A considerable effort has been devoted to understanding the mechanisms of morphogenesis. It is known that vertebrate development starts off with a roughly round mass of cells, which gradually acquires a bilateral elongated aspect and progressively forms a recognizable animal by large-scale “convergent extension” movements. During this process, cells perform both collective and individual movements, such as conformational changes, rosette reorganization, alignments along the Antero-Posterior axis, intercalation, epiboly, etc. However, the relation between the global changes of the shape of the developing embryo and activities of individual cells remains elusive. What is the cause and what is the effect? Regulation of patterning processes is traditionally ascribed to genetic factors that create a complex morphogenetic field of diffusible molecules. However, it is unclear how biochemical factors alone can orchestrate the individual cell events in such a way that they provide a smooth evolution of the organization plans of the embryo on different stages of development, delivering at each step a functioning organism.

In a series of articles, we engaged the laws of hydrodynamics to treat the tissue movements and deformation on early stages of embryogenesis. Considering a chicken embryo as an example (Fig. 1), we managed to web together different aspects of tetrapod morphogenesis and give a scientific rationale to the early steps of the body plan establishment.

Are the slow fluid dynamics applicable to embryonic tissue? We believe so. To prove this hypothesis, we studied viscoelastic properties of the chicken blastula and early gastrula by means of a recently introduced air-puff tonometer. We have found that at these early stages, the embryonic tissue behaves as a viscous fluid and thus is subjected to the laws of hydrodynamics. A similar conclusion was also made by other authors in reference 10.

To address quantitatively the embryonic tissue flows in blastula and early gastrula of the chicken embryos, we recorded cell trajectories using particle imaging velocimetry. It was found that the vortex flow seen in the epiblast during the primitive streak initiation, acquires a clear hyperbolic pattern of streamlines that “revolve” toward and away from a neutral point at later stages, with four vortices of opposite chiralities in the lateral regions of the embryo. The flow is present until the vertebrate bauplan becomes recognizable. Assuming that the embryo tissue behaves as a viscous fluid, we proposed, and confirmed this hypothesis in a numerical model, that formation of this complex flow pattern does not require an explicit point-by-point time and space morphogenetic coding. On the contrary, it can be formed directly by the laws of hydrodynamics due to the strong winding of the lateral tissue sheared by the rapidly extending medial axis, because a localized pull in a continuous viscous medium suffices to induce long range effects, such as large scale vortices.

The hyperbolic rotatory flow gives straightforwardly the pattern of the animal bauplan (or “archetype” or “prototype” as coined by Darwin). The axial structures are formed along the midline in the areas with a strong, bidirectional straightforward flow; the smooth continuation of the hyperbolic flow toward the posterior and anterior areas creates, in a self-consistent manner, head, heart and tail, while the rotation away from the stagnation point creates the umbilical area and four limb plates with opposite chiralities.

As the flow is viscous, the flow map is associated with its specific pattern of stress gradients. In reference 6, we predicted in a numerical model and confirmed in measurements that the limb plates (regions with a rotatory flow) are concomitant with the stress minima. Via mechanotransduction pathways, the stress gradients in the embryo can specifically induce/modify genetic expression, acting as the “physical morphogenes,” and thus cooperate with biochemical signals to specify the pattern of development.

In this connection, a very important question is that of the symmetry breaking factor that determines the specific flow map in a given phylum. In the search for this element in vertebrates, we identified the invagination of cells (through the primitive streak in chicken), which creates a strong pulling action “from underneath.” The duplication and reversal of traction forces across the primitive streak stabilizes what is called in physics a quadrupolar movement and a hyperbolic character of the flow.

Thus, from a physical point of view, the crucial steps of morphogenesis of vertebrates, and probably similarly in other phyla, can be described as an initial broken symmetry which is up-scaled by a slow, continuous, viscoelastic flow to the body plan of the animal. Because of this, the animal morphogenesis cannot be understood on the basis of static descriptions of morphogenetic fields alone. At the same time, this work points to important physical parameters that are controlled by genetic expressions, e.g., viscosity, elastic modulus, bending modulus, shear...
thresholds, etc. By determining these characteristics at a quantitative level, genes guarantee the stability of the flow and thus successive appearance of the animal plans inside a given phylum in a non-intuitive, but still physical, order.

Figure 1. Chicken embryo, HH 6 (A), embryo cell trajectories (B). During the early stages of convergent extension, the embryo undergoes an in-plane, long ranged, hyperbolic tissue flow with four conspicuous windings. This flat flow becomes 3D by a viscoelastic buckling and collapse of the folds against each other as they are themselves transported in the flow. The flow map is upscaled into the organization plan of the animal. (1) The axial structures are formed along the midline in the areas with a strong, bidirectional straightforward flow. (2) Four extremities with opposite chiralities originate from the regions of vortex-type flow in the lateral areas above and below the fixed point. (3) The area of the hyperbolic point, from where the tissue expands cranially and caudally, becomes the yolk sac stalk. The flow map of the embryo can be easily traced even in the adult vertebrate, for example, in a cat [dorsal view of a cat (C)].

References