For several years Mark Neyrinck has been studying the behavior of infant galaxies using a non-traditional approach: the science of folding. In this article, he recaps and examines how origami mathematics can be used to understand the Universe.

The Origami Cosmic Web

My personal origami voyage began with a colloquium by Robert Lang at the Space Telescope Science Institute in Baltimore. I was working on a new geometrical method [1] of detecting structures that correspond to galaxies in computer models and I was astonished to see a connection to paper origami. I wondered: could origami mathematics be useful to understand the universe?

In Einstein's theory of general relativity, gravity comes about through distortions of a four-dimensional spacetime "sheet". But gravity also causes a different kind of sheet to distort and fold: the three-dimensional cosmological sheet of dark matter. It turns out that the way this dark matter folds up to form structures like our galaxy is not unlike origami.

A fresh sheet of origami paper has no folds. Similarly, at the Big Bang, when matter was nearly uniformly distributed in the universe, the cosmological sheet had no folds. But some locations had more matter than others. There, the sheet further bunched up, drawing matter from all around to form galaxies. Elsewhere, the sheet stretched out, forming voids between galaxies. The rich got richer, the poor got poorer.

What do I mean by "folding" for the cosmological sheet? Usually, 2D origami paper folds up in 3D. The 3D cosmological sheet folds up in 6D! But thankfully, a lot of the process can be understood without thinking in 6D, which is impossible! Think of a 2D origami work that afterwards can be squashed into a book without further creasing; much of the structure can be understood with a 2D picture of it. Similarly, the cosmological sheet "folds flat" in 3D, and much of the structure can be understood in 3D.

This folding process is one reason that a galaxy is not just a pile of matter, unstructured and random. Instead, matter folds up to construct it, much like an origami twist fold. And just as pleats must stick out of a folded-up origami twist, filaments of matter must stick out of a galaxy after it forms. For example, Fig. 1 shows two galaxies (twist folds) in a 2D universe. The top twist fold can be folded from paper, but the bottom fold, more typical in cosmological origami, can't be folded from paper without paper crossing itself. It can happen in cosmology because there are more dimensions to fold in!

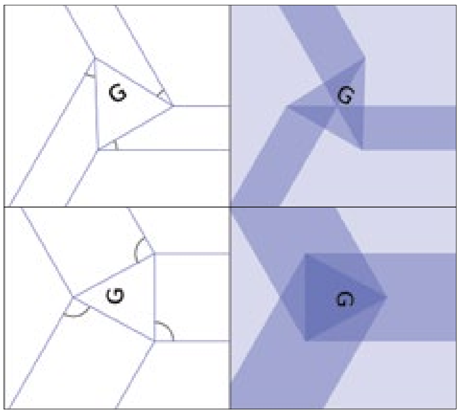


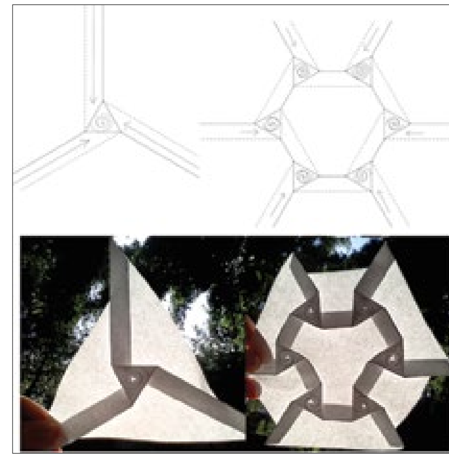
Fig.1 Top: a 60° triangular twist fold. Bottom: a 180° twist fold, typical in cosmic origami, but impossible in paper origami. Left: pre-folding. Right (purple): post-folding, in which multiple layers of the sheet overlap.

Fig. 2 shows a model universe produced with a state-of-the-art computer code [2]; its new technique can resolve the intricate structure inside each galaxy. While the physics computing this is accurate, the pattern is quite idealized: a pentagonal tiling of voids, in which galaxies form at the corners, and cosmic filaments are strung between them.

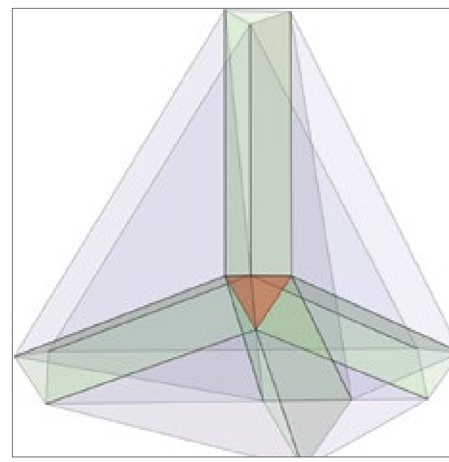
Fig. 3 shows a paper-origami representation of a galaxy, and a hexagonal system of galaxies, each joined to its neighbor by a filament pleat. The hexagonal space between the galaxies is called a void.

This is just 2D; what about 3D? To make a stab at visualizing 3D origami, visualize a big cube of "ghost Jello," a special kind of Jello

Left. At Johns Hopkins University, Mark Neyrinck led students to create a representation of structures outlined by observed galaxies in the universe. They used large-format inkjet printer to print folding lines and galactic data onto glassine paper. (Photo by Benjamin Andrew. Developed with a Creative Use of Technology Grant from the Digital Media Center, Johns Hopkins University)



Right. Fig.3 Paper-origami representations of a galaxy, and a hexagonal ring of galaxies, outlining a void. The patterns are (left) a triangular twist fold, and (right) a tessellation element from tiled hexagons by origami artist Eric Gjerde. See some printable patterns at http://skysrv.pha.jhu.edu/~neyrinck/origalaxies.html



Right below. Fig.4. A crease pattern for a 3D tetrahedral twist fold. Each surface shown is a crease.

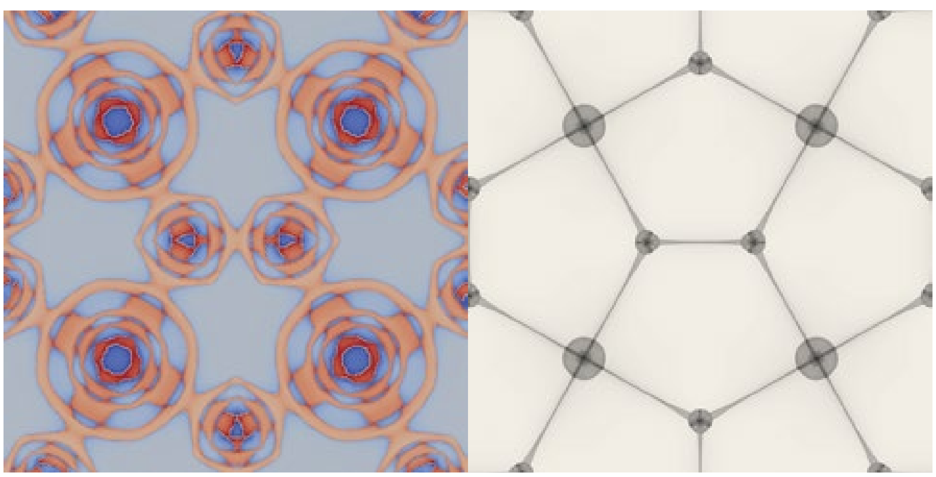


Fig.2 How a 2D universe would fold up to form a pentagonal tiling of voids. Left: the "crease pattern," showing matter at its initial location on the cosmological sheet, before folding up. If the sheet were placed on a table and flat-folded like paper origami, blue regions would end up face-up, and red regions face-down. Borders between red and blue regions are the creases. Right: the "folded form," rendered as though backlit. In light regions, the sheet has stretched out, allowing a lot of light through. Dark regions are high-density (with a lot of the sheet in a small area), with multiple layers overlapping.

that can pass through itself as many times as it pleases. A crease in the Jello triggers a reflection, like a mirror; the Jello from one side of the mirror gets pushed through to the other side, ending up inverted (turning a right hand into a left hand).

A 2D galaxy forms like an origami twist fold; similarly, a 3D galaxy forms like a 3D twist fold. What is this? In a 2D twist fold, a polygon rotates by some angle, generating pleats from each edge. In a 3D twist fold, a solid shape (a polyhedron) inverts, and then undergoes a 3D rotation. In doing so, it generates a wealth of structure: from each edge, a pleat; and from each face, a "filament" (an extrusion, like PlayDoh pressed through a pattern, of a 2D twist fold). The simplest, most symmetric example is shown in Fig 4: a tetrahedral twist fold [3]. When many galaxies form together, the network of matter linking them up is known as the "cosmic web." This cosmic web is like soap-bubble foam, with galaxies at each corner where bubbles meet. Coming back to the question I asked at the beginning: yes, origami mathematics does seem to be useful to understand the universe. Based on my work, it even makes testable predictions: if galaxies rotate (and they do), so must filaments sticking out of them. Furthermore, galaxies joined by a filament should rotate mostly together, like objects attached to ends of a rod. In fact, this is consistent with astronomical observations; nearby galaxies tend to be spinning in the same direction. The approximate model still needs to be fully tested, but even if the details are only roughly right, the concept remains: the universe seems to be one big origami tessellation. ⛴

**Mark Neyrinck (researcher at Institute for Computational Cosmology, Durham University). Images 1 to 4 courtesy of Mark Neyrinck.*

References
[1] Falck, Neyrinck & Szalay, http://adsabs.harvard.edu/abs/2012ApJ...754..126F
[2] Sousbie & Colombi, http://adsabs.harvard.edu/abs/2016JCoPh.321..644S
[3] Neyrinck, http://adsabs.harvard.edu/abs/2014arXiv1408.2219N [Origami^6 article]
[4] Neyrinck, http://adsabs.harvard.edu/abs/2016MNRAS.460..816N

For animations illustrating how 3D twist folds operate, see **http://skysrv.pha.jhu.edu/~neyrinck/irrotet** *and* **http://skysrv.pha.jhu.edu/~neyrinck/rotet.mov**