipation of energy along the discontinuities of the solution (the shocks), the other one is related to small-scale rotations, a dissipation mechanism particularly relevant to incompressible flows. The energy dissipation also controls the residual of the momentum equation, as measured in the Kantorovich (dual Lipschitz) norm.



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## Participants

**Prof. Dr. Debora Amadori**

Dipartimento di Matematica  
Università degli Studi dell'Aquila  
via Vetoio, 1  
67010 L'Aquila (AQ)  
ITALY

**Prof. Dr. Christophe Chalons**

Laboratoire de Mathématiques  
Université Versailles SQY  
45, avenue des Etats Unis  
78000 Versailles Cedex  
FRANCE

**Prof. Dr. Sylvie Benzoni-Gavage**

Institut Camille Jordan  
Université Claude Bernard Lyon 1  
43 blvd. du 11 novembre 1918  
69622 Villeurbanne Cedex  
FRANCE

**Prof. Dr. Alina Chertock**

Department of Mathematics  
North Carolina State University  
Campus Box 8205  
Raleigh, NC 27695-8205  
UNITED STATES

**Prof. Dr. Stefano Bianchini**

SISSA - ISAS  
Via Bonomea 265  
34136 Trieste  
ITALY

**Prof. Dr. Rinaldo M. Colombo**

Dipartimento di Matematica  
Università degli Studi di Brescia  
Via Branze 38  
25123 Brescia  
ITALY

**Dr. Raul Borsche**

Fachbereich Mathematik  
T.U. Kaiserslautern  
Erwin-Schrödinger-Straße  
67653 Kaiserslautern  
GERMANY

**Prof. Dr. Andrea Corli**

Dipartimento di Matematica  
Università di Ferrara  
Via Machiavelli 35  
44121 Ferrara  
ITALY

**Dr. Benjamin Boutin**

UFR Mathématiques - IRMAR  
Université de Rennes I  
Campus de Beaulieu  
35042 Rennes Cedex  
FRANCE

**Prof. Dr. Gianluca Crippa**

Département Mathematik & Informatik  
Universität Basel  
Spiegelgasse 1  
4051 Basel  
SWITZERLAND

**Prof. Dr. Alberto Bressan**

Department of Mathematics  
Pennsylvania State University  
University Park, PA 16802  
UNITED STATES

**Johannes Daube**

Abtlg. für Angewandte Mathematik  
Universität Freiburg  
Hermann-Herder-Strasse 10  
79104 Freiburg i. Br.  
GERMANY

**Dr. Carlotta Donadello**

Maître de conférences  
Laboratoire de Mathématiques  
Université de Franche-Comté  
16, route de Gray  
25030 Besancon Cedex  
FRANCE

**Prof. Dr. Mauro Garavello**

Dipartimento di Matematica e  
Applicazioni  
Universita di Milano-Bicocca  
Edificio U5  
via Roberto Cozzi 53  
20125 Milano  
ITALY

**Dr. Jan Giesselmann**

Institut für Angewandte Analysis  
und Numerische Simulation  
Universität Stuttgart  
Pfaffenwaldring 57  
70569 Stuttgart  
GERMANY

**Dr. Paola Goatin**

INRIA - Team ACUMES  
2004, route des Lucioles - BP 93  
06902 Sophia Antipolis Cedex  
FRANCE

**Prof. Dr. Edwige Godlewski**

Laboratoire Jacques-Louis Lions  
Université Paris 6  
4, Place Jussieu  
75252 Paris Cedex 05  
FRANCE

**Prof. Dr. Graziano Guerra**

Dipartimento di Matematica e  
Applicazioni  
Universita di Milano-Bicocca  
Edificio U5  
via Roberto Cozzi 53  
20125 Milano  
ITALY

**Prof. Dr. Philippe Helluy**

Institut de Mathématiques  
Université de Strasbourg  
7, rue René Descartes  
67084 Strasbourg Cedex  
FRANCE

**Prof. Dr. Helge Holden**

Department of Mathematical Sciences  
Norwegian University of Science &  
Technology  
A. Getz vei 1  
7491 Trondheim  
NORWAY

**Prof. Dr. Axel Klar**

Fachbereich Mathematik  
T.U. Kaiserslautern  
Erwin-Schrödinger-Straße  
67653 Kaiserslautern  
GERMANY

**Prof. Dr. Christian Klingenberg**

Institut für Mathematik  
Universität Würzburg  
Emil-Fischer-Strasse 40  
97074 Würzburg  
GERMANY

**Prof. Dr. Dietmar Kröner**

Abteilung für Angewandte Mathematik  
Universität Freiburg  
Hermann-Herder-Strasse 10  
79104 Freiburg i. Br.  
GERMANY

**Prof. Dr. Philippe G. LeFloch**

Laboratoire Jacques-Louis Lions  
Université Paris 6  
4, Place Jussieu  
75252 Paris Cedex 05  
FRANCE

**Prof. Dr. Tai-Ping Liu**

Institute of Mathematics  
Academia Sinica  
No. 1, Sec. 4, Roosevelt Road  
Taipei 10617  
TAIWAN

**Prof. Dr. Stephan Luckhaus**

Mathematisches Institut  
Universität Leipzig  
Postfach 10 09 20  
04109 Leipzig  
GERMANY

**Prof. Dr. Maria****Lukacova-Medvidova**

Mathematisches Institut  
FB Mathematik/Physik/Informatik  
Johannes-Gutenberg-Universität  
55099 Mainz  
GERMANY

**Prof. Dr. Francesca Marcellini**

Dipartimento di Matematica e  
Applicazioni  
Università di Milano-Bicocca  
Edificio U5  
via Roberto Cozzi 53  
20125 Milano  
ITALY

**Dr. Stefano Modena**

Fakultät für Mathematik & Informatik  
Universität Leipzig  
Augustusplatz 10/11  
04109 Leipzig  
GERMANY

**Prof. Dr. Siegfried Müller**

Institut f. Geometrie & Praktische  
Mathematik  
RWTH Aachen  
Templergraben 55  
52062 Aachen  
GERMANY

**Anders S. Nordli**

Department of Mathematical Sciences  
Norwegian University of Science &  
Technology  
A. Getz vei 1  
7491 Trondheim  
NORWAY

**Prof. Dr. Gabriella A. Puppo**

Dipartimento di Scienza e Alta  
Tecnologia  
Università degli Studi dell'Insubria  
Via Valleggio, 11  
22100 Como  
ITALY

**Prof. Dr. Nils Henrik Risebro**

Department of Mathematics  
University of Oslo  
P. O. Box 1053 - Blindern  
0316 Oslo  
NORWAY

**Prof. Dr. Christian Rohde**

Institut für Angewandte Analysis und  
Numerische Simulation  
Universität Stuttgart  
Pfaffenwaldring 57  
70569 Stuttgart  
GERMANY

**Dr. Elena Rossi**

Dipartimento di Matematica e  
Applicazioni  
Università di Milano-Bicocca  
Edificio U5  
via Roberto Cozzi 53  
20125 Milano  
ITALY

**Prof. Dr. Giovanni Russo**

Dipartimento di Matematica e  
Informatica  
Citta Universitaria  
Viale A. Doria, 6 - 1  
95125 Catania  
ITALY

**Dr. Veronika Schleper**

Institut für Angewandte Analysis und  
Numerische Simulation  
Universität Stuttgart  
Pfaffenwaldring 57  
70569 Stuttgart  
GERMANY

**Prof. Michael Shearer**

Department of Mathematics  
North Carolina State University  
Campus Box 8205  
Raleigh, NC 27695-8205  
UNITED STATES

**Prof. Dr. Eitan Tadmor**

Center for Scientific Computation  
and Mathematical Modeling (CSCAMM)  
CSIC Building # 406  
University of Maryland  
Paint Branch Drive  
College Park MD 20742-3289  
UNITED STATES

**Ferdinand Thein**

Institut für Analysis und Numerik  
Otto-von-Guericke-Universität  
Magdeburg  
Postfach 4120  
39016 Magdeburg  
GERMANY

**Prof. Dr. Manuel Torrilhon**

Aachen Institute for Advanced Study in  
Computational Engineering Sciences  
RWTH Aachen  
Schinkelstrasse 2  
52062 Aachen  
GERMANY

**Prof. Dr. Konstantina Trivisa**

Department of Mathematics  
University of Maryland  
College Park, MD 20742-4015  
UNITED STATES

**Prof. Dr. Athanasios E. Tzavaras**

Applied Mathematics and  
Computational Sciences  
King Abdullah University of Science &  
Technology (KAUST)  
Thuwal 23955-6900, Jeddah  
SAUDI ARABIA

**Prof. Dr. Gerald Warnecke**

Institut für Analysis und Numerik  
Otto-von-Guericke-Universität  
Magdeburg  
39016 Magdeburg  
GERMANY

**Franziska Weber**

Seminar for Applied Mathematics  
ETH Zürich  
Rämistrasse 101  
8092 Zürich  
SWITZERLAND

**Prof. Dr. Michael Westdickenberg**

Institut für Mathematik  
RWTH Aachen  
Templergraben 55  
52062 Aachen  
GERMANY

