

Theory of the lattice Boltzmann equation: Symmetry properties of discrete velocity sets

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The lattice Boltzmann equation replaces continuous particle velocity space by a finite set; the velocity distribution function then varies over a finite-dimensional vector space instead of over an infinite-dimensional function space. The number of linearly independent moments of the distribution function in a lattice Boltzmann model cannot exceed the number of velocities; finite dimensionality therefore necessarily induces linear dependencies among the moments that do not exist in a continuous theory. Given a finite velocity set, it is important to know which moments are free of these dependencies. Elementary group theory is applied to the solution of this problem. It is found that decomposing the velocity set into subsets that transform among themselves under an appropriate symmetry group makes it straightforward to uncover linear dependencies among the moments. The construction of some standard two- and three-dimensional models is reviewed from this viewpoint, and procedures for constructing higher-dimensional models are suggested.

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I. INTRODUCTION

A guiding principle of this series of papers is the formulation of the lattice Boltzmann equation (LBE) as a discrete kinetic theory [1–10]. In kinetic theory, moments of the distribution function $f(\mathbf{x}, \boldsymbol{\xi}, t)$ over the space of velocities $\boldsymbol{\xi}$ are the components of tensors of various ranks [11,12] that define continuum fluid properties like mass, momentum, energy, stress, and heat flux. Analogous moments can be formed in the discrete setting of the lattice Boltzmann equation; however, since the number of linearly independent moments cannot exceed the number of velocities, discreteness permits linear dependencies that do not exist in the continuous case [13].

Thus, in kinetic theory, the number of linearly independent moments of order n ,

$$M_n(\mathbf{x}, t) = \int d\boldsymbol{\xi} \underbrace{\boldsymbol{\xi} \cdots \boldsymbol{\xi}}_{n \text{ times}} f(\mathbf{x}, \boldsymbol{\xi}, t), \quad (1)$$

is equal to the number of linearly independent products $\boldsymbol{\xi} \cdots \boldsymbol{\xi}$ in the integrand—namely, $(n+1)(n+2)/2$ in three dimensions and $(n+1)$ in two dimensions. But in a discrete kinetic theory, in which the integral over continuous velocity space $\boldsymbol{\xi}$ in Eq. (1) is replaced by a sum over a finite velocity set $\mathbf{C}$ with N elements,

$$M_n(\mathbf{x}, t) = \sum_{\mathbf{c} \in \mathbf{C}} \underbrace{\mathbf{c} \cdots \mathbf{c}}_{n \text{ times}} f(\mathbf{x}, \mathbf{c}, t) \quad (2)$$

the factor $f(\mathbf{x}, t)$ restricts the number of linearly independent moments to at most N . Therefore, if $N < (n+1)(n+2)/2$, the tensor defined in the discrete theory by Eq. (2) necessarily has fewer independent components than its continuous counterpart defined by Eq. (1). Such a reduction remains possible due to linear dependencies even if $N \geq (n+1)(n+2)/2$. When-

ever a tensor in a discrete theory has fewer independent components than its continuous counterpart, we will say that the tensor is *incomplete* in this discrete theory; if it has the same number, we will say that it is *complete*.

Incomplete tensors in a discrete model are artifacts without continuous analogs; a fundamental problem in discrete kinetic theory is therefore given a finite velocity set $\mathbf{C} = \{\mathbf{c}_i\}$ to determine what tensors are complete. The purpose of this paper is to develop a systematic approach to solve this problem. The approach is based on the observation that the discrete velocity set $\{\mathbf{c}_i\}$ is not an arbitrary collection, but is chosen to be as symmetric as possible so that the model can mimic the physical isotropy of the fluid. In particular, two-dimensional models typically are based on a discrete velocity set with the symmetry of a square; that is, it is invariant under a group of transformations of two-dimensional $\boldsymbol{\xi}$ space that map the set of four velocities $\{(\pm 1, \pm 1)\}$ into itself, and three-dimensional models are typically based on a velocity set with the symmetry of a cube; that is, it is invariant under a group of transformations of three-dimensional $\boldsymbol{\xi}$ space that map the analogous set of eight velocities $\{(\pm 1, \pm 1, \pm 1)\}$ into itself.

It is natural to exploit the symmetry of the configuration of discrete velocities by applying the elementary representation theory of finite groups (cf. [14,15]). Although models can and have been constructed case by case using elementary methods, group theory offers the advantages of a systematic and unified approach. We do not claim that group theory results in a “better” way to construct models, in the sense of being faster, easier to formulate, or even easier to understand. We only contend that group theory provides a natural approach that reveals some problems common to constructing any discrete model, which can be hidden by lengthy al-

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Theory Of The Lattice Boltzmann Equation Symmetry Properties Of Discrete Velocity Sets

KJ Lindholm-Leary



Theory Of The Lattice Boltzmann Equation Symmetry Properties Of Discrete Velocity Sets:

Theory of the Lattice Boltzmann Equation Nasa Technical Reports Server (Ntrs),2013-08 In the lattice Boltzmann equation continuous particle velocity space is replaced by a finite dimensional discrete set The number of linearly independent velocity moments in a lattice Boltzmann model cannot exceed the number of discrete velocities Thus finite dimensionality introduces linear dependencies among the moments that do not exist in the exact continuous theory Given a discrete velocity set it is important to know to exactly what order moments are free of these dependencies Elementary group theory is applied to the solution of this problem It is found that by decomposing the velocity set into subsets that transform among themselves under an appropriate symmetry group it becomes relatively straightforward to assess the behavior of moments in the theory The construction of some standard two and three dimensional models is reviewed from this viewpoint and procedures for constructing some new higher dimensional models are suggested **Parallel Processing and Applied**

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