



ROBERT J. LANG
ORIGAMI

From Tsuru to Satellites: the art and science of origami

Robert J. Lang
www.langorigami.com

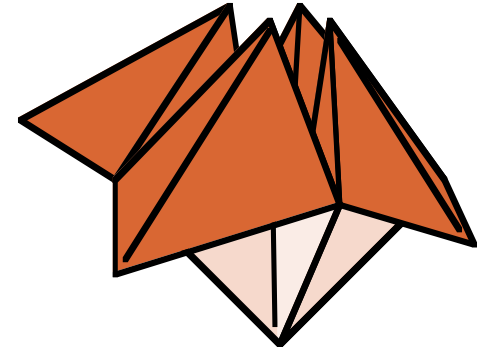
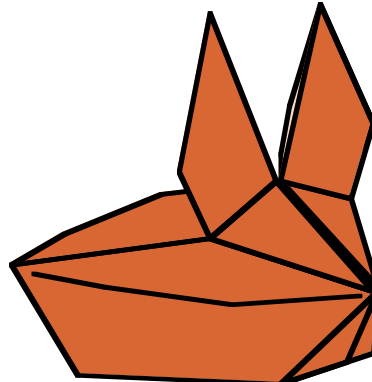
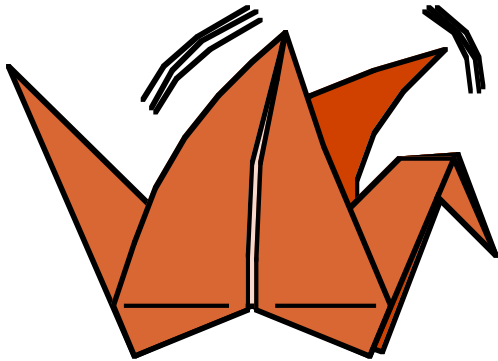
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What is Origami?

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- Japanese paper-folding.





History



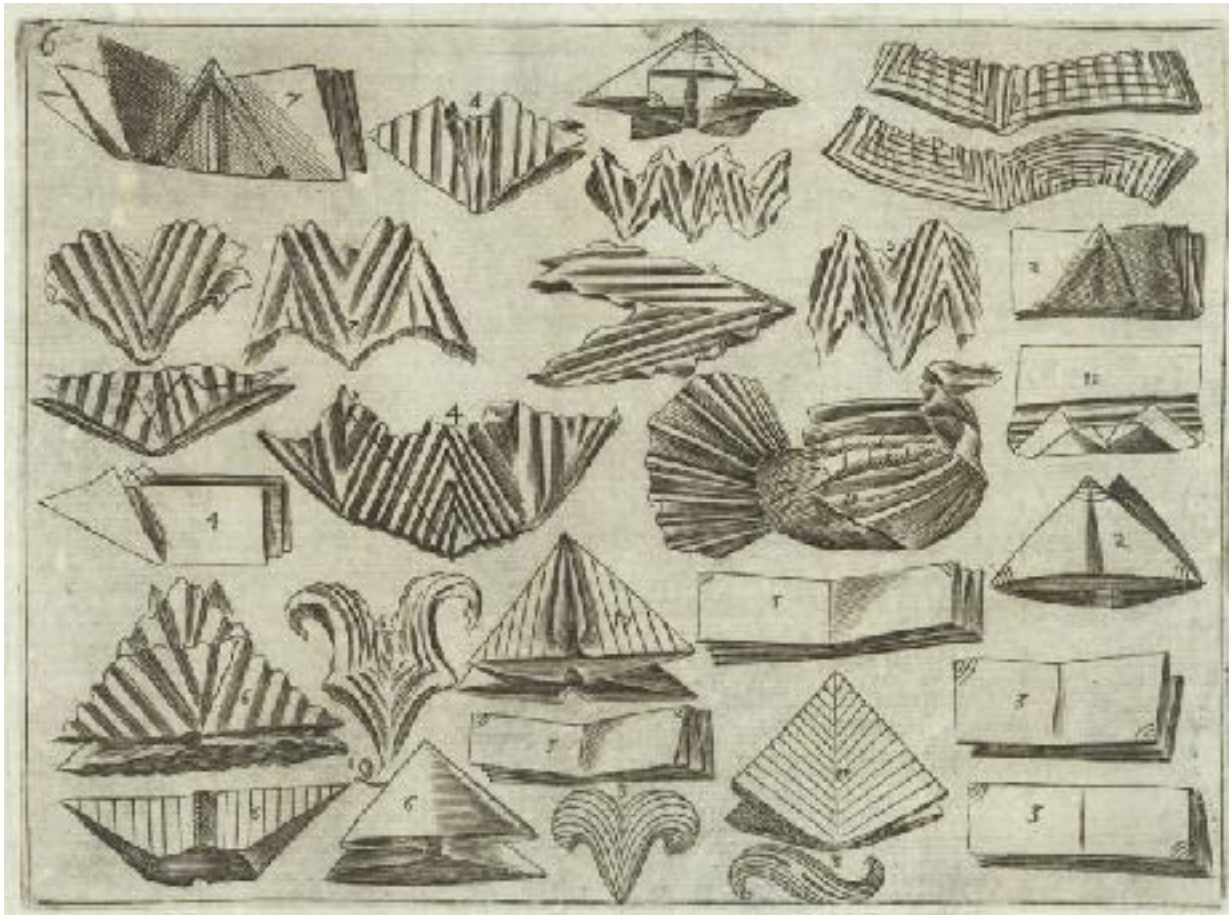
- Paperfolding is ancient and a multi-cultural practice.



Europe

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Li Tre trattati 1639 by Messer Mattia Giegher Bavaro

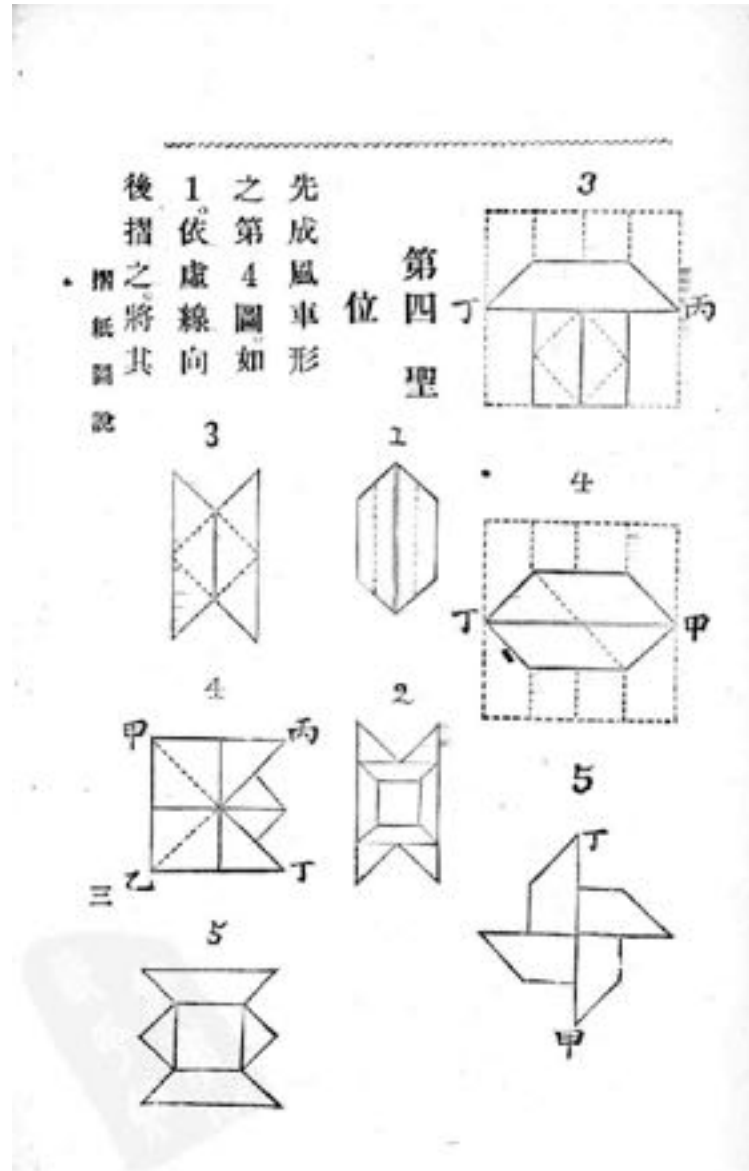


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China

折纸图说 (zhe zhi tu shuo), 1914
by GUI Shaolie



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Image courtesy of Xiaoxian Huang



Mesoamerica

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- Aztec folded headdress from the Codex Borbonicus, ~1500s



Images courtesy of Mary Miller, Yale University

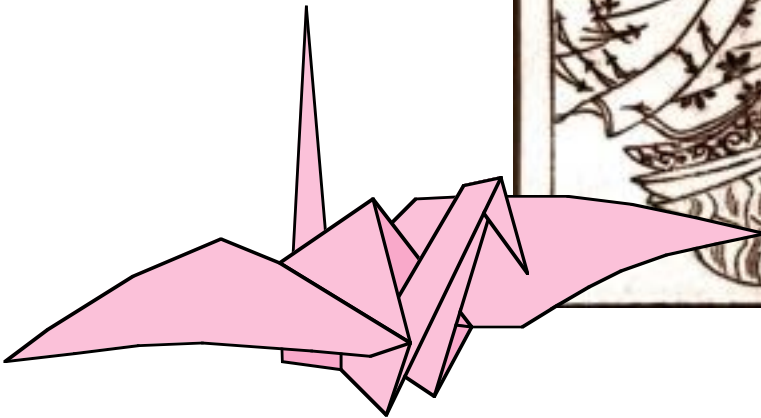
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Early Origami in Japan

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- Origami circa 1797.



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Oldest known crane

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- A “kozuka” (samurai sword accessory) decorated with origami cranes
- Artist and style suggest ~1600 CE

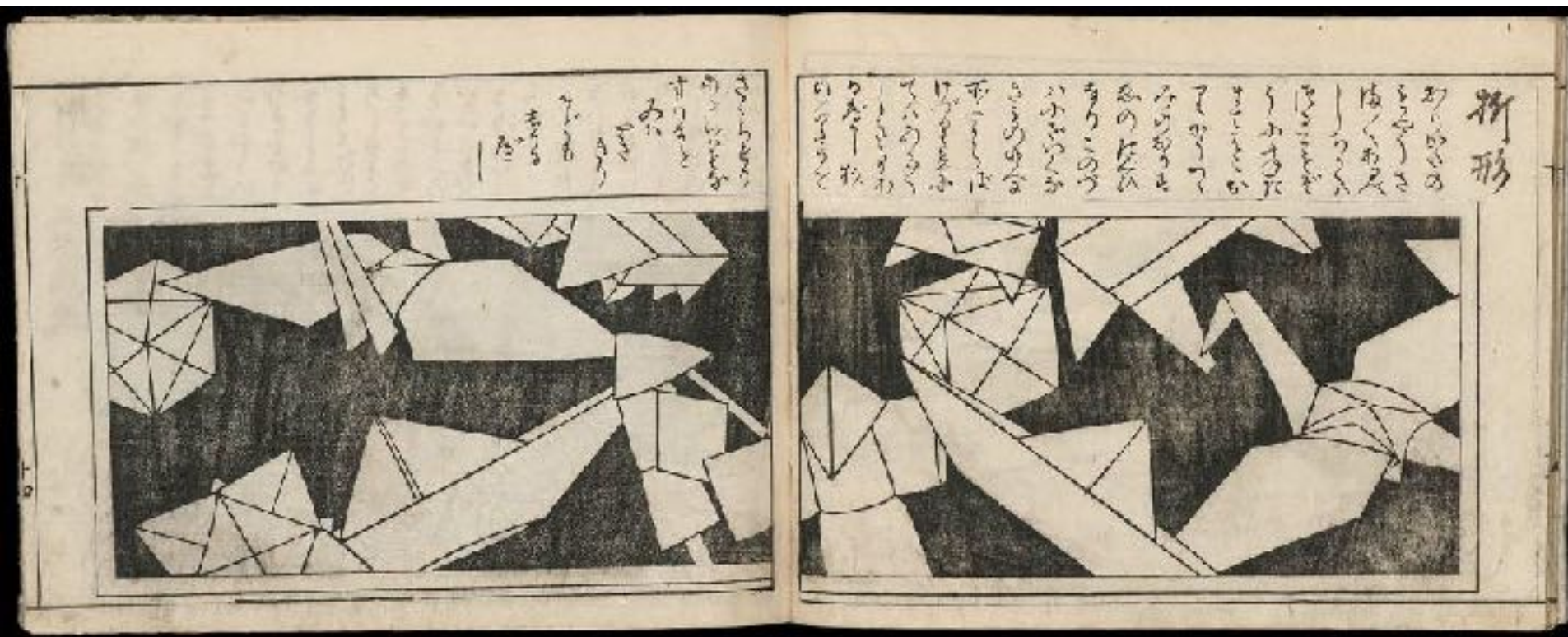




Earliest (but not first)

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- Japanese book from 1734: Crane, boat, table, “yakko-san”
- By 1734, it is already well-developed





Modern Origami

- Akira Yoshizawa (1911-2005)
- Inspired a worldwide renaissance of origami



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有隣堂新春特別展
一枚の紙から。
折り紙芸術を確立した天才
吉澤章創作折り紙展
国際折り紙研究会40周年記念

美しさと優しさ、そして生命感をも感じさせる吉澤章の「創作折り紙の世界」。国際的な創作折り紙作家のすばらしい作品を通して、その人と創作折り紙の魅力を紹介します。

会期／平成7年1月3日(木)～11日(土) 10時～18時
会場／横浜セザンヌ町・有隣堂ギャラリー(本町吉澤館2階)
主催／国際折り紙研究会
協賛／折り紙国際協会・折り紙研究会・折り紙教育委員会・横浜教育委員会

有隣堂
入場無料

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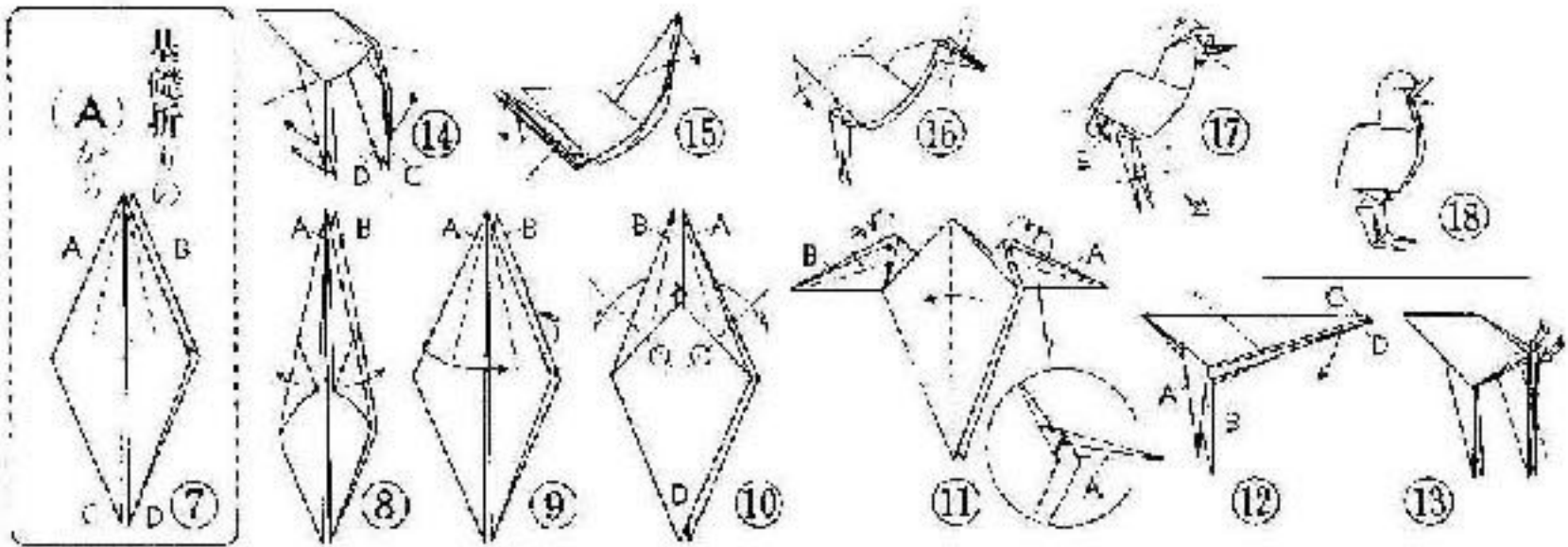
有隣堂
入場無料



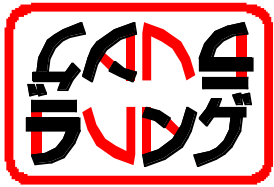
Modern Origami

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- Yoshizawa: new creations plus a common language.



A. Yoshizawa, *Origami Dokuhon I*



Origami Today

- “Black Forest Cuckoo Clock,”
- One sheet, no cuts

誌上作品展

“造形の魔術師”

ロバート・J・ラング

不切二枚折りの可能性に挑む



アメリカの物理学者にして折り紙作家、ロバート・J・ラング。折りの技術の粋を集めたような彼の作品群は、折り紙を知らない人々をも驚かすほどにはじかない。なにしろ、すべての作品が一枚の紙だけを使い、一か所たりとも切らず、勝手に作られているのだから。しかし何より驚くべきは彼の造形センスだろう。対象の特徴を的確にとらえリアルに折り出す力強さは、折り紙の一方の可能性である幾何造形の技を極める。なにほともあれ彼の作品を、正確な複製自身のコメントも付記した本、シンプルで、芸術性といった点について日本人とは微妙に異なる感覚がうかがえて興味深い。

CUCKOO CLOCK 鳩時計

作者より●これはドイツの伝統的鳩時計。私はこの作品には芸術的側面があると思っている。実はこれ以前にいくつか、パズル的な時計を作った。それらには美術的側面もついていなかったが、雛子を引くとドアが開き、鳥が出てくるものだった。しかしこの作品はそれがない。芸術作品としてその必要を感じなかったから。1対10の比率の長方形の紙(マフールペーパー)を使っている。もっと長くすればより容易に折れるが、チャレンジという側面も残ったかった。

Photo: Studio Akira
Illustration: Tadahito Nishikawa

Ibex







What Changed?

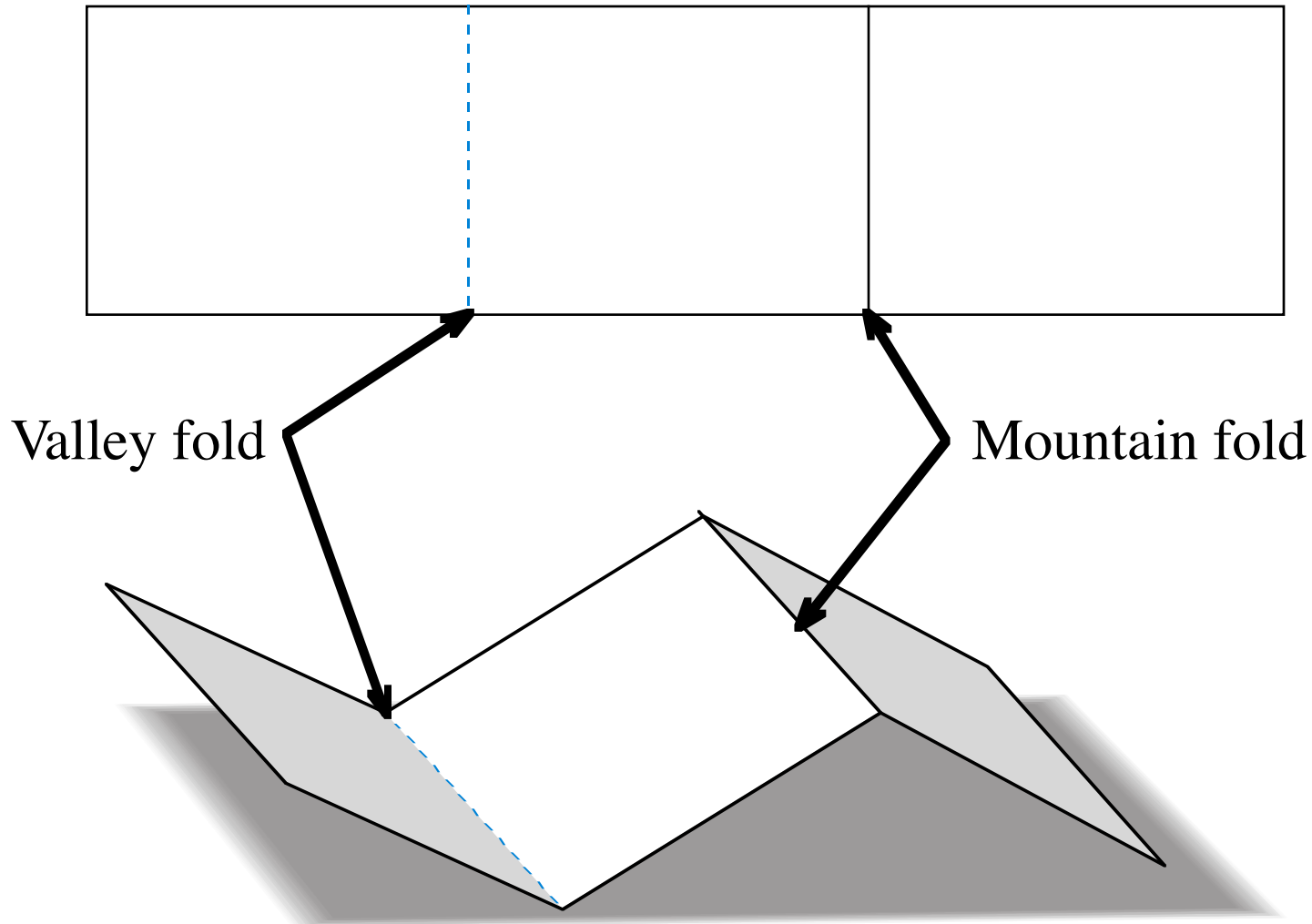
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- Math!



Basic Folds of Origami

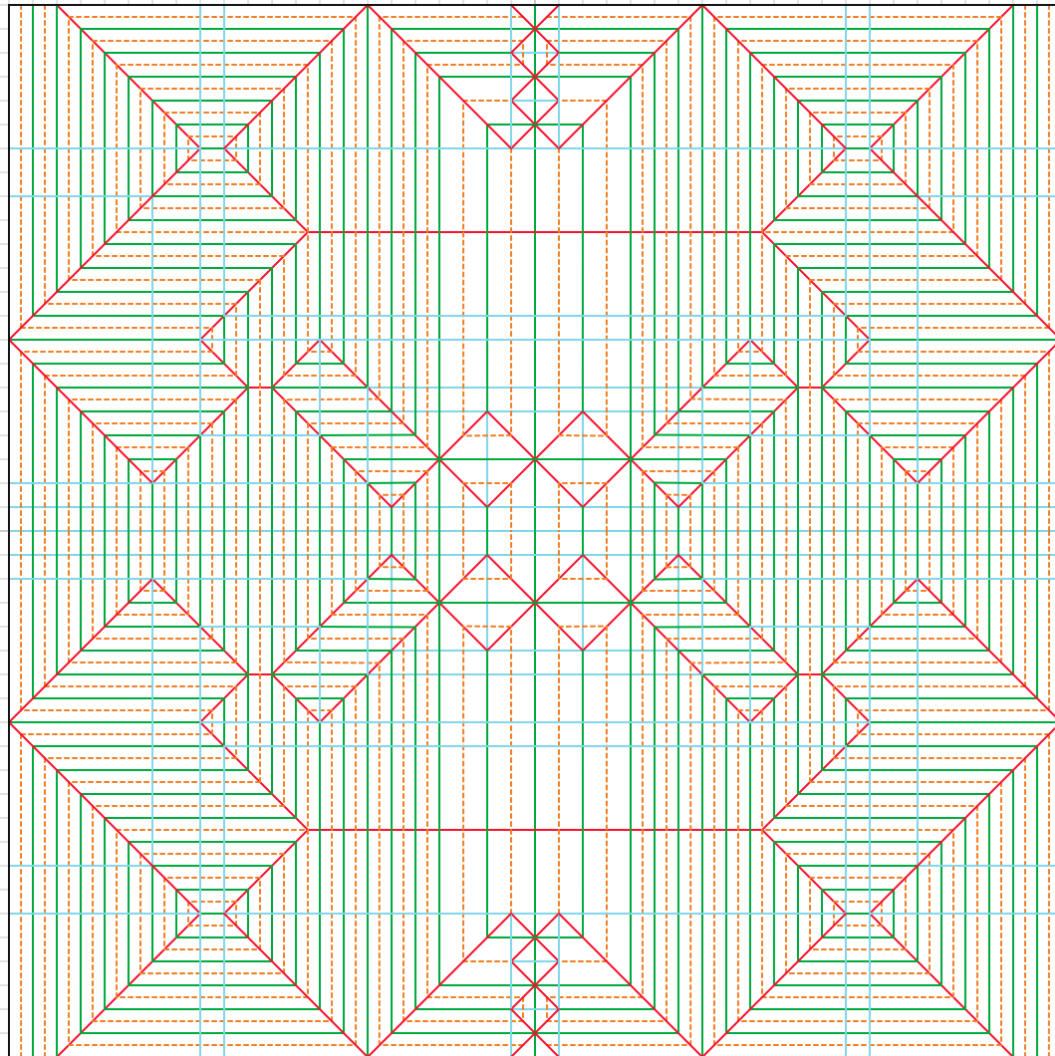
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Crease Patterns

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Crease Patterns



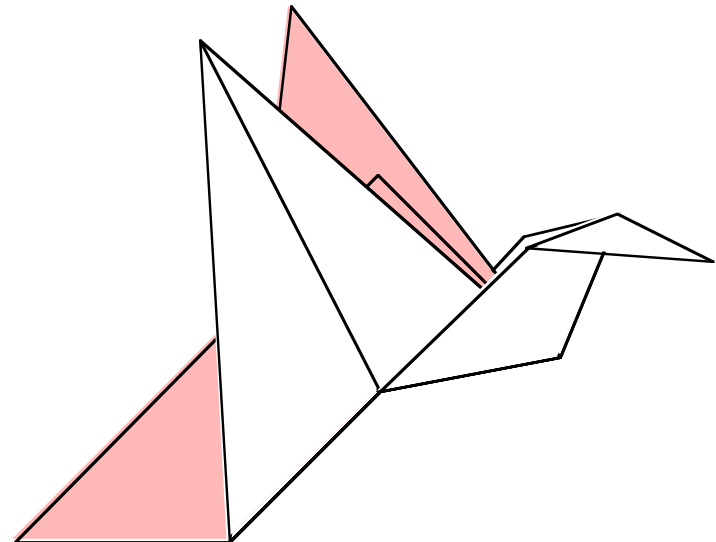
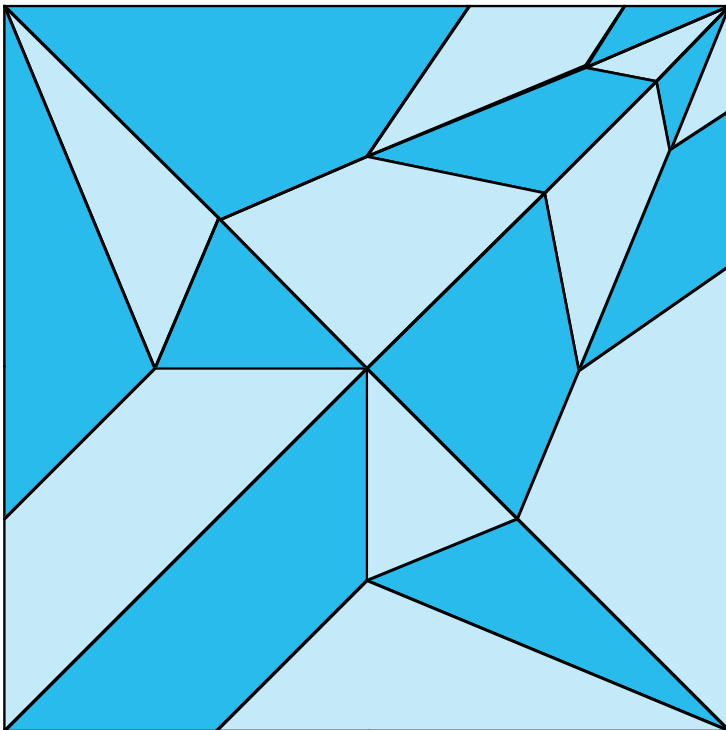
- The design of an origami figure is encoded in the crease pattern
- What constraints are there on such patterns?



Properties of Crease Patterns

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- 2-colorability



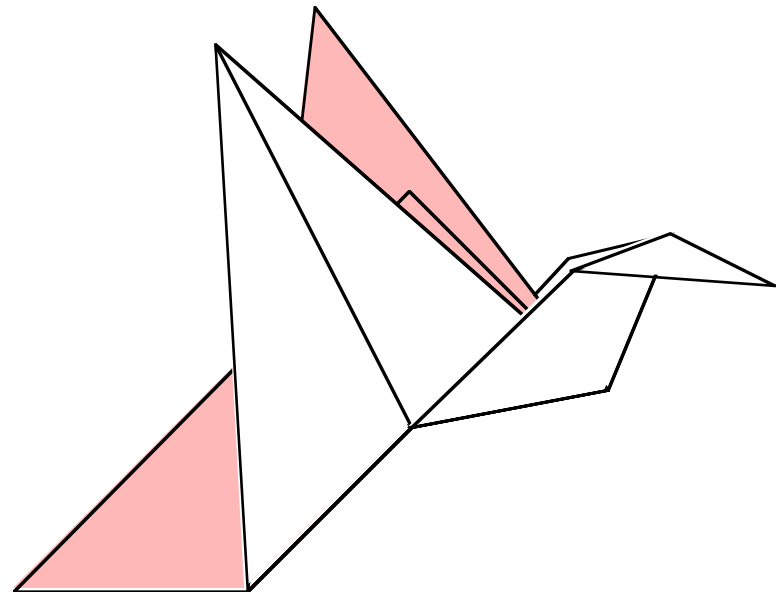
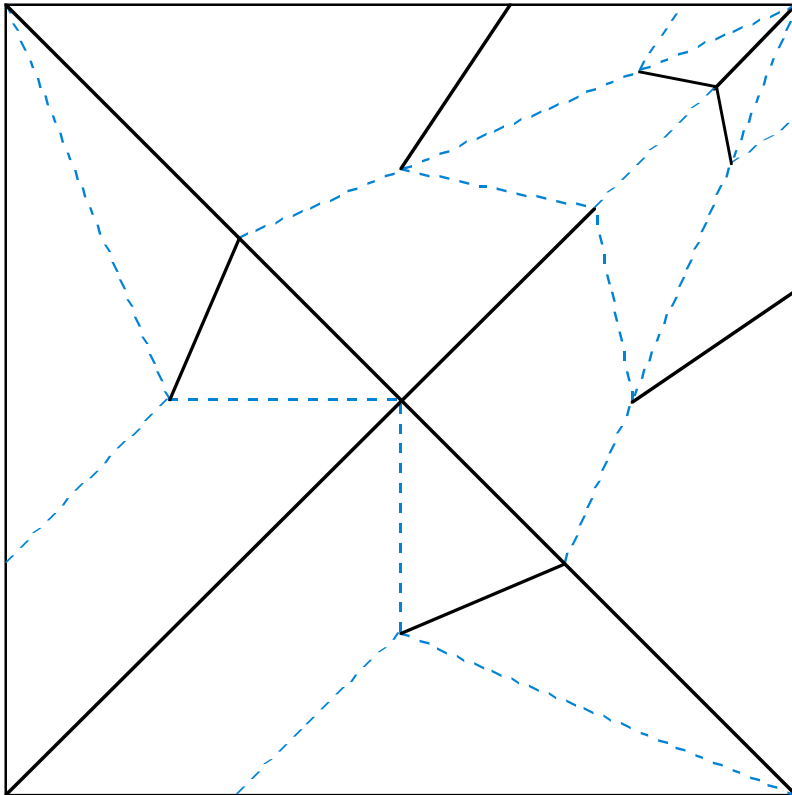
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Mountain-Valley Counting

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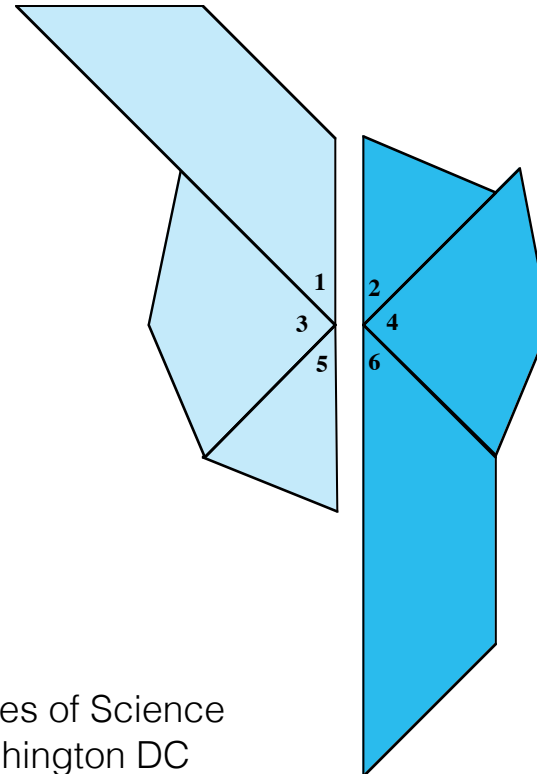
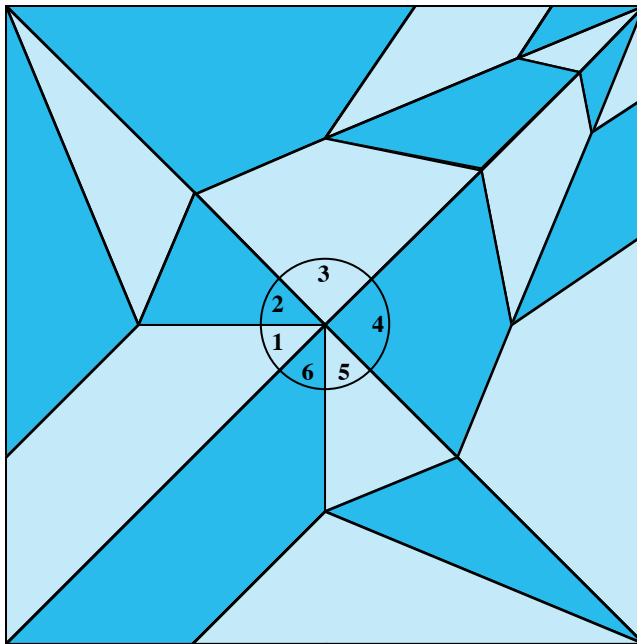
- Interior vertices: $M - V = \pm 2$





Angles Around a Vertex

- Alternate angles around a vertex sum to a straight line



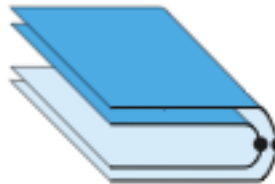
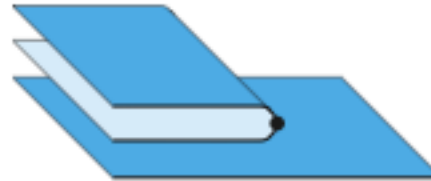


Layer Ordering

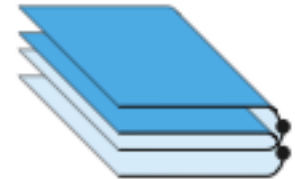
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- No self-intersection at overlaps.

VALID



NOT VALID





Flat-Foldability

- A crease pattern is “flat foldable” iff it satisfies:
 - 2-colorability (easy, all vertices even degree)
 - Maekawa Condition (M-V parity) at every interior vertex
 - Kawasaki Condition (Angles) at every interior vertex
 - Justin Conditions (Ordering) for all facets and creases

That’s all we need to describe flat origami.



But is it useful, or just fun?

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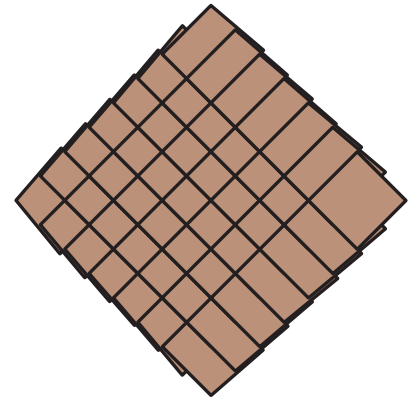
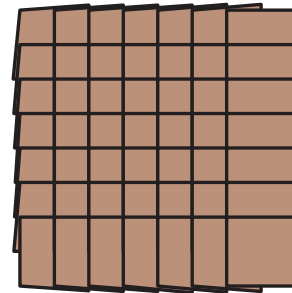
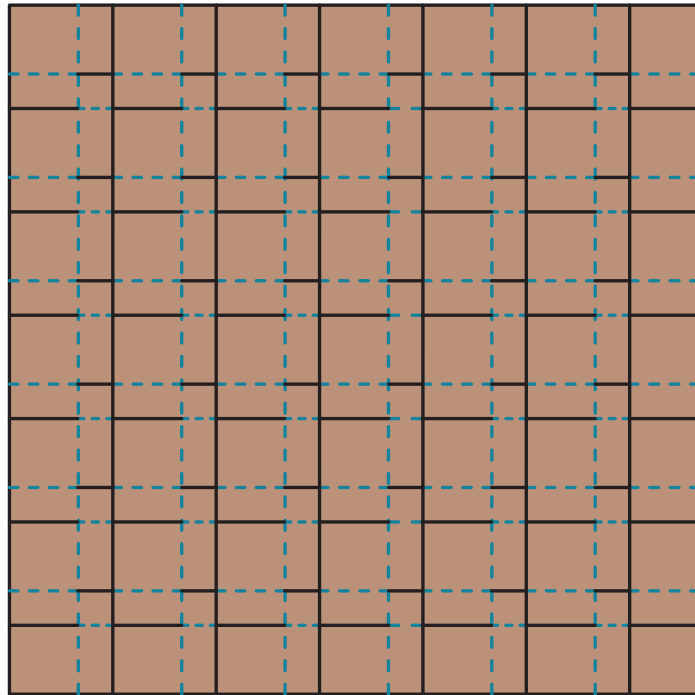
- Flat-foldability rules (math)...
- lead to crease pattern matching rules (application)...
- and thus, the generation of beauty (art)...
- and even practical functional objects (\$\$\$)!



Textures

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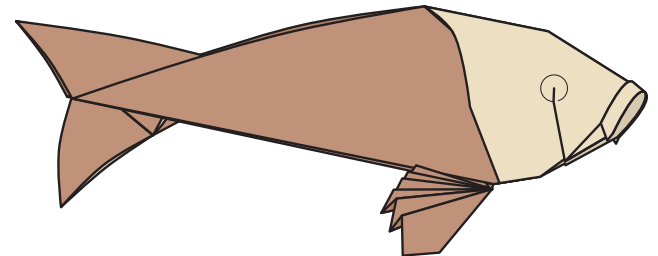
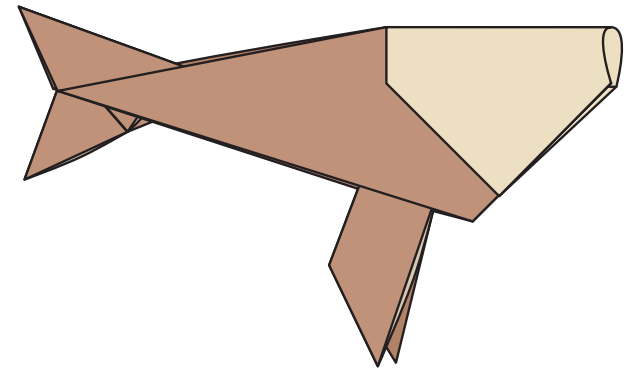
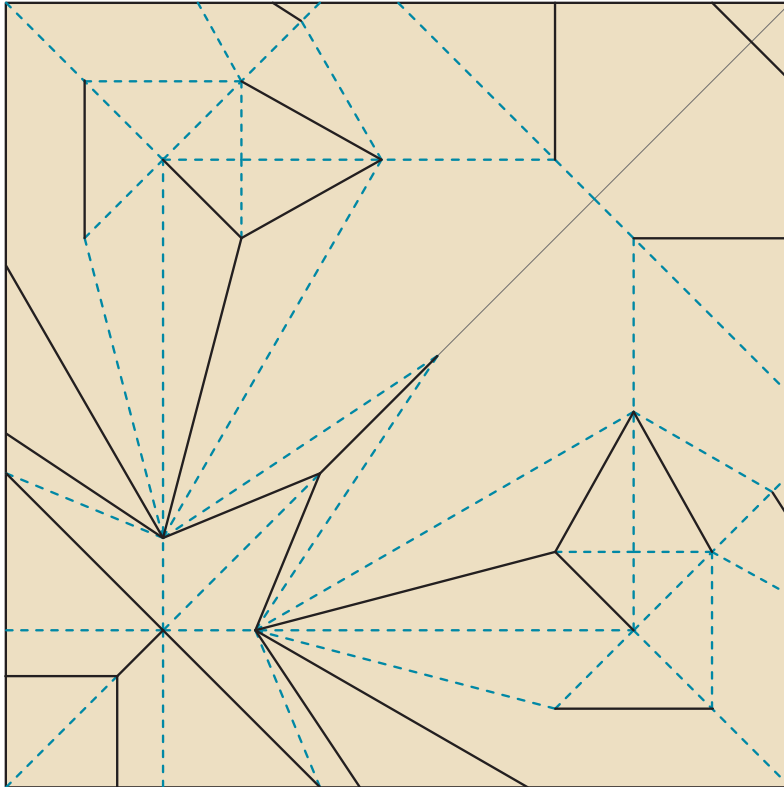
- Patterns of pleats
- Integrate with existing forms





The recipient form

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Western Pond Turtle



Rattlesnake



Rattlesnake II





On demand

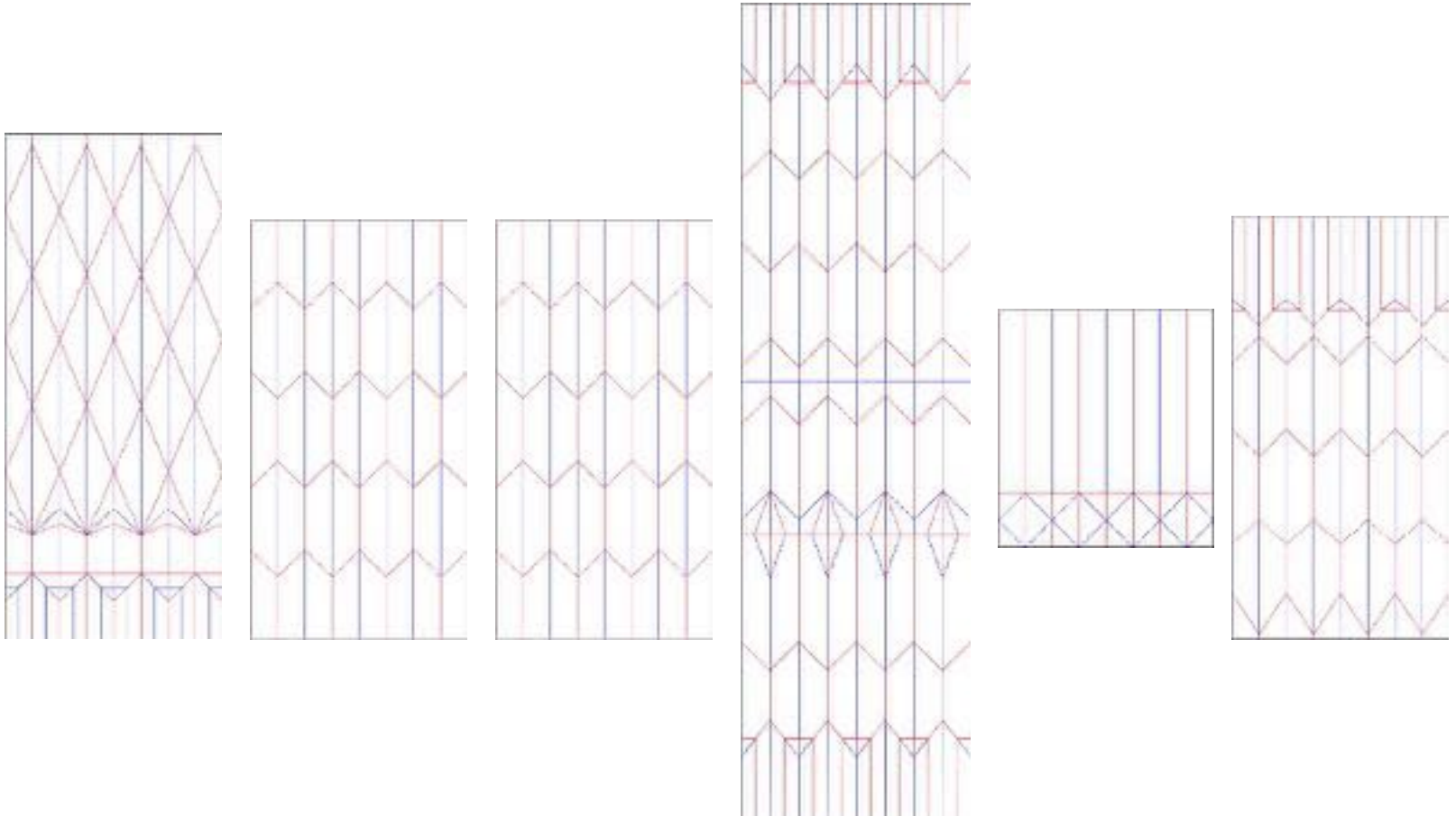
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- A geometric design
 - five letters for a corporate logo
 - one week to design and fold



Six crease patterns...

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March 14, 2012

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- The Google Doodle honored Akira Yoshizawa



read the whole story at:

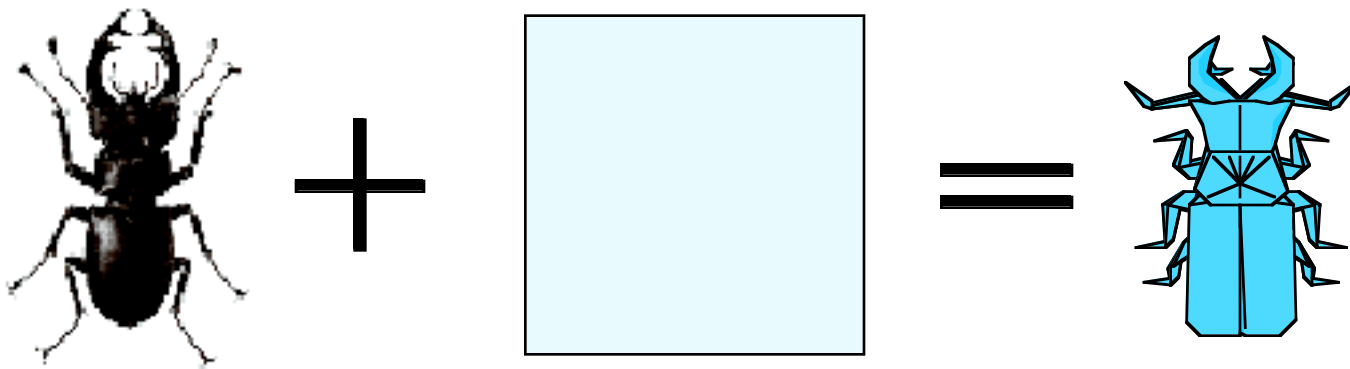
<http://tinyurl.com/yoshizawa-doodle>



Origami design

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- The fundamental equation:
- given a desired subject, how do you fold a square to produce a representation of the subject?



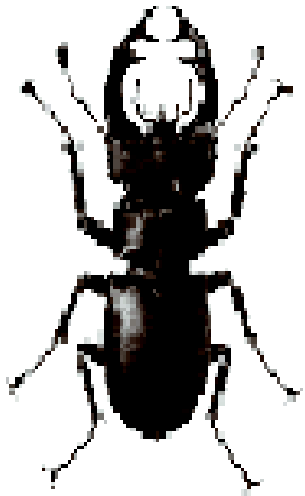




A four-step process

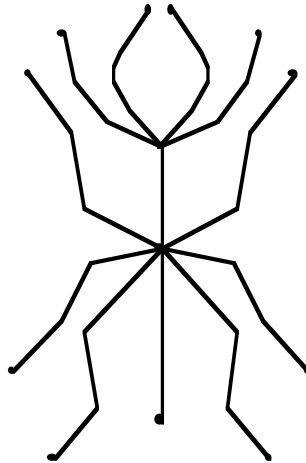
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Subject



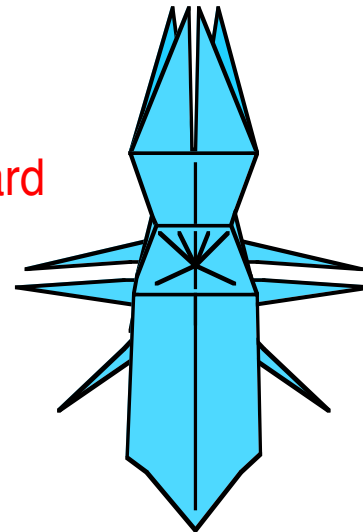
easy
→

Tree



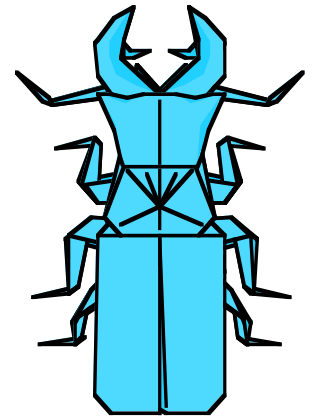
Hard
→

Base



easy
→

Model

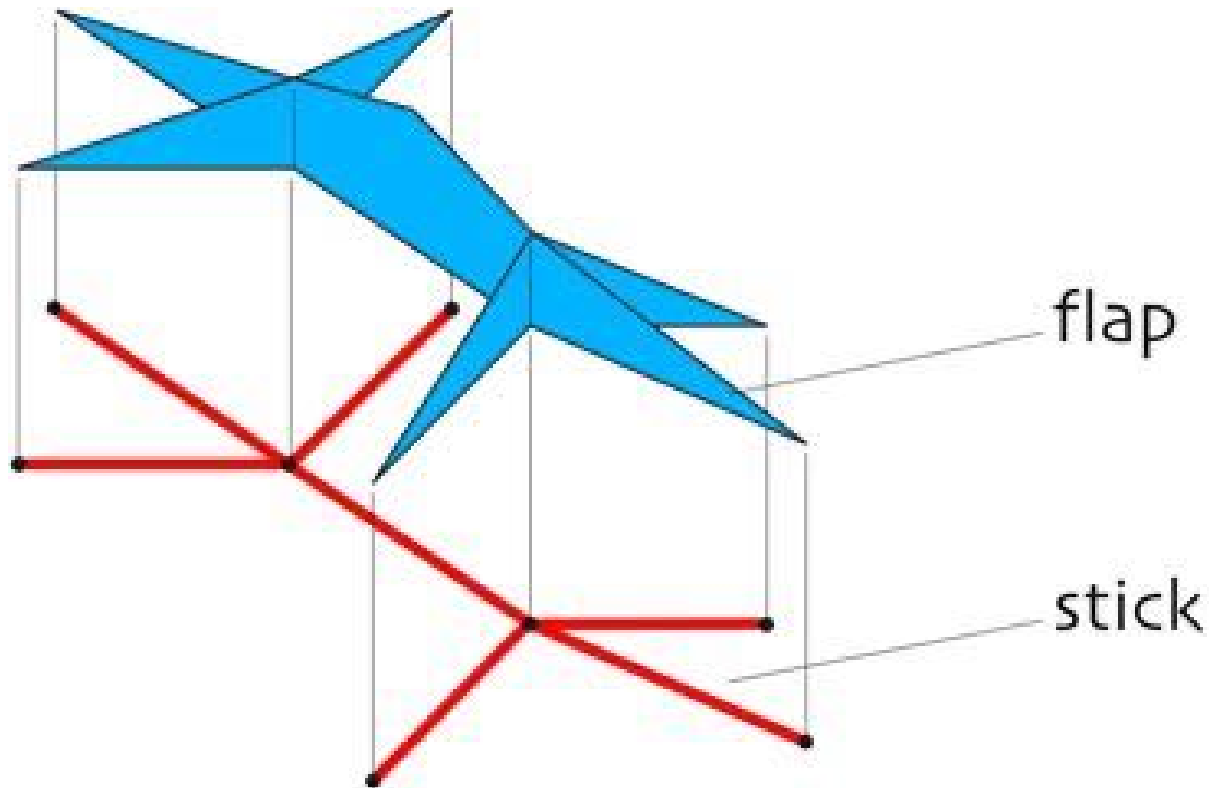




The hard step

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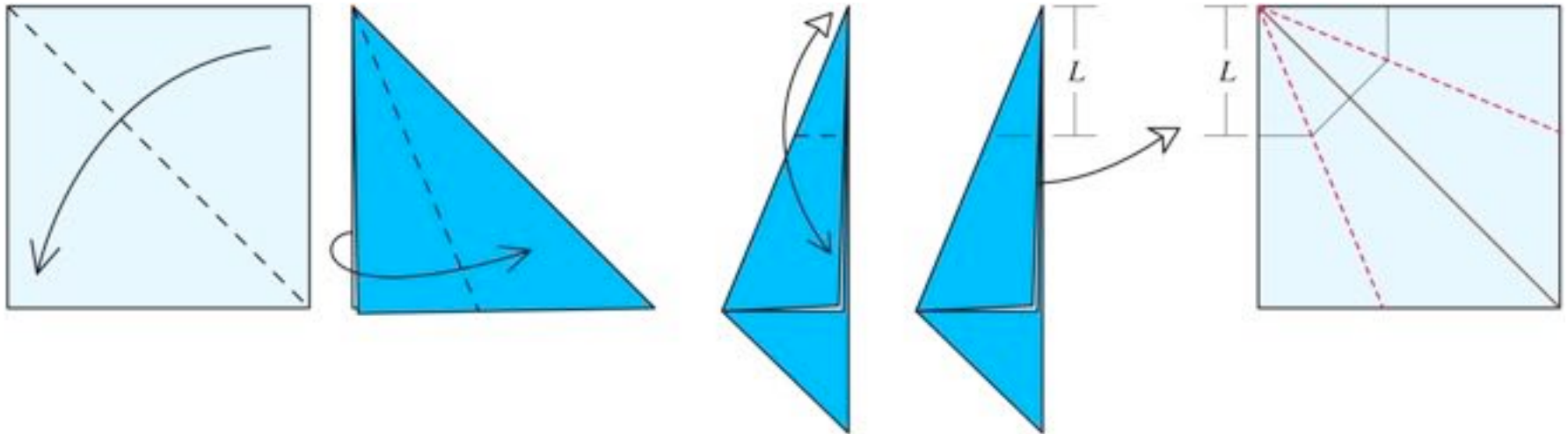
- How do you make a specified bunch of flaps?





How to make a flap

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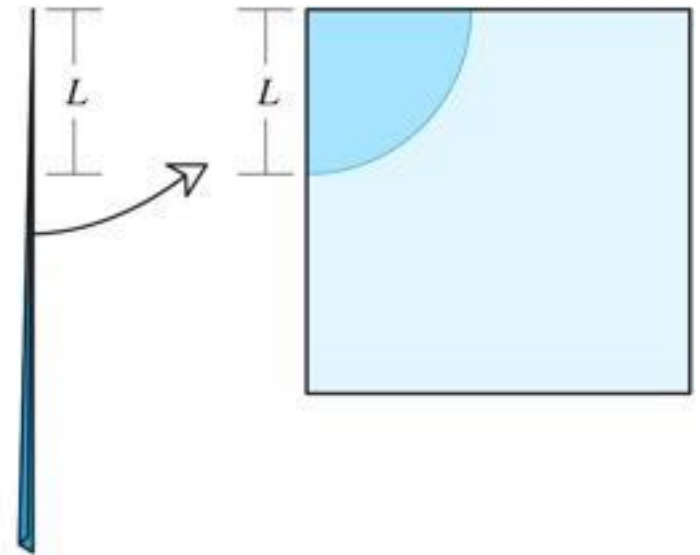
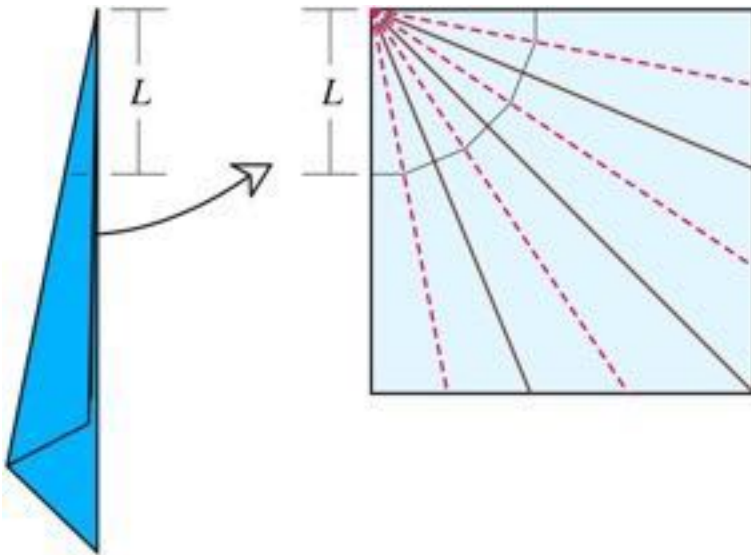




Limiting process

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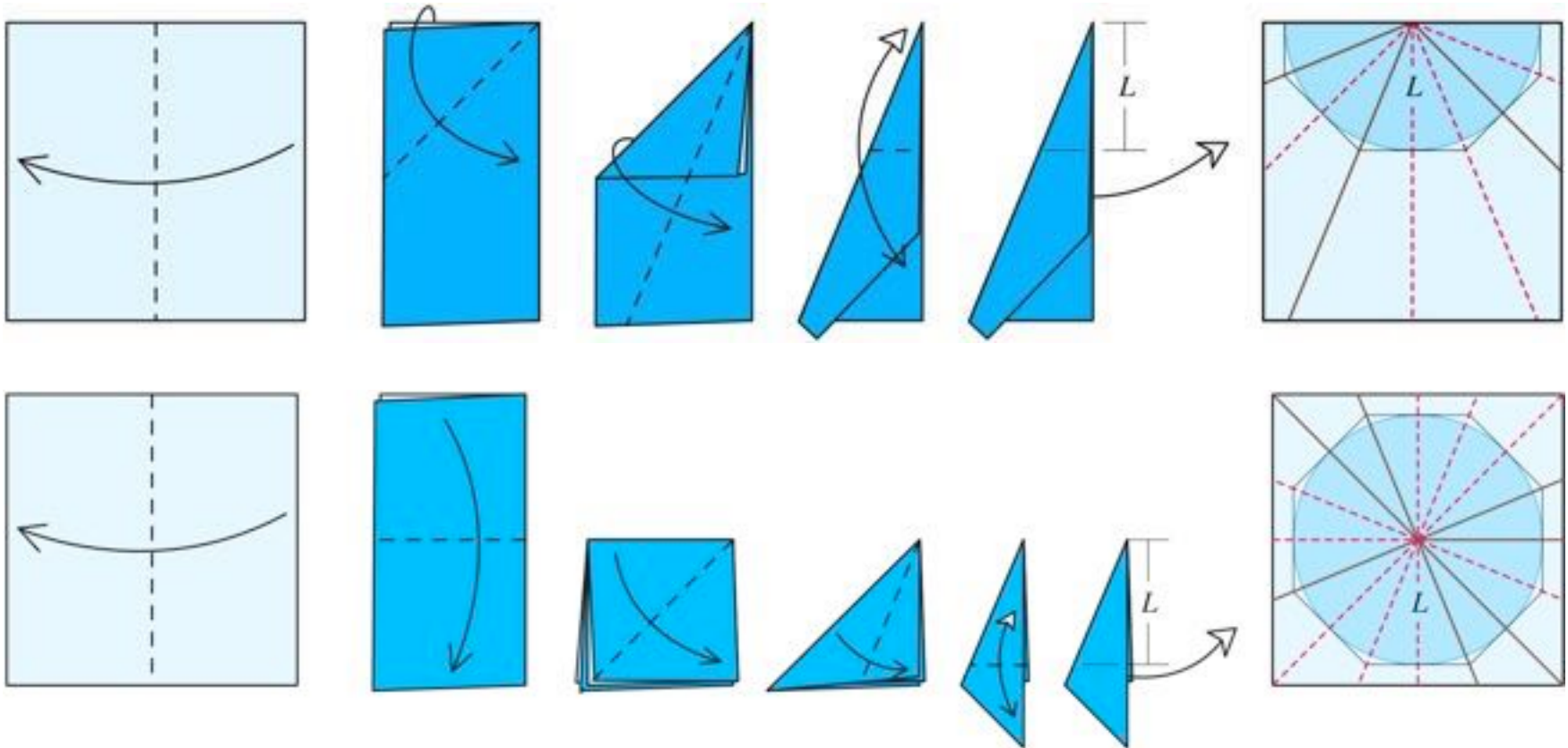
- Skinnier flap leads to...
- A (quarter) circle!





Other types of flap

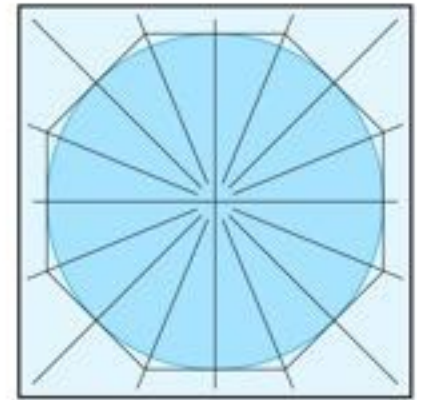
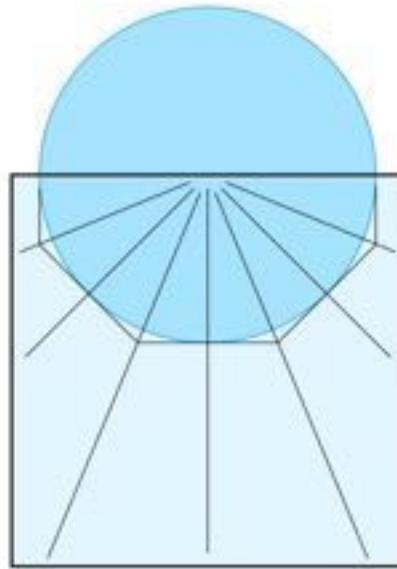
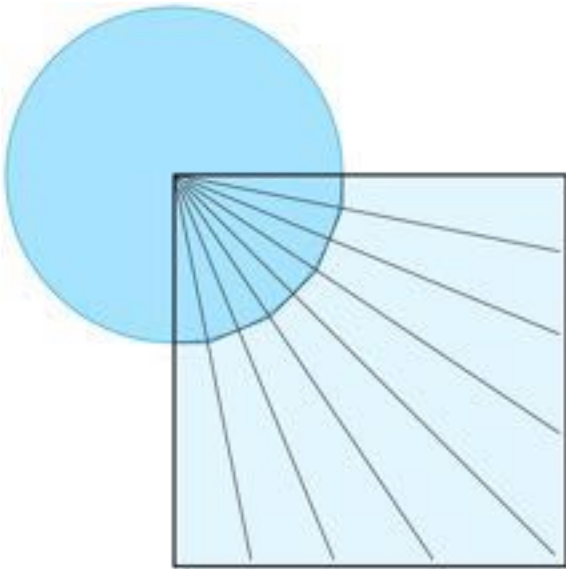
- Flaps can come from edges...
- ...and from the interior of the paper.





Unify

- They're all circles

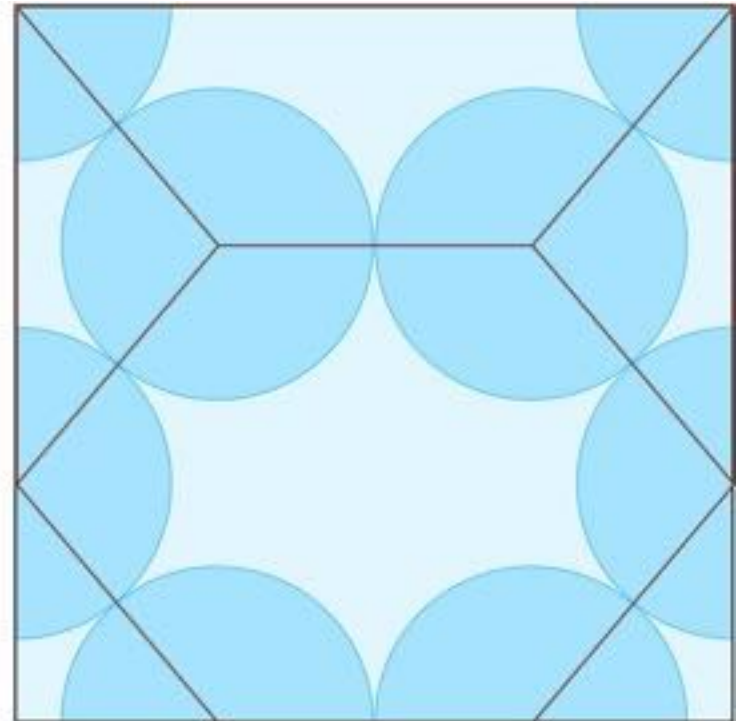
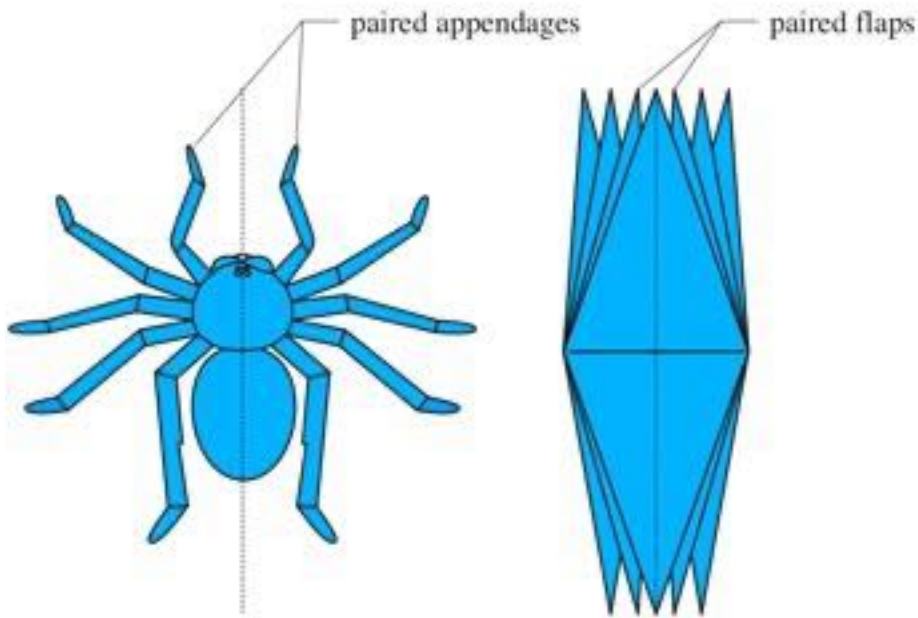




Circle Packing

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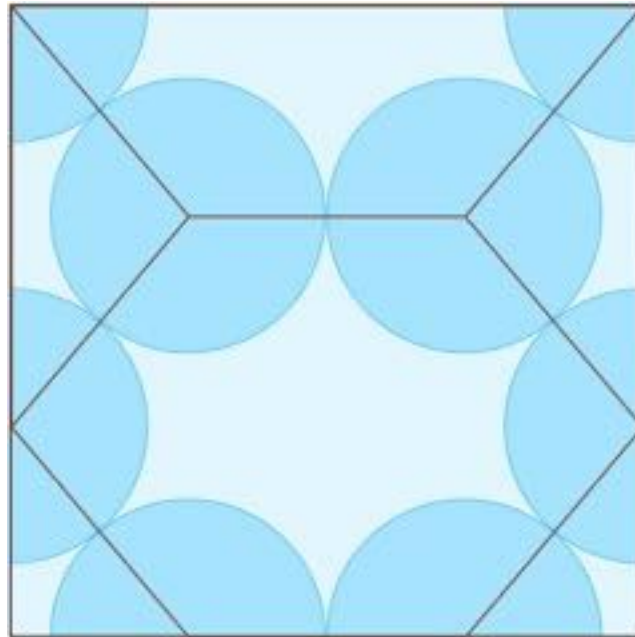
- Many flaps: use many circles.





Creases

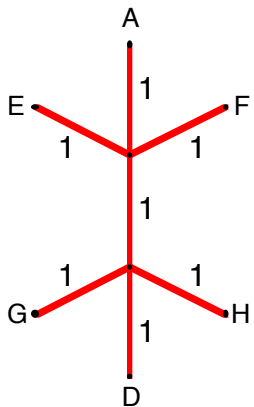
- The lines between the centers of touching circles are always creases.
- But there needs to be more. Fill in the polygons, but how?



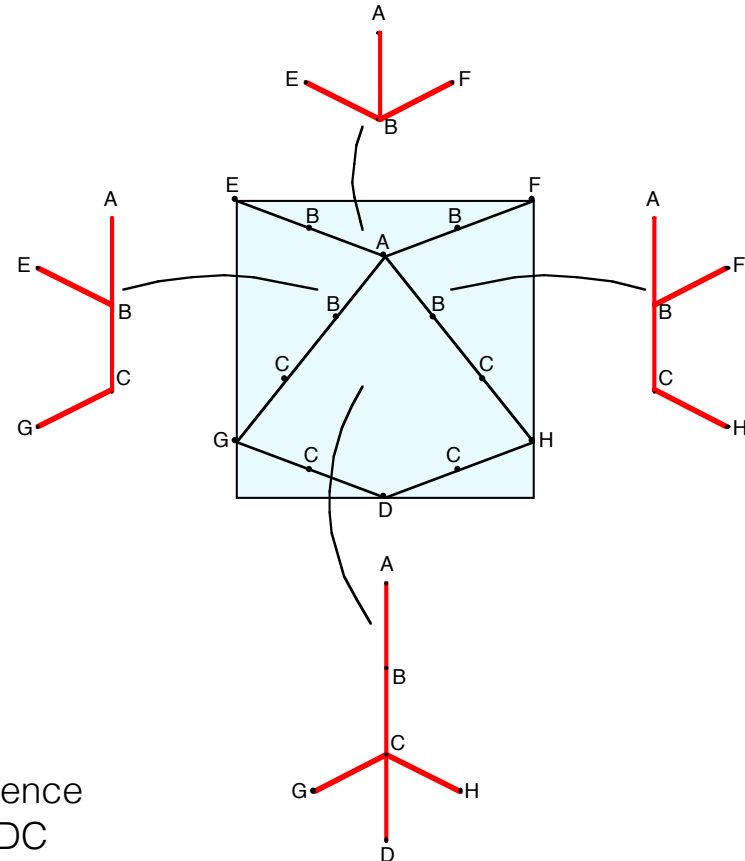
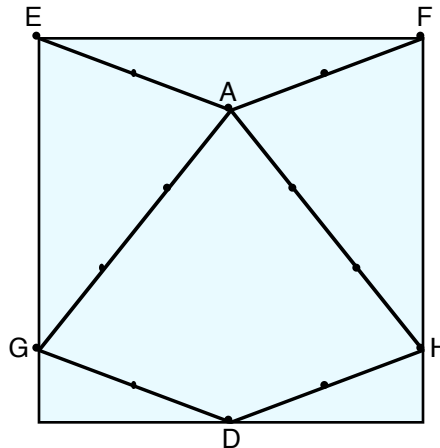


Divide and conquer

- The creases divide the square into distinct polygons that correspond to pieces of the stick figure.



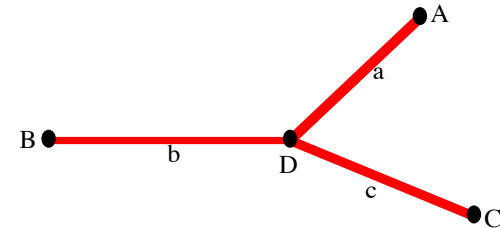
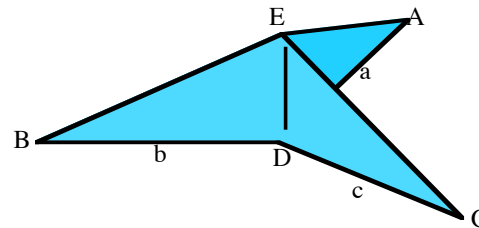
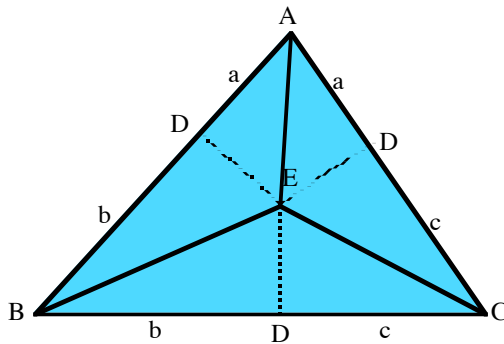
$$m=0.267$$





Molecules

- Crease patterns that collapse a polygon so that its edges form a stick figure are called “bun-shi,” or molecules (Meguro)
- Different molecules are known from the origami literature.
- Triangles have only one possible molecule.

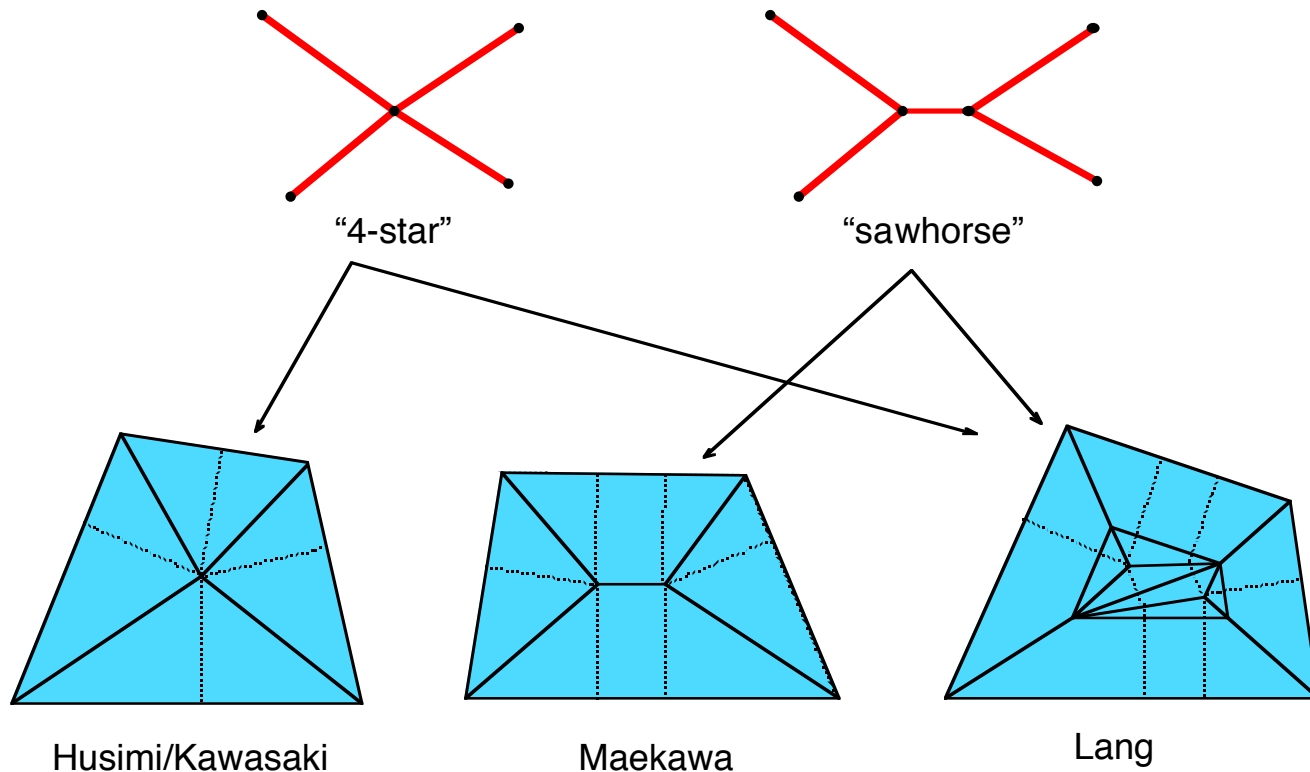


the “rabbit ear” molecule



Quadrilateral molecules

- There are two possible trees and several different molecules for a quadrilateral.
- Beyond 4 sides, the possibilities grow rapidly.

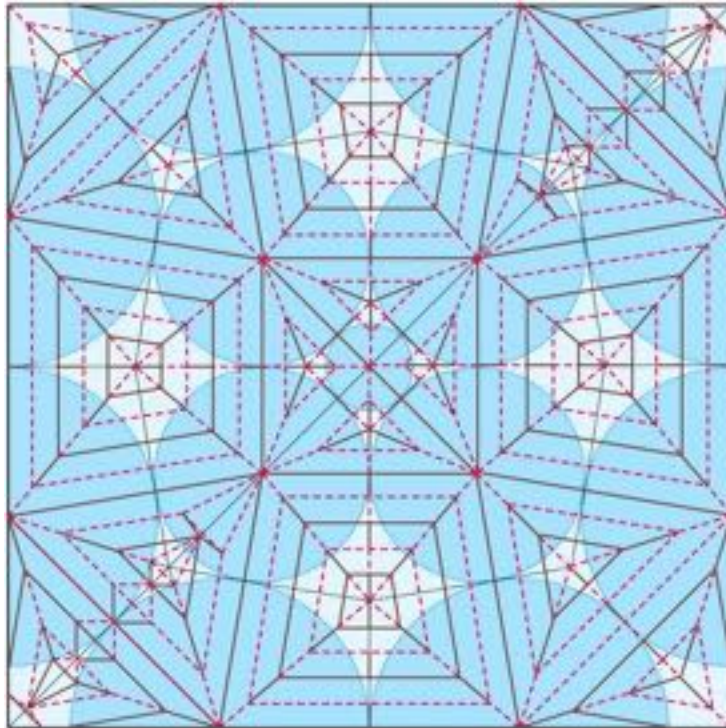




Circles and Rivers

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- Pack circles, which represent all the body parts.
- Fill in with molecular crease patterns.
- Fold!







Circle-River Design

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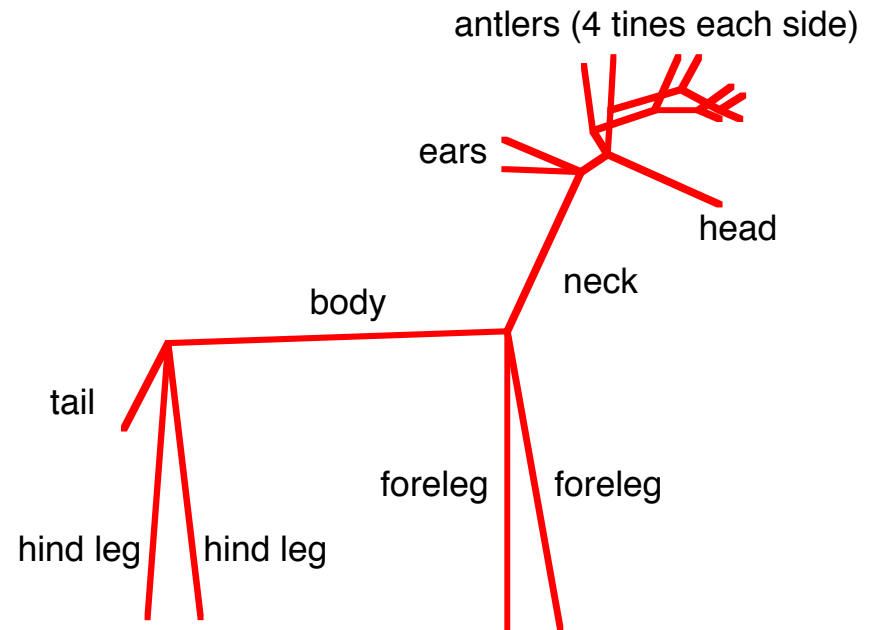
- The combination of circle-river packing and molecules allows an origami composer to construct bases of great complexity using nothing more than a pencil and paper.
- But what if the composer had more...
- Like a computer?



Computer-Aided Origami Design

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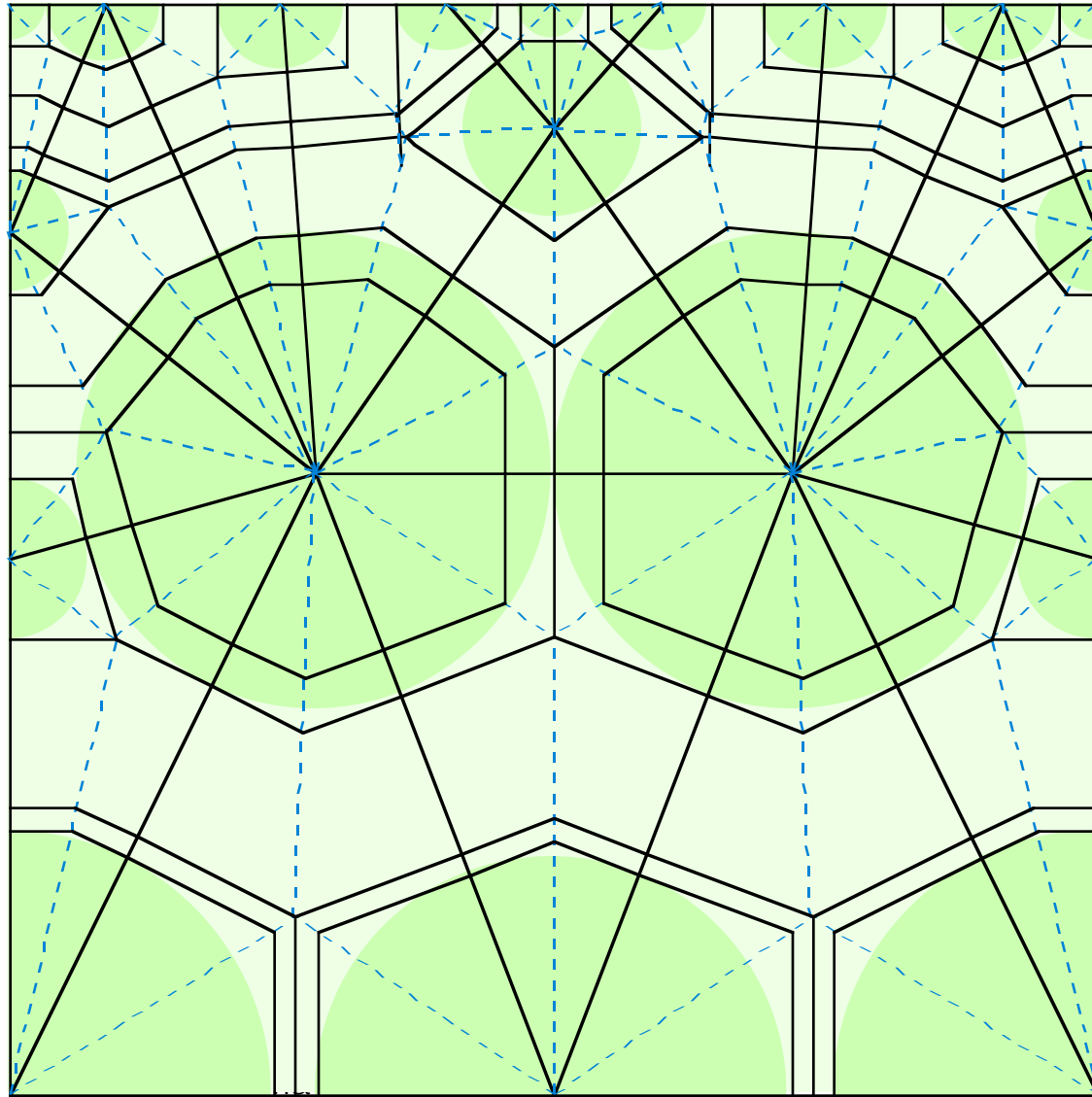
- 16 circles (flaps)
- 9 “rivers “ (connections)
- 200 equations!





The crease pattern

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Roosevelt Elk



Bull Moose





TreeMaker Software

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- Algorithms are described in
 - R. J. Lang, “A Computational Algorithm for Origami Design,” 12th ACM Symposium on Computational Geometry, 1996
 - R. J. Lang, Origami Design Secrets (A K Peters, 2003)
- Macintosh/Linux/Windows binaries and source available (free!) from
 - <http://www.langorigami.com/treemaker.htm>



The Bug Wars

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- 1970s: “Insects are impossible”
- 1980s: “Insects are possible”
- 1990s: Battle of the species!

Tarantula









Ka

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“Samurai Helmet” Beetle

Eupatorus gracilicornis





Euthysanius Beetle

Praying Mantis



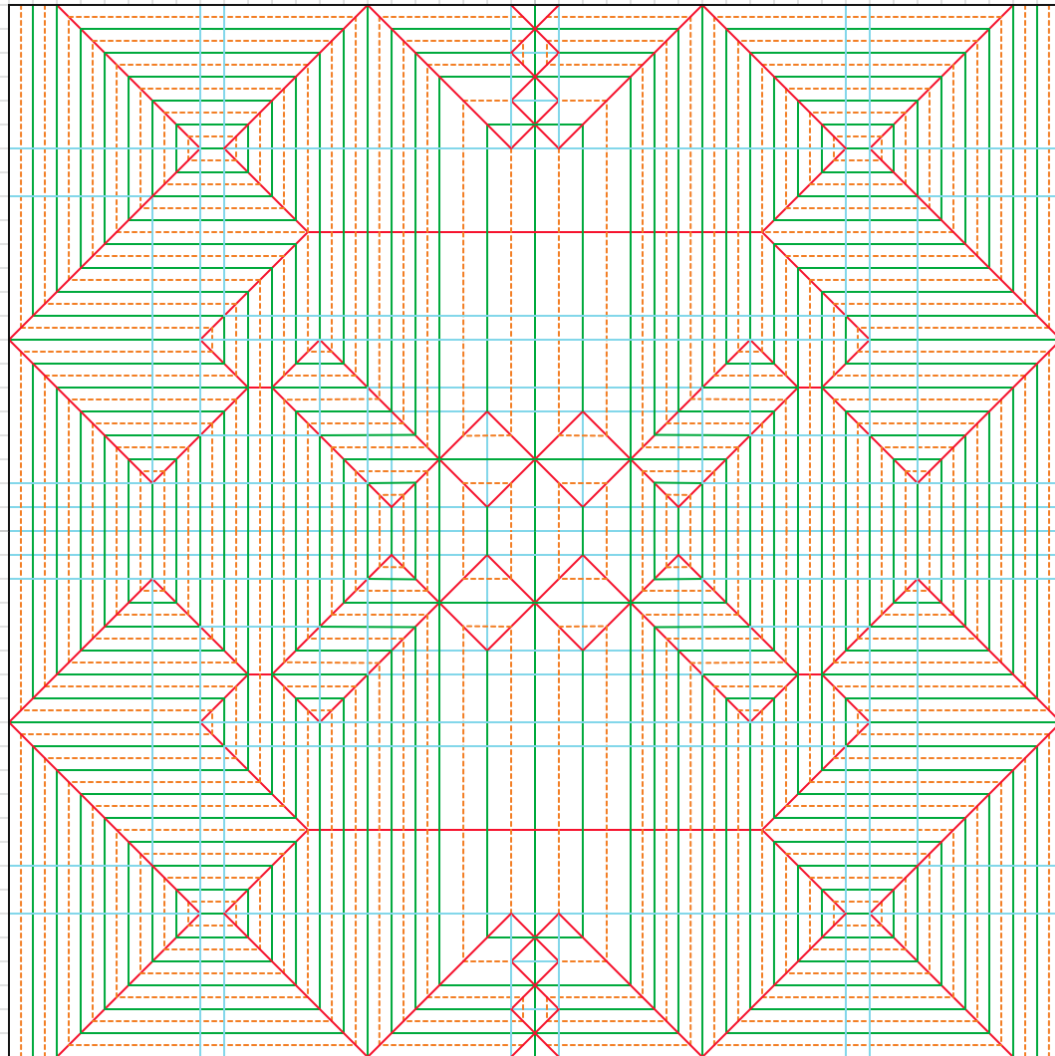
Two Praying Mantises





Crease Patterns

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Centipede





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Tick

Tick on Quarter





Representational

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Dancing Crane



Barn Owl

Grizzly Bear



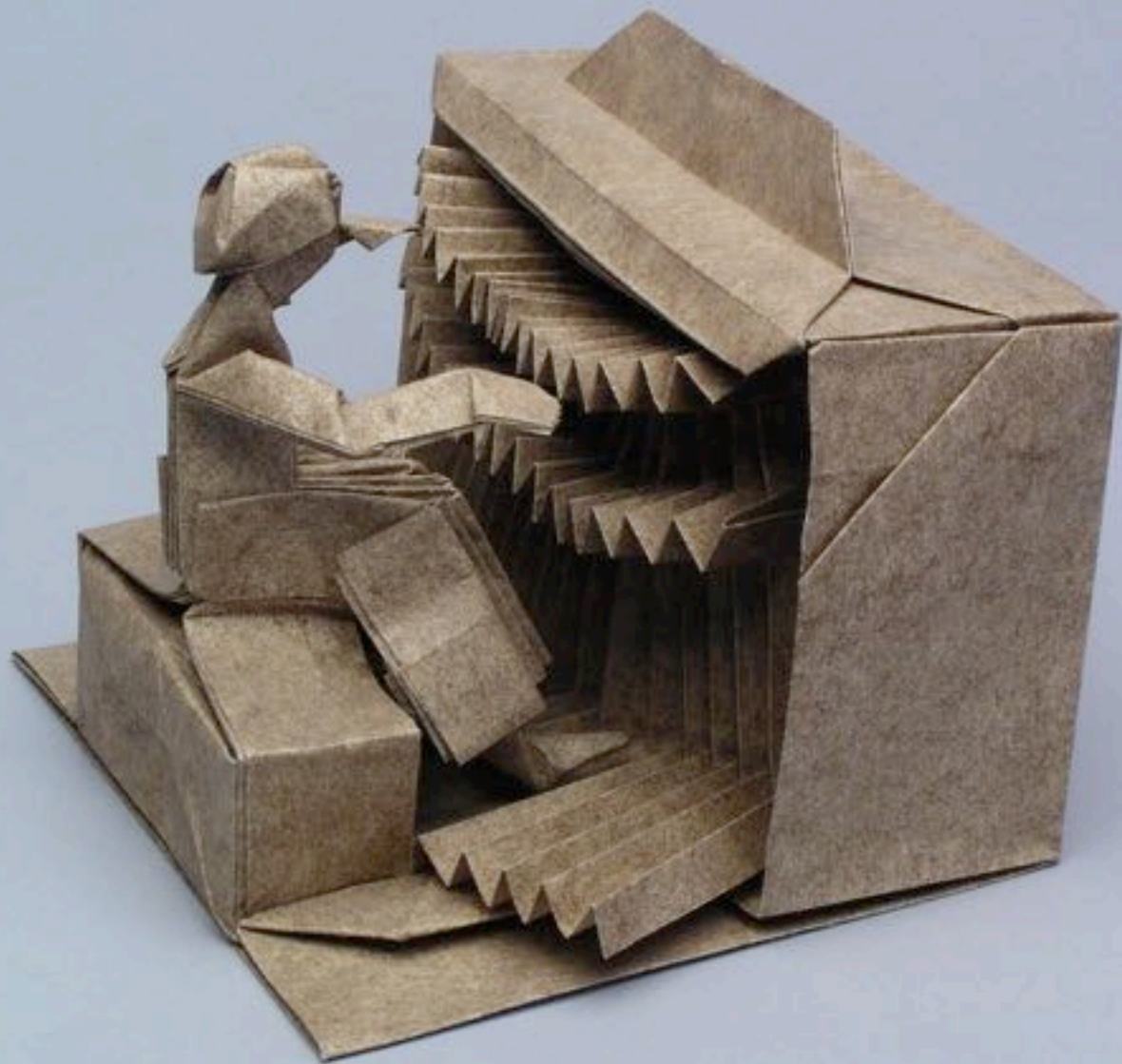
Tree Frog













Origami on Demand

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- Create “almost anything”
- graphics, advertisements, commercials



Its legend is well known.

Assembly +





Origami Software

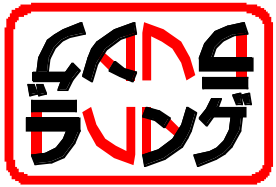


- TreeMaker (Lang) — shapes with appendages
- Origamizer (Tachi) — arbitrary surfaces
- ReferenceFinder (Lang) — finds folding sequences
- Tess (Bateman) — constructs origami tessellations
- Rigid Simulator (Tachi) — flexible surface linkages
- Oripa (Jun Mitani) — crease pattern folder
- BP Studio (Mu-Tsun Tsai) — shapes with appendages
- ...and more!



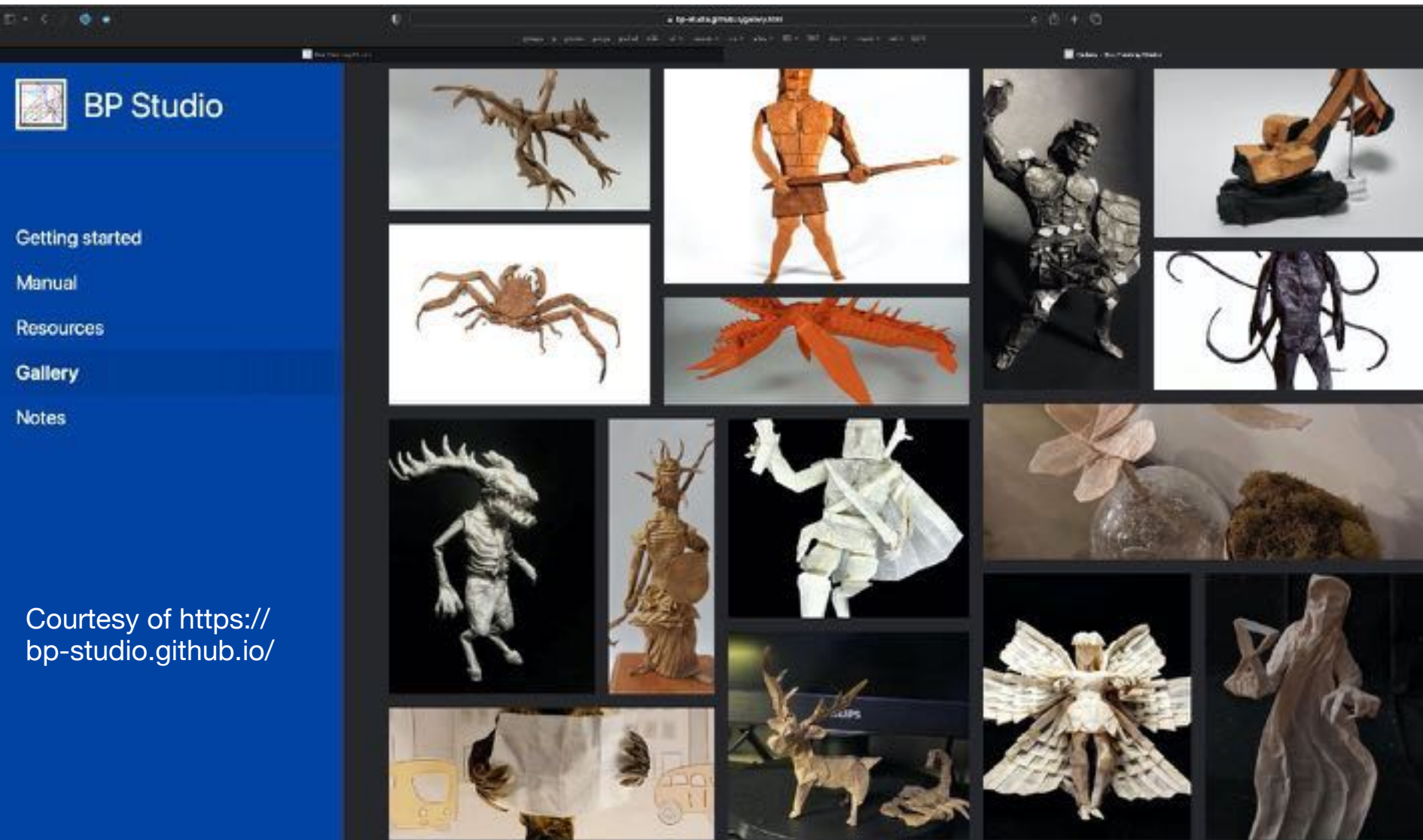
Box-pleating

- Origami design on a grid (pack squares, not circles)
- No computer needed! (Just use graph paper)
- But if you have a computer...
 - BP Studio, written by Mu-Tsun Tsai



BP-Studio Gallery

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ORIGAMI



Courtesy of <https://bp-studio.github.io/>



Tachi's Teapot (via *Origamizer*)

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ORIGAMI



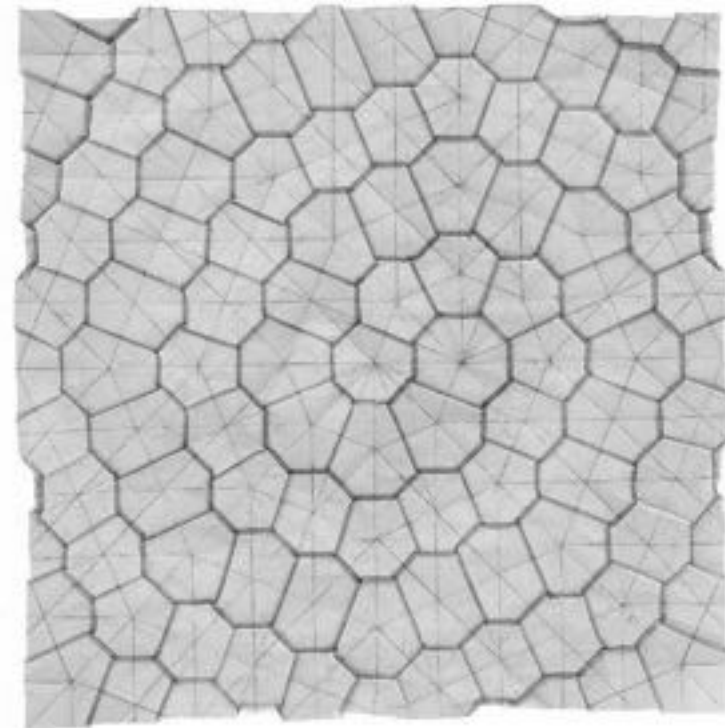
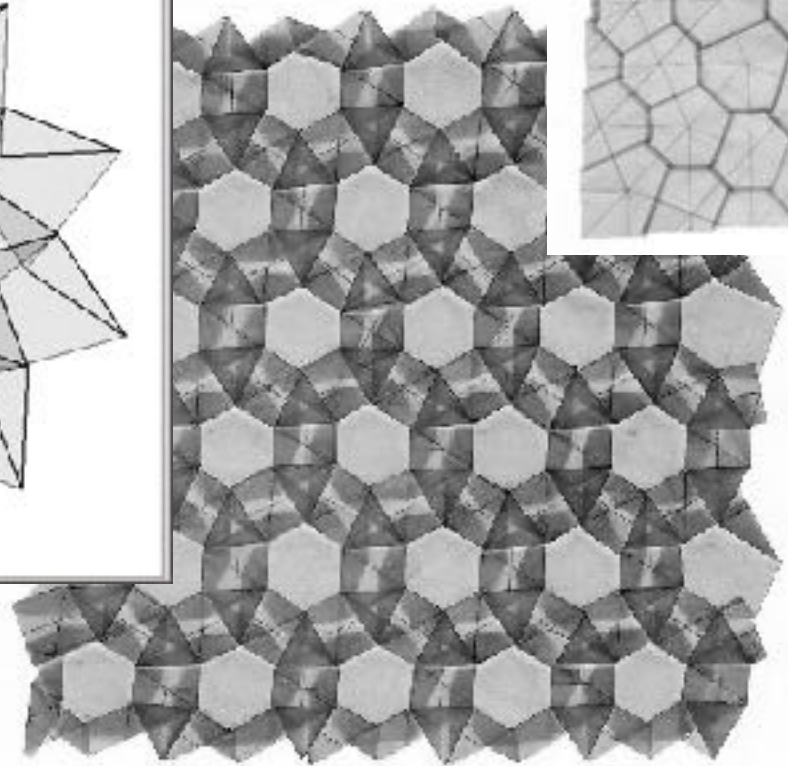
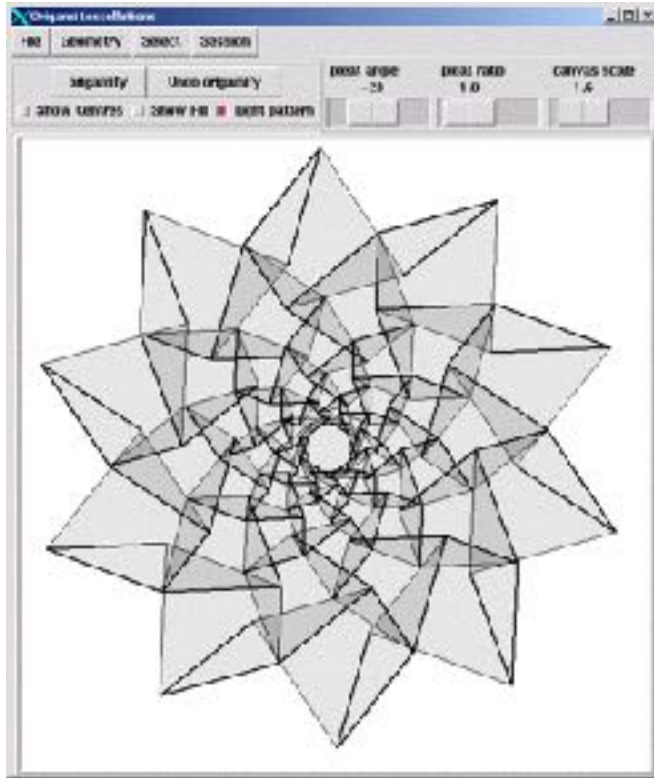
The "Utah teapot"



Computed crease pattern



Bateman's Tess





Geometric Origami

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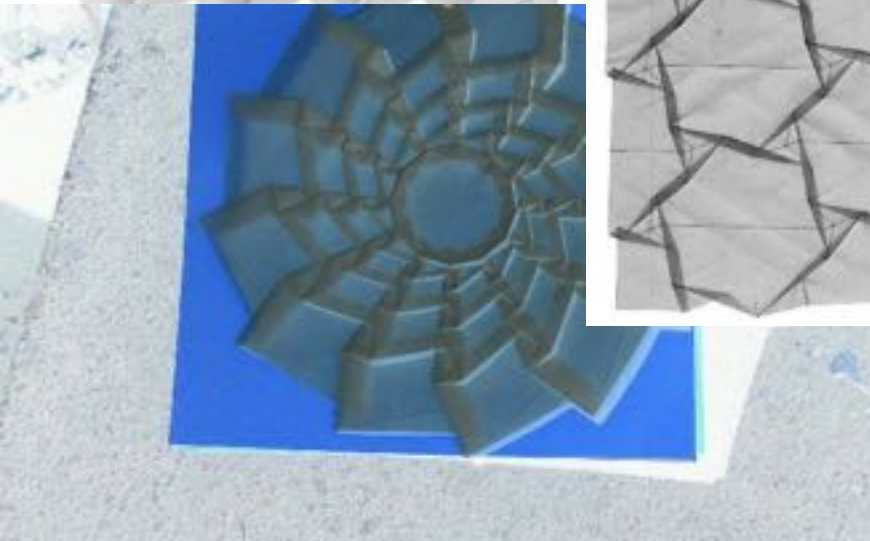
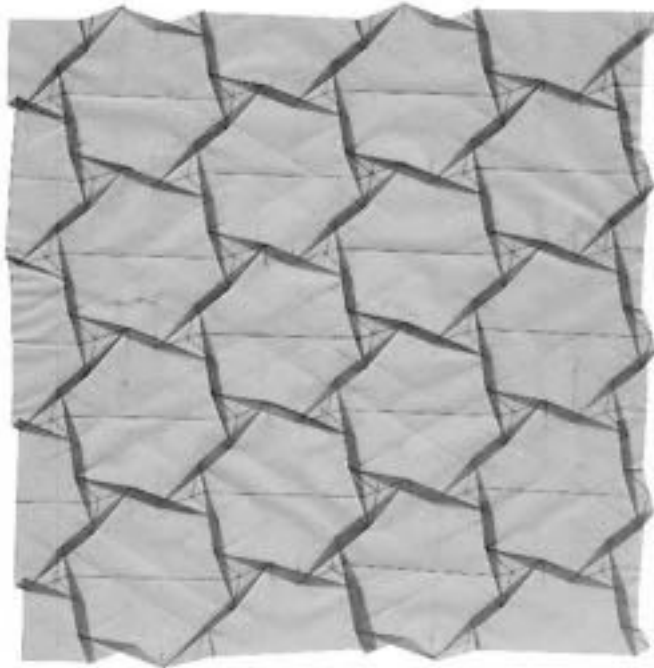
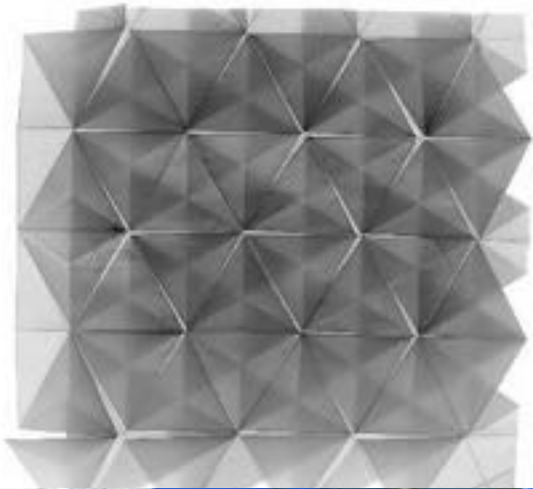
- Mathematical descriptions have permitted the construction of elaborate geometrical objects from single-sheet folding:
 - Flat Tessellations (Resch, Palmer, Bateman, Cooper, Gjerde)
 - 3-D faceted tessellations (Fujimoto, Huffman)
 - Curved surfaces (Huffman, Mosely)
 - ...and more!



Tessellation Examples

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- Examples from www.papermosaics.co.uk



Spiral Tessellation



Egg17 Tessellation

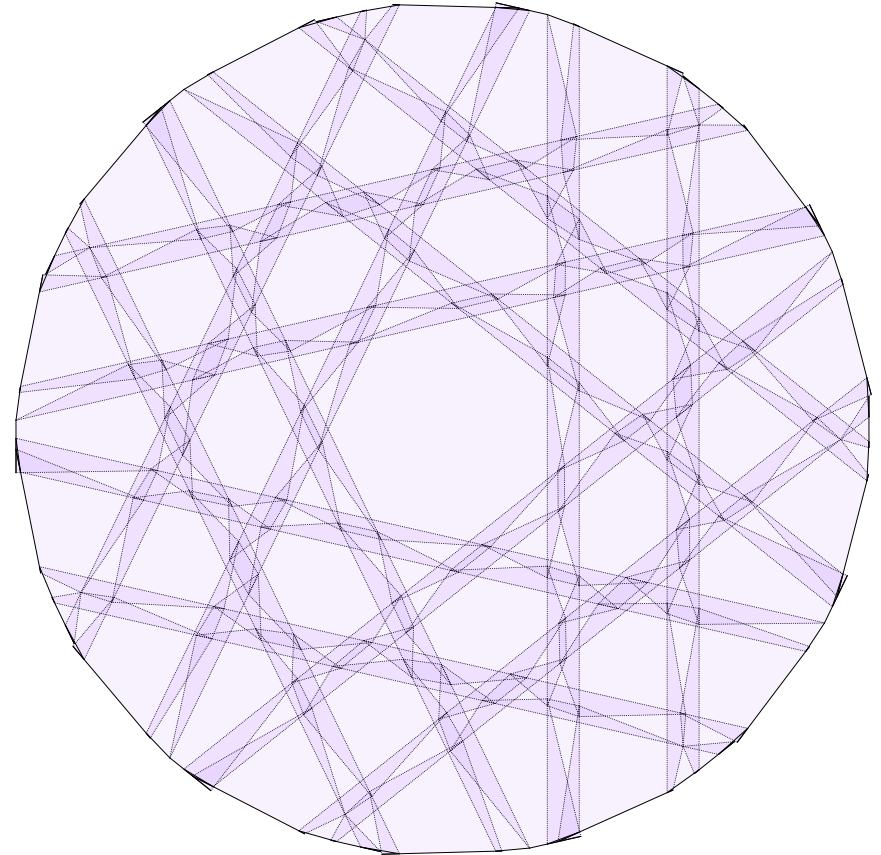
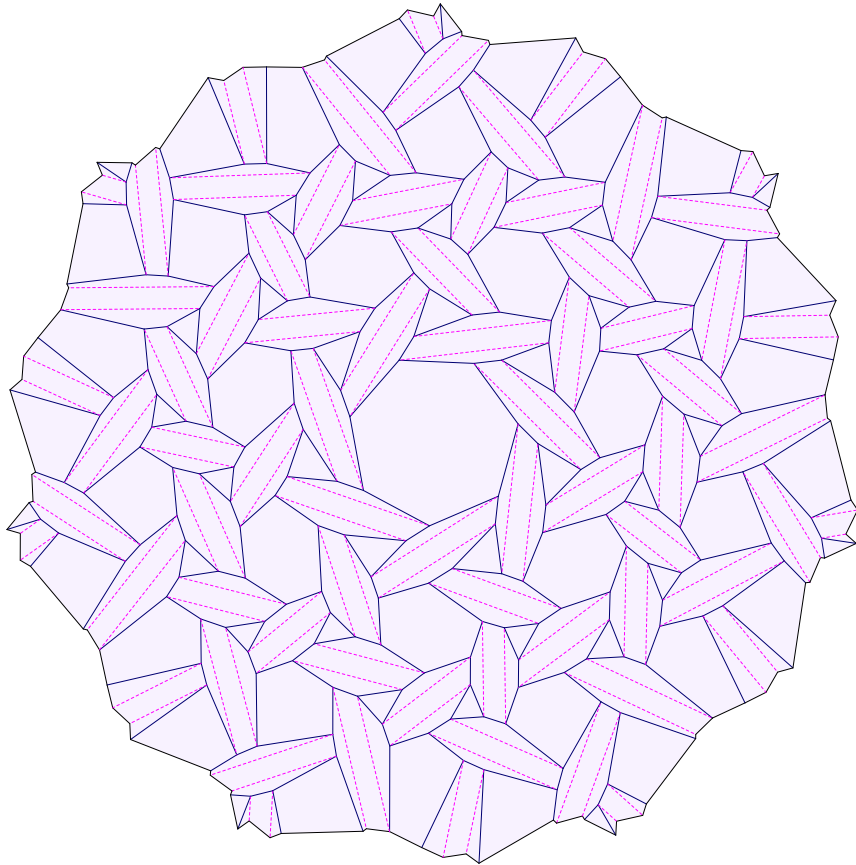






7-fold 2-layer CP & FF

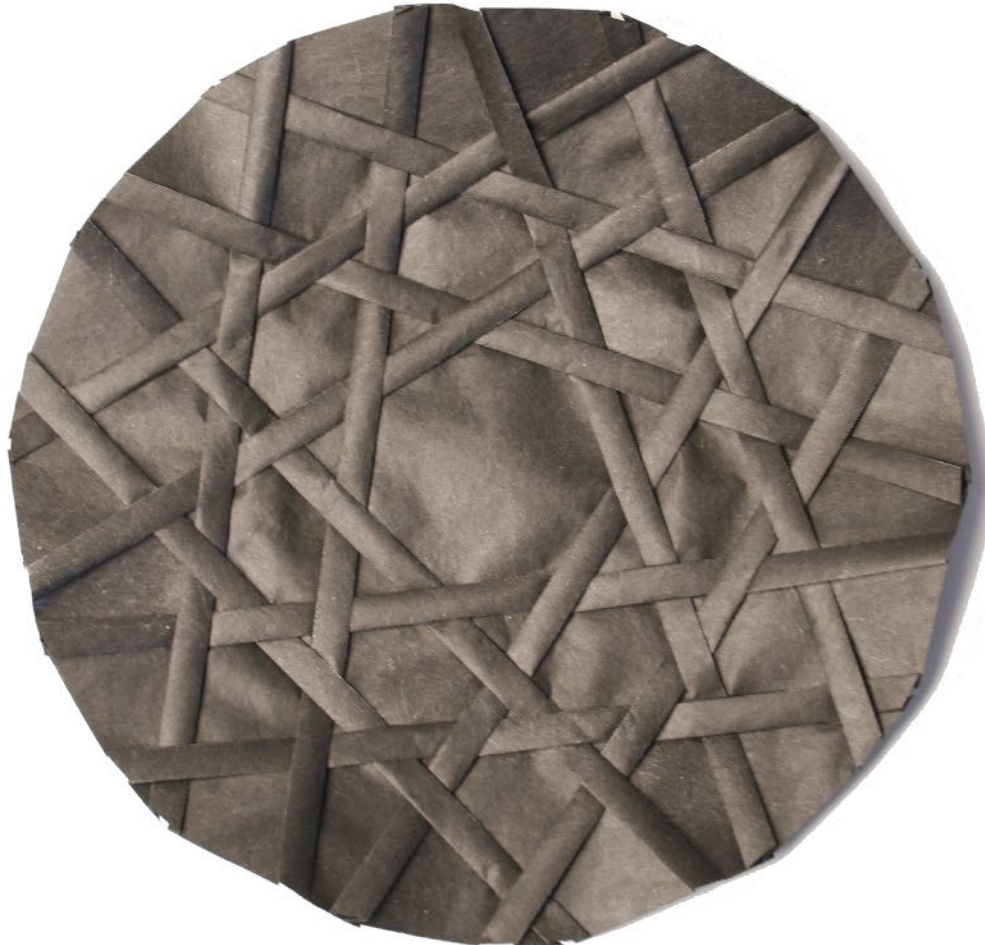
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7-fold 2-layer

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Generalizations

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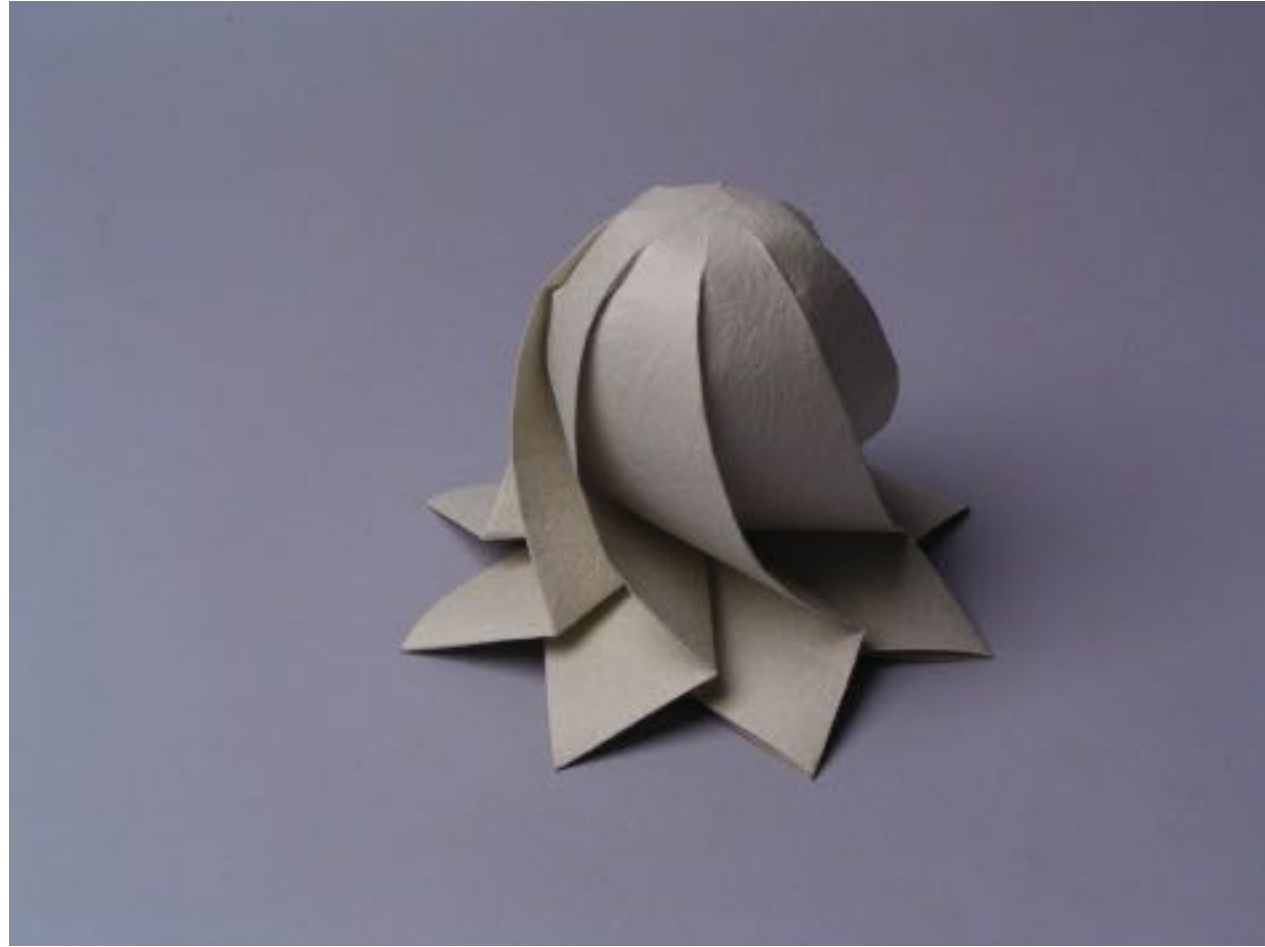
- 3D (non-flat)
- Curved folds
- Thick folds
- Stretching/deformation
- Needed for the Real World!



Flanged sphere

ROBERT J. LANG
ORIGAMI

- Concept demo'd by Palmer in 2000
- Inspiration for my generalization



ROBERT J. LANG
ORIGAMI











Ron Resch

- Computer scientist and artist Ron Resch designed (and patented) 2- and 3-D tessellations back in the 1960s
- See US Patent 3,407,588.

Fig. 10.

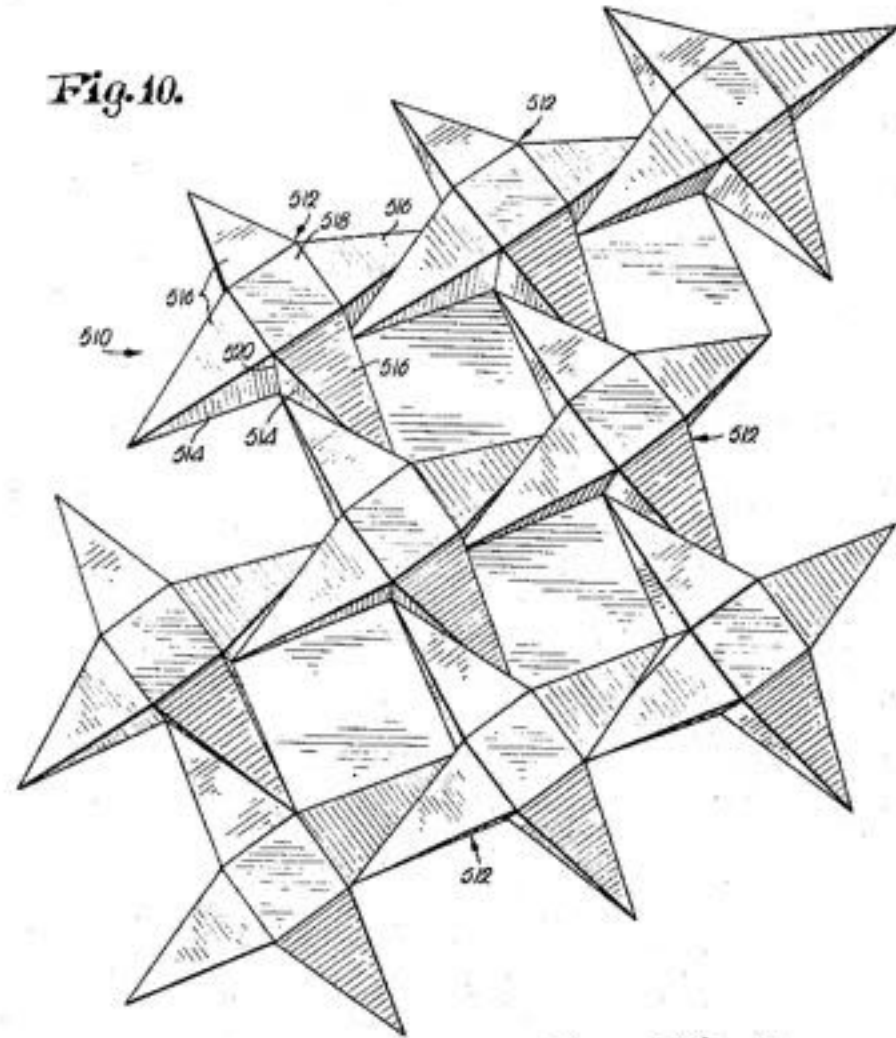
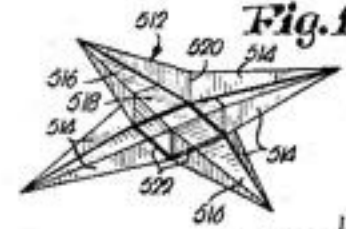


Fig. 11.



INVENTOR
Ronald D. Resch

Fig. 12.

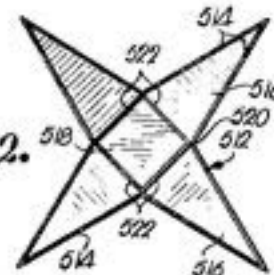




FIGURE VII. This composite windload based by a University of Utah professor and student K. C. Wilson, is a kind of bow. While the bow is copyrighted by its inventor, finger posing, the fingers may be held by a nationalistic buffoonism of the finger winks, thus allowing the bow to be embraced as an official.

Plate VIII. Three ultimate by R. Henry, University of Utah. One has effectively the smooth covering now to be employed, as well as have a single object, may be repeated with a given action.

Plate 16. *Enallagma cyathigerum* L. Ovary and the
abdomen of a larva and pupa.

Plate 5. Warrock also did some studies in specular reflection (reflecting light).

Plate XI. *Guadalupe* (4444) showing (1) Hole
(2) and (3) (see text).

Photo 2011. This mirrored glass does lack Pharo's highlight technique (see Fig. 10) and is thus probably another student's. Given transparency algorithms based on the work of N. Lischke fix the elements of Glass.

Plate XIV, page 498. Plates XV-XXIV, pages 500-511.

Salmonella *Salmonella*. These photographs are the work of the author, Vincent S. Riquelme, Professor, University of Utah, with photography assistance from K. Gates. All of the images are computer renditions of single- or double-exposed three-dimensional models. These data represent the most complete 3D images that have been obtained to date. Some being captured, as in animal models, *Salmonella* (left); others being taken, as in human patients, *Salmonella* (right). Images taken, as in the case of *Salmonella*, and of several other bacterial pathogens, are available for download from our website, www.3d-salmonella.org. For information, please visit www.3d-salmonella.org.

Photo 20 This is an iteration of the idea seen in Photo 2.XIII of a road structure to guide users down structural obstructions. The program also allows the user to change and observe the width of the road at its height off the ground plane, with a few variations, and to move through it (Photos 2.XIII and 20.03V).

Male 200. A class of evolution from 18 to 1984 (see Table 1) and 1984 (see Table 1).

Plate XXIII. An oblique view looking up of

Plate 2M11. Transverse view of the inflexure of the fore- to fifth NIV, which is one form of a folded edge on a cylindrical body.

Plate X.3. The design prompts the author's technique for plotting mixed results from a single event with values on the physical base-line graphic of each strip is lost, even as the results are taken.

FIGURES XX and XXI. Engravings of additional variations of developable surfaces with double principal curvatures.

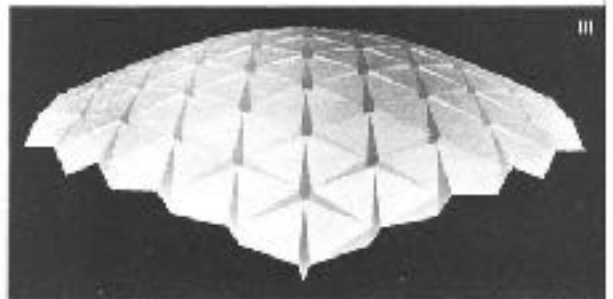
Plates XXXI and XXXIV. From a series of mounted long exposure views of a variation of this structure (Plates XXV and XXIII) as might be seen by an observer traveling through it, with slow suggestion of scale change.

Page 662

Plates XIV–XXIII. The work of Dr. H.

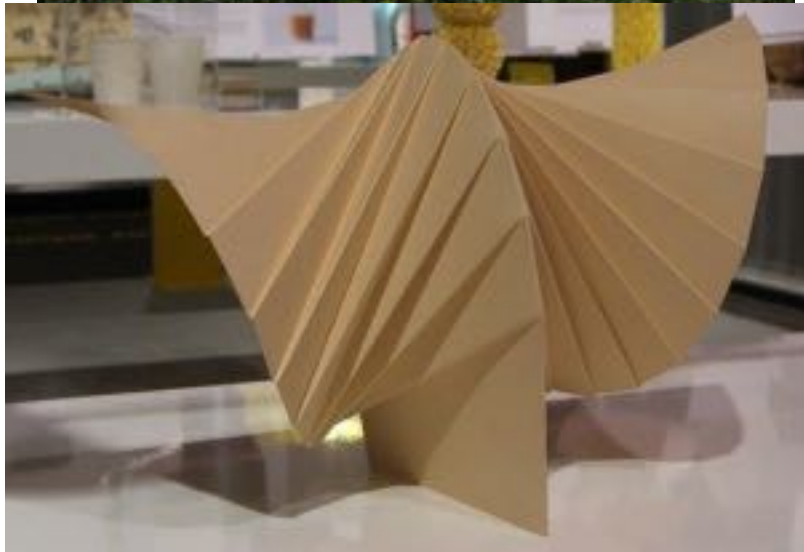
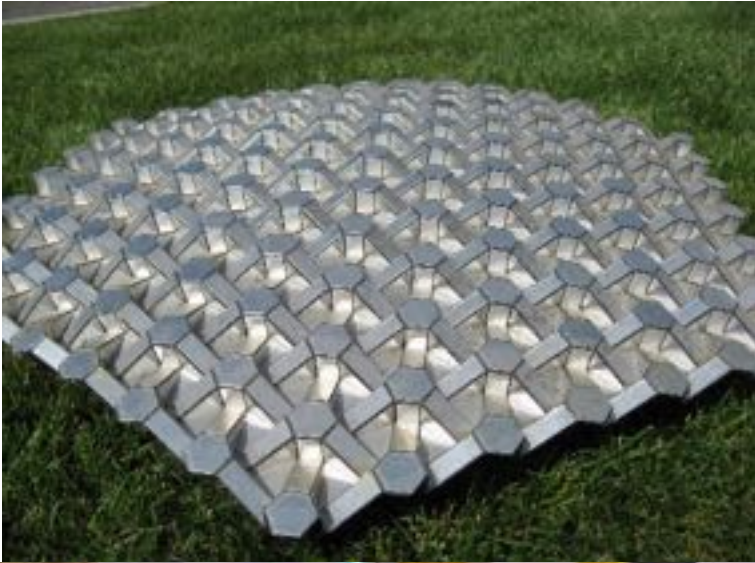
Christiansburg, University of Idaho. He has published papers on the following topics: the relationship between the structural properties of various independent training and bounding stimuli; properties of an object are suggested by state a collection of the visual shape. (Dance X200 and X2010).

Notes XXIX-XXXII. These patterns represent the only work in this gallery not previously included in the University of Utah. The patterns, produced by MAGE Columns, are good examples of abstractions in judiciously defined objects.



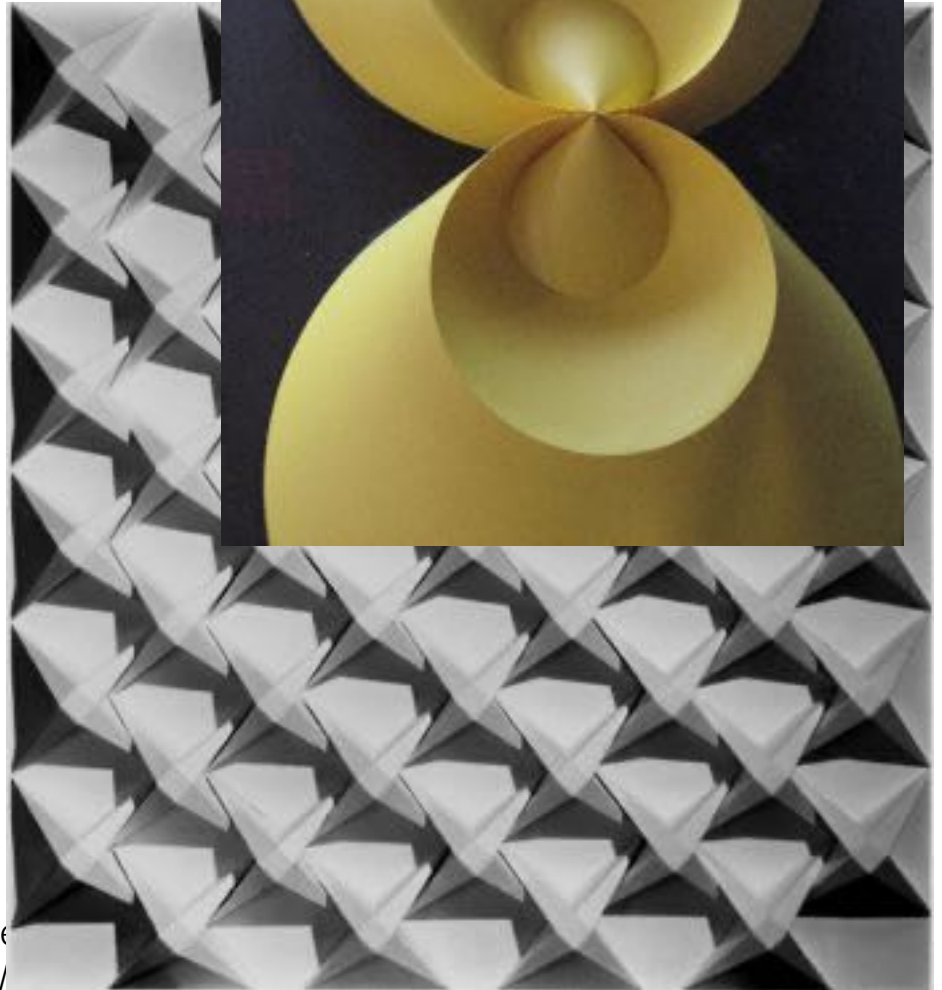


Ron Resch



Acade

May 2024 | V





David Huffman

- Developed both faceted and curved forms
- Is almost unknown in origami
- But is famous in computers (Huffman Codes)



- reconstruction of original David Huffman design







Applications in the Real World



- Mathematical origami has found many applications in solving real-world technological problems, in:
 - Space exploration (telescopes, solar arrays, deployable antennas)
 - Automotive (air bag design)
 - Medicine (sterile wrappings, implants)
 - Consumer electronics (fold-up devices)
 - ...and more.



Miura “map-fold”

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ORIGAMI

- A map of Venice with one degree of freedom



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Miura-Ori, by Koryo Miura

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- First “origami in space”
- Solar array, flew in 1995





Solar Sail

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ORIGAMI

- Japanese Aerospace Exploration Agency
- Mission flown in August 2004
- First deployment of a solar sail in space





Solar Sail

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ORIGAMI



<http://www.isas.jaxa.jp/e/snews/2004/0809.shtml>



James Webb Space Telescope

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- Multiply segmented mirror folds into thirds

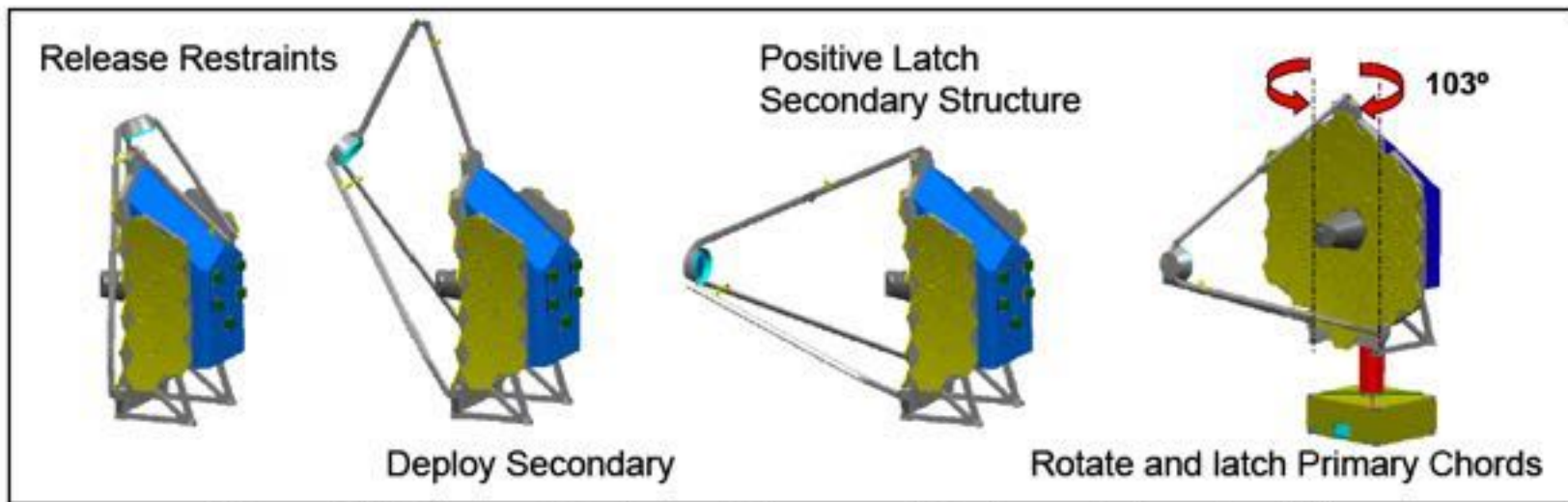
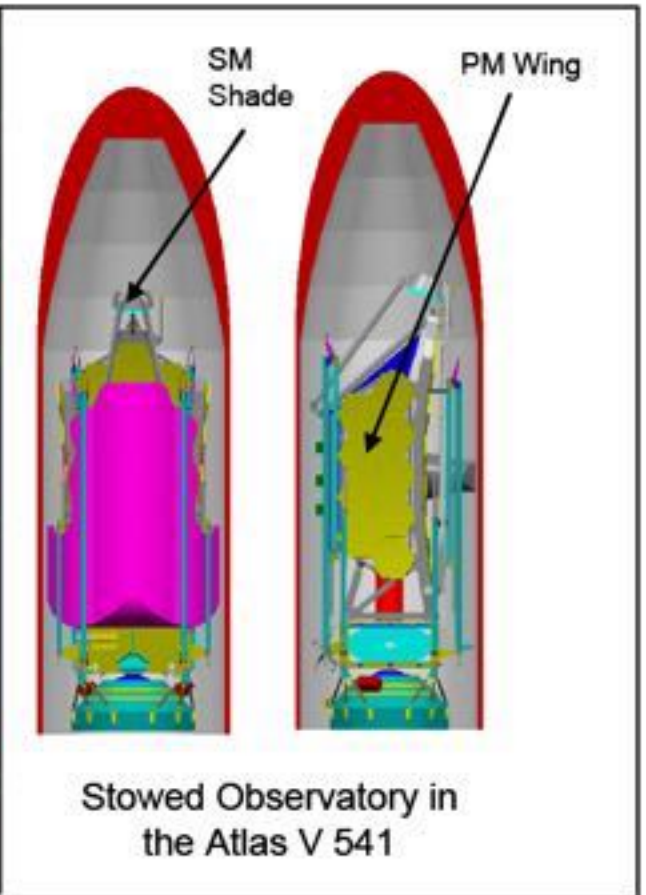
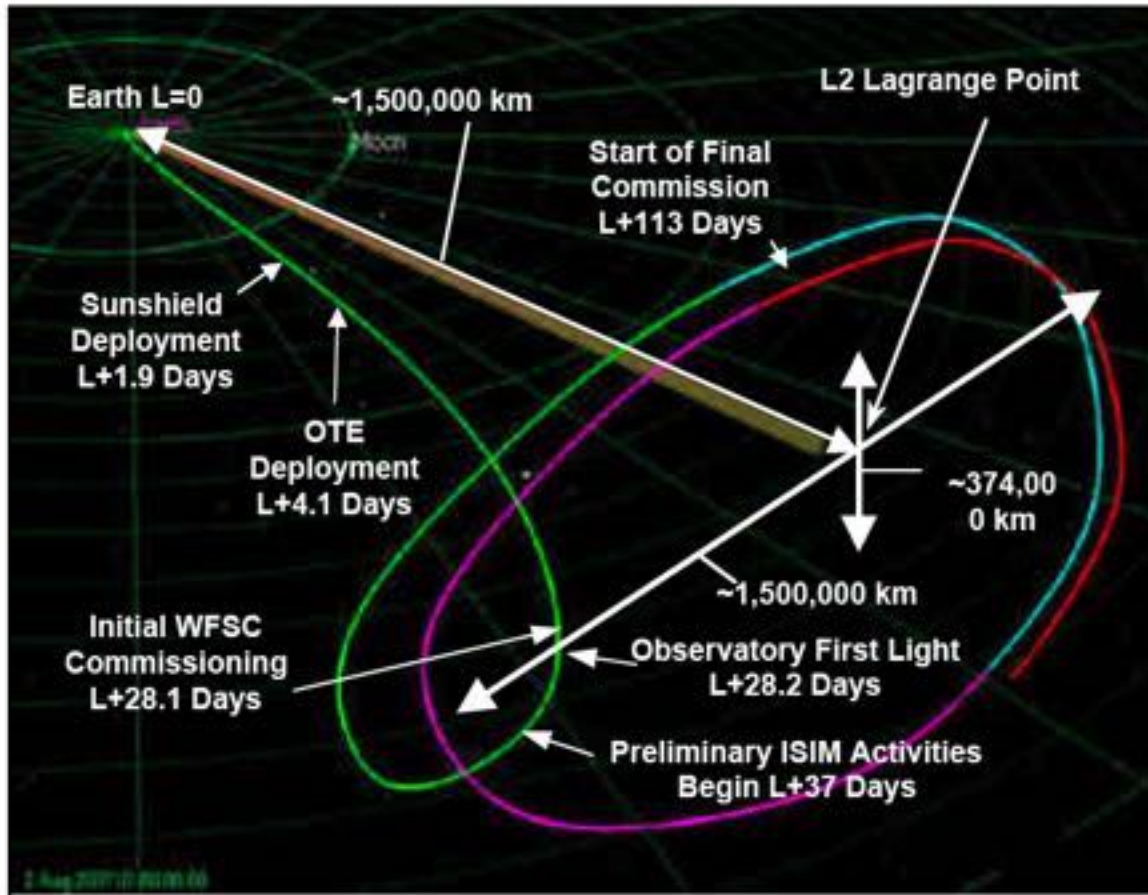


Figure 10. Telescope Deployment Sequence (Deployment steps 4 and 5)



JWST Stowage

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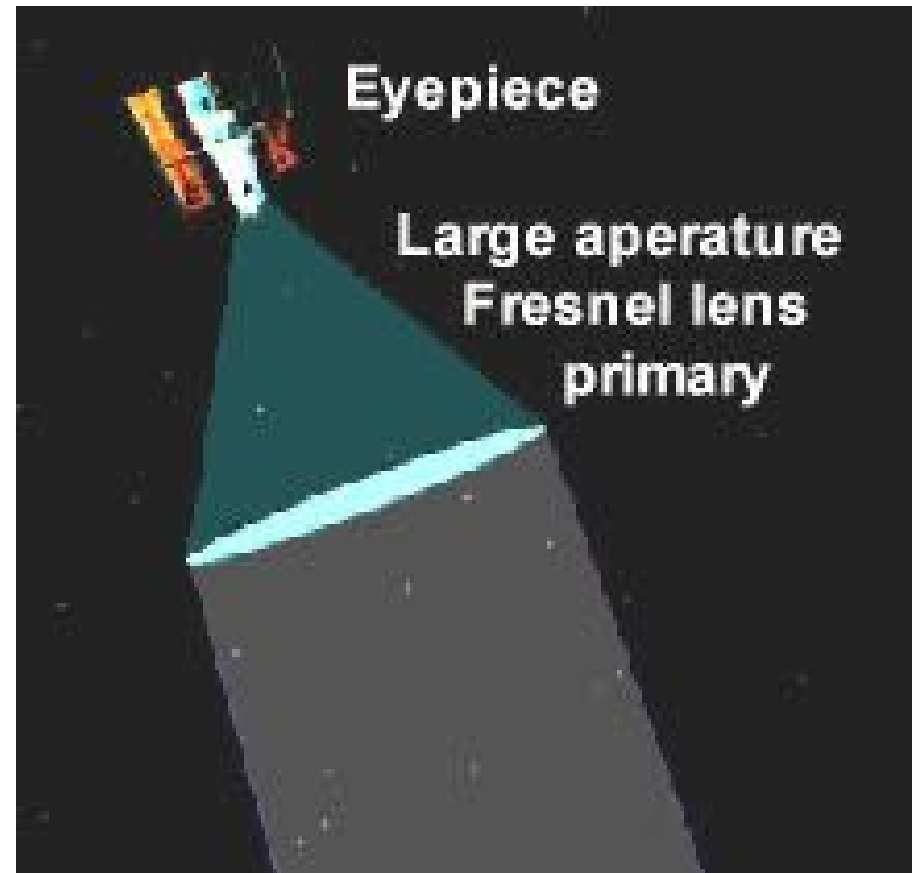




The “Eyeglass” Telescope

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ORIGAMI

- Lawrence Livermore National Laboratory
- Geostationary orbit
- 100 meter diameter (a football field)





The lens and the problem

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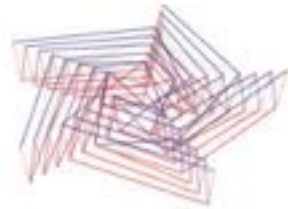
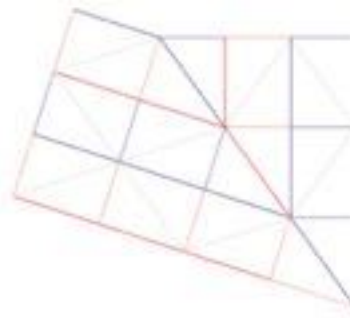
- The 100-meter lens must fold down to 3 meters





Analysis

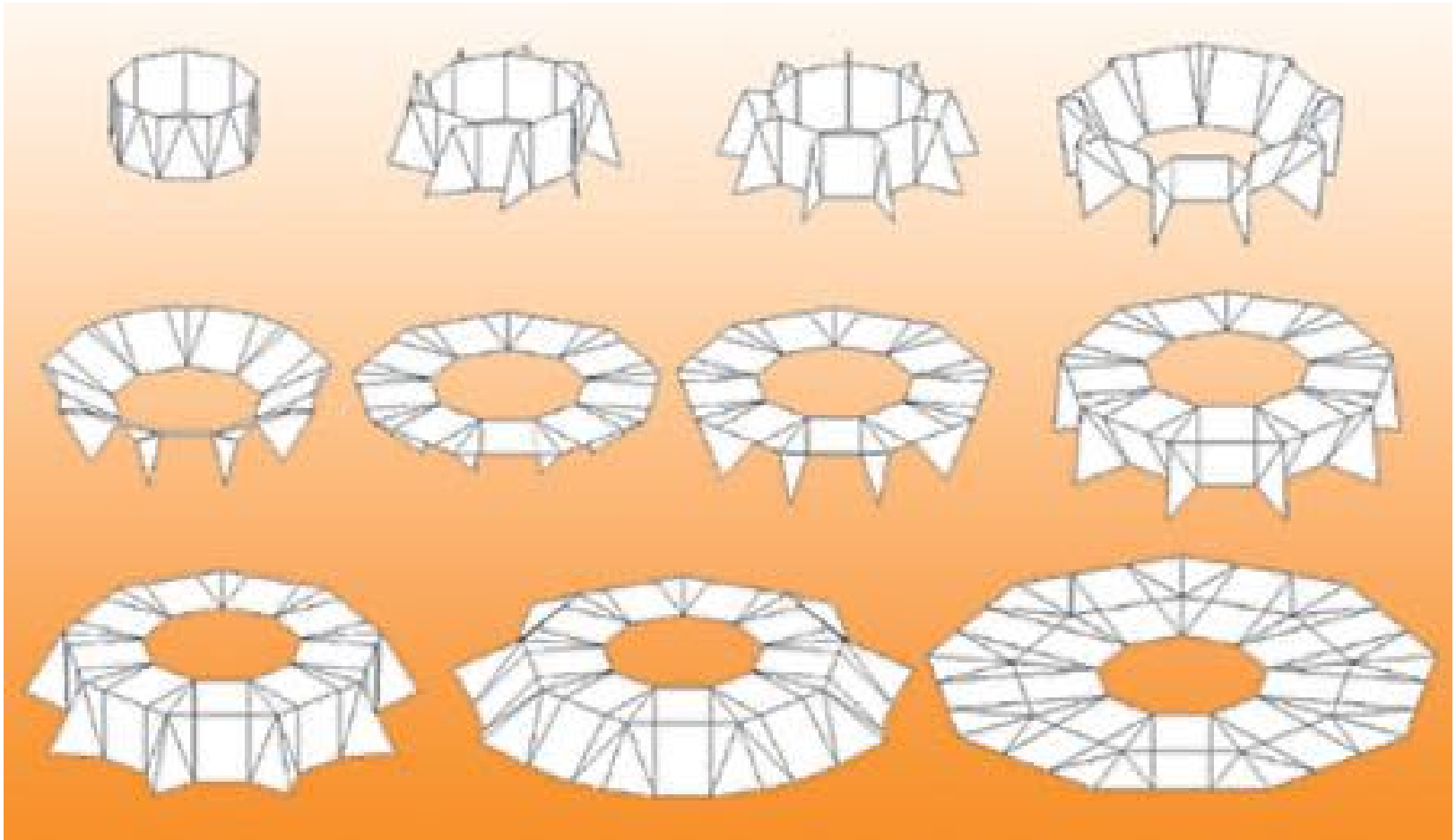
- Analyzed several families of collapsing structures, including “flashers” and umbrella-like patterns
- Initial modeling in Mathematica™ solving NLCO that enforce isometry between folded and unfolded state, followed by 3D modeling at LLNL





Umbrella

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Foldable 3.7 meter Eyeglass

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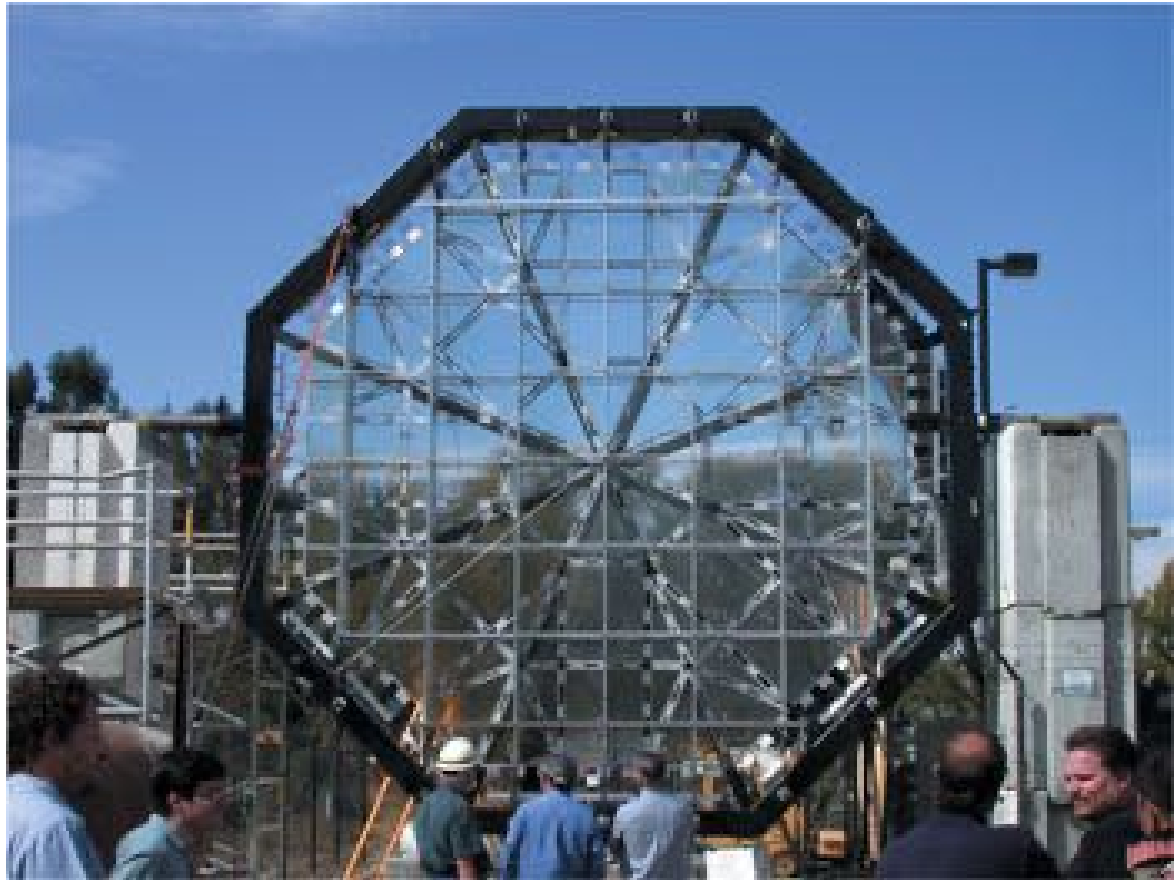




5-meter prototype

ROBERT J. LANG
ORIGAMI

- The 5-meter prototype folds to about 1.5 meter.

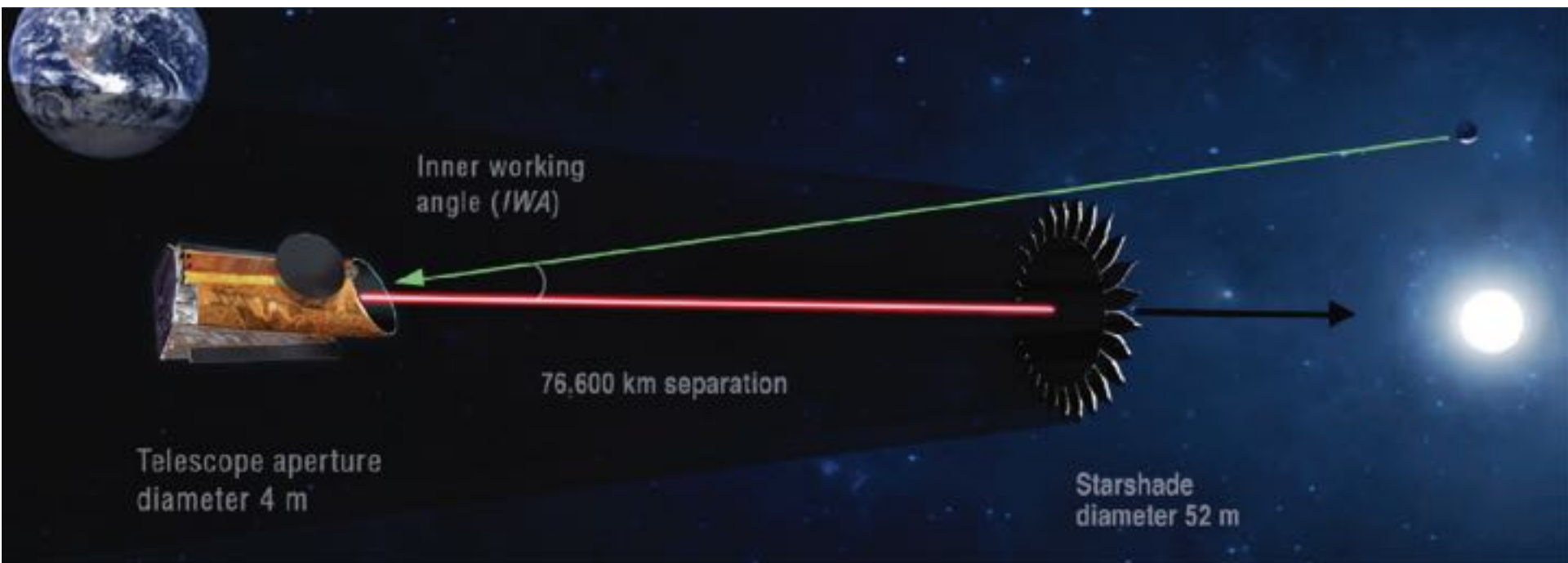




Starshade

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ORIGAMI

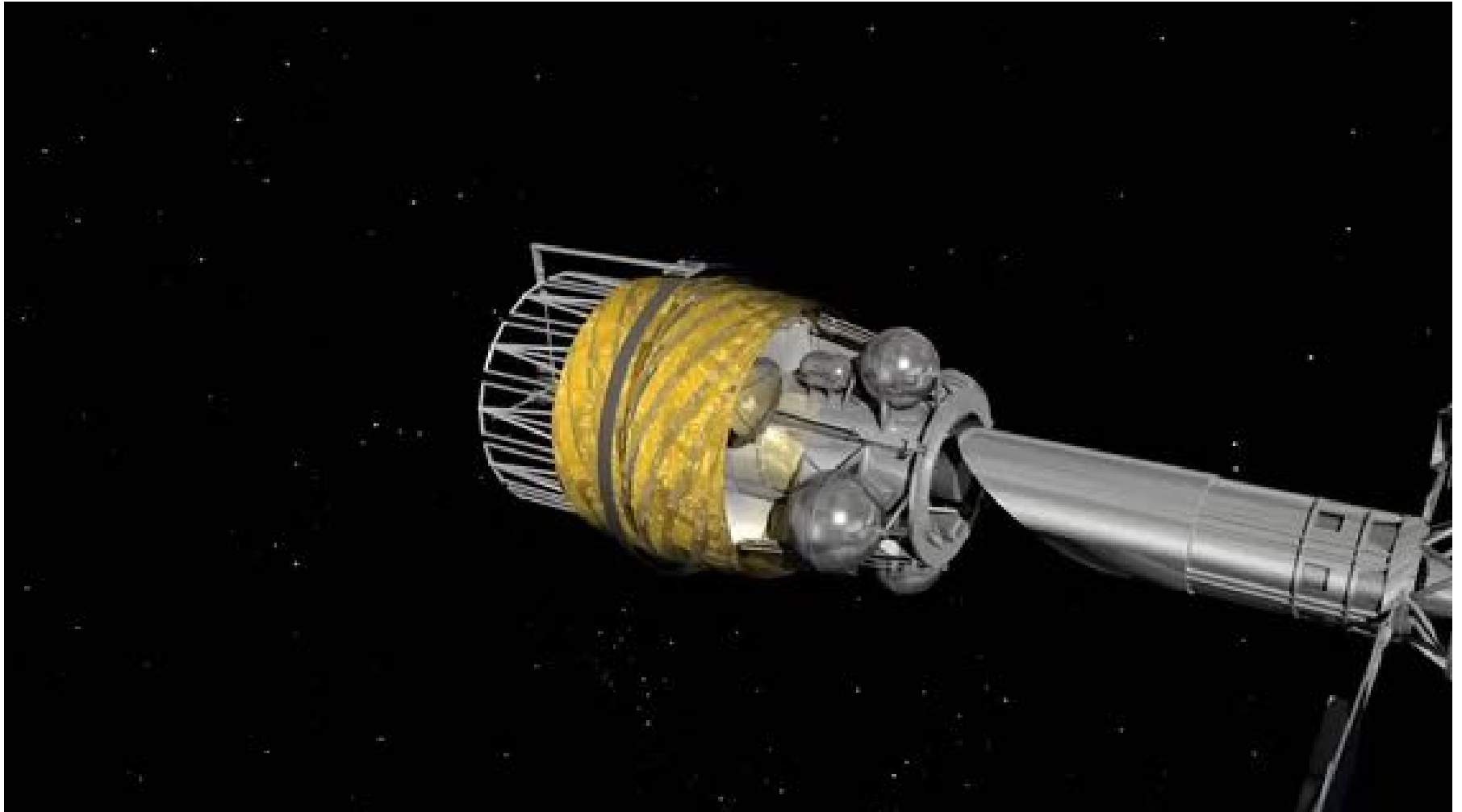
- A space-based telescope to seek extrasolar planets





Deployment

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JPL - Starshade

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ORIGAMI

- 52 m occulter to fly in formation with a telescope to search for extra-solar planets

Courtesy of Manan Arya, JPL

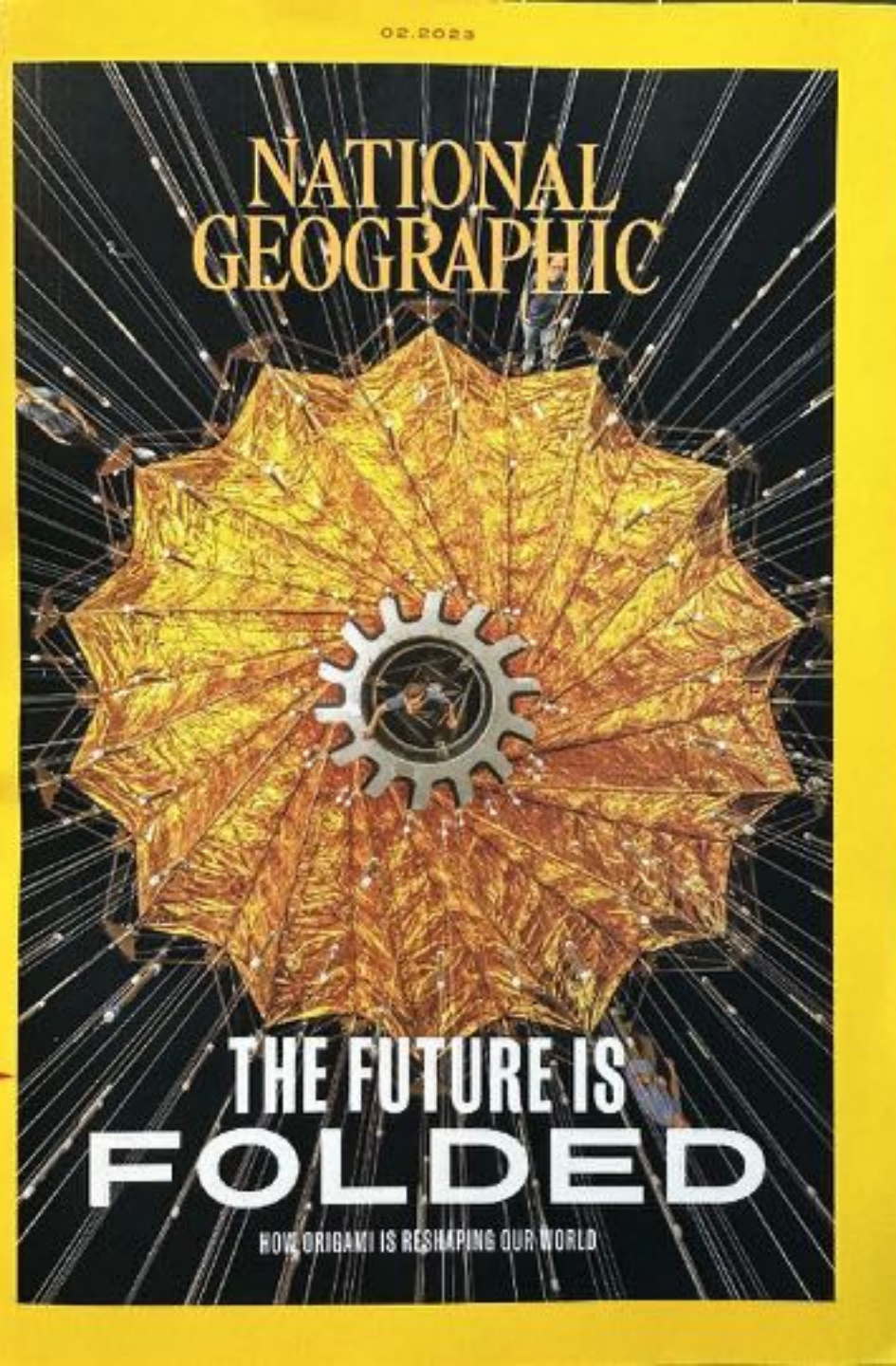




Video courtesy of Manan Arya, NASA/JPL



- February 2023 National Geographic cover feature



National Academies
May 2024



Inflatable Mast : Origami

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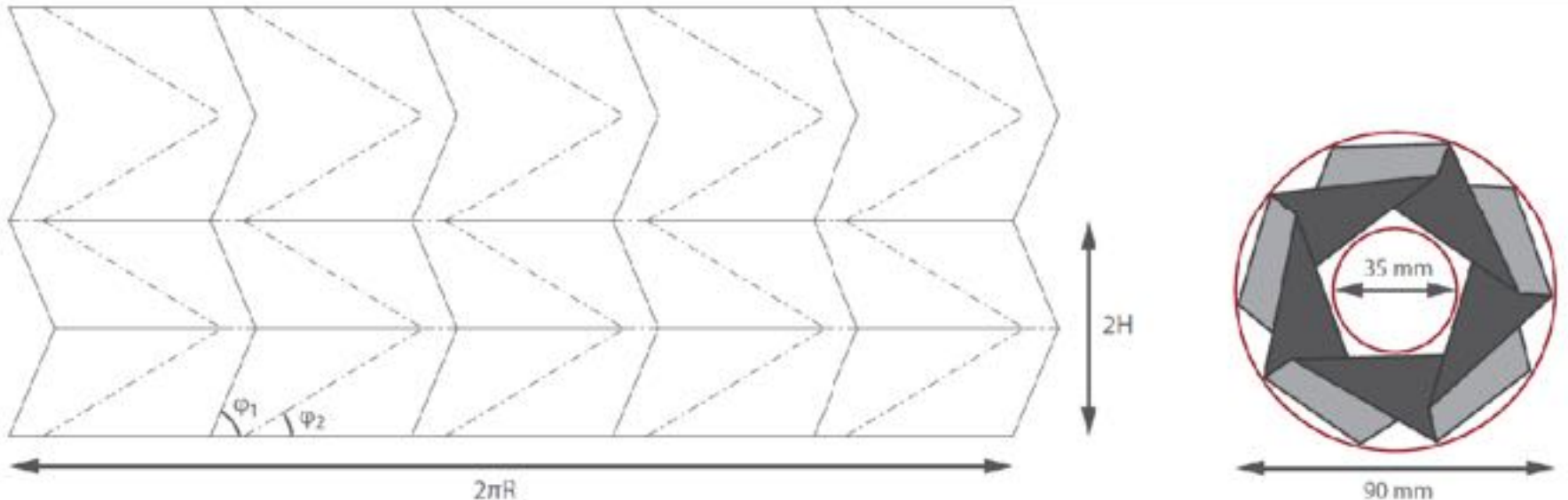
Work by Mark Schenk, Surrey Space Center, Surrey, UK

• Selected Fold Pattern

The selected fold pattern for the inflatable boom:

$$D = 90 \text{ mm} \quad n = 5 \quad \varphi_1 = 67^\circ \quad H/R = 0.67$$

The pattern was selected for minimal material deformation, small outer diameter, large open cross-section, and foldability.



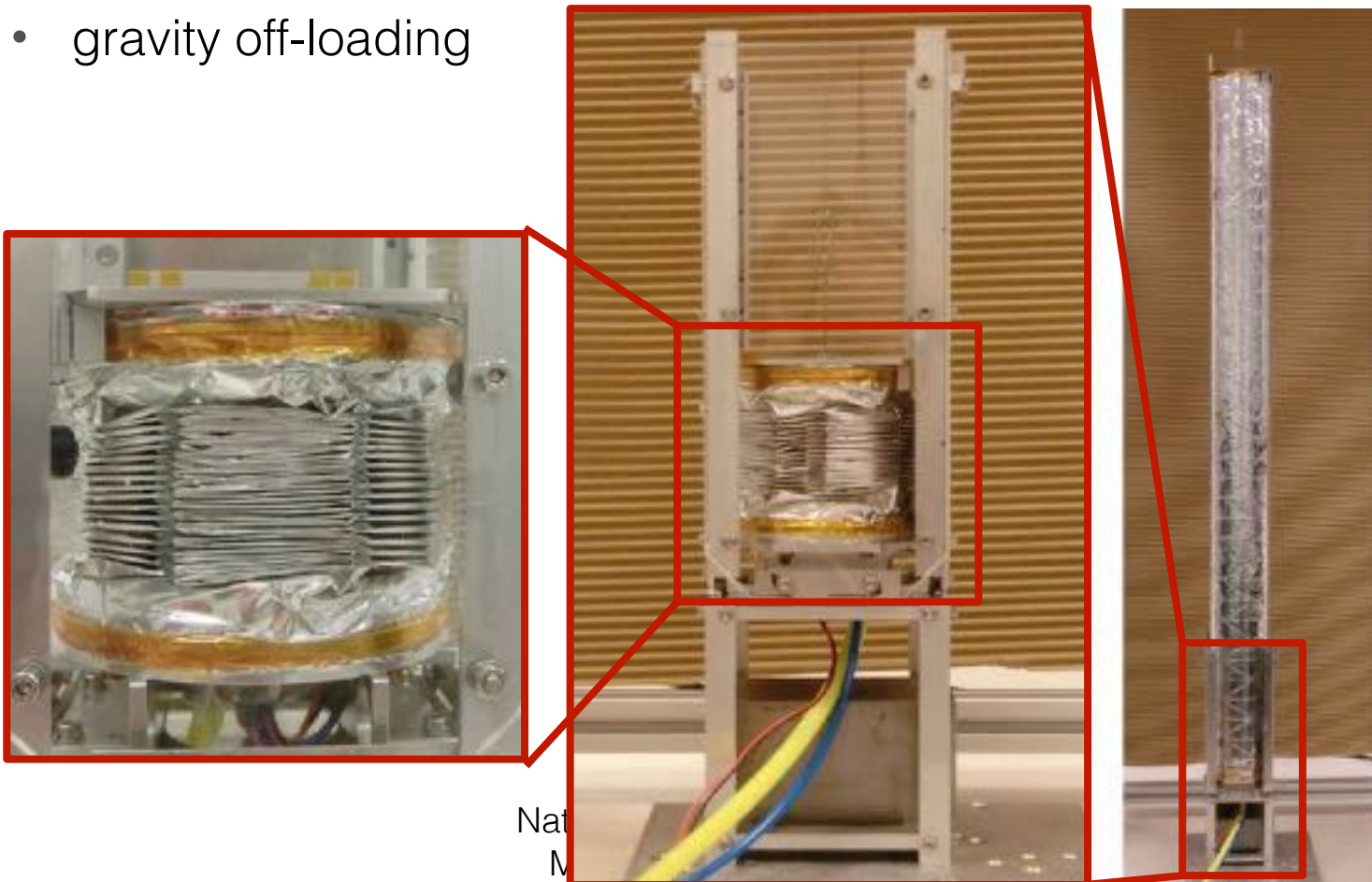


Inflatable Mast : Manufacture & Testing

ROBERT J. LANG
ORIGAMI

Boom Deployment Testing

- reliable deployment in ambient & vacuum conditions
- gravity off-loading



Nat
M



Oru Kayak

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ORIGAMI



Images courtesy of orukayak.com





Twist Bottle

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- Twist bottle by James Hart (2009)



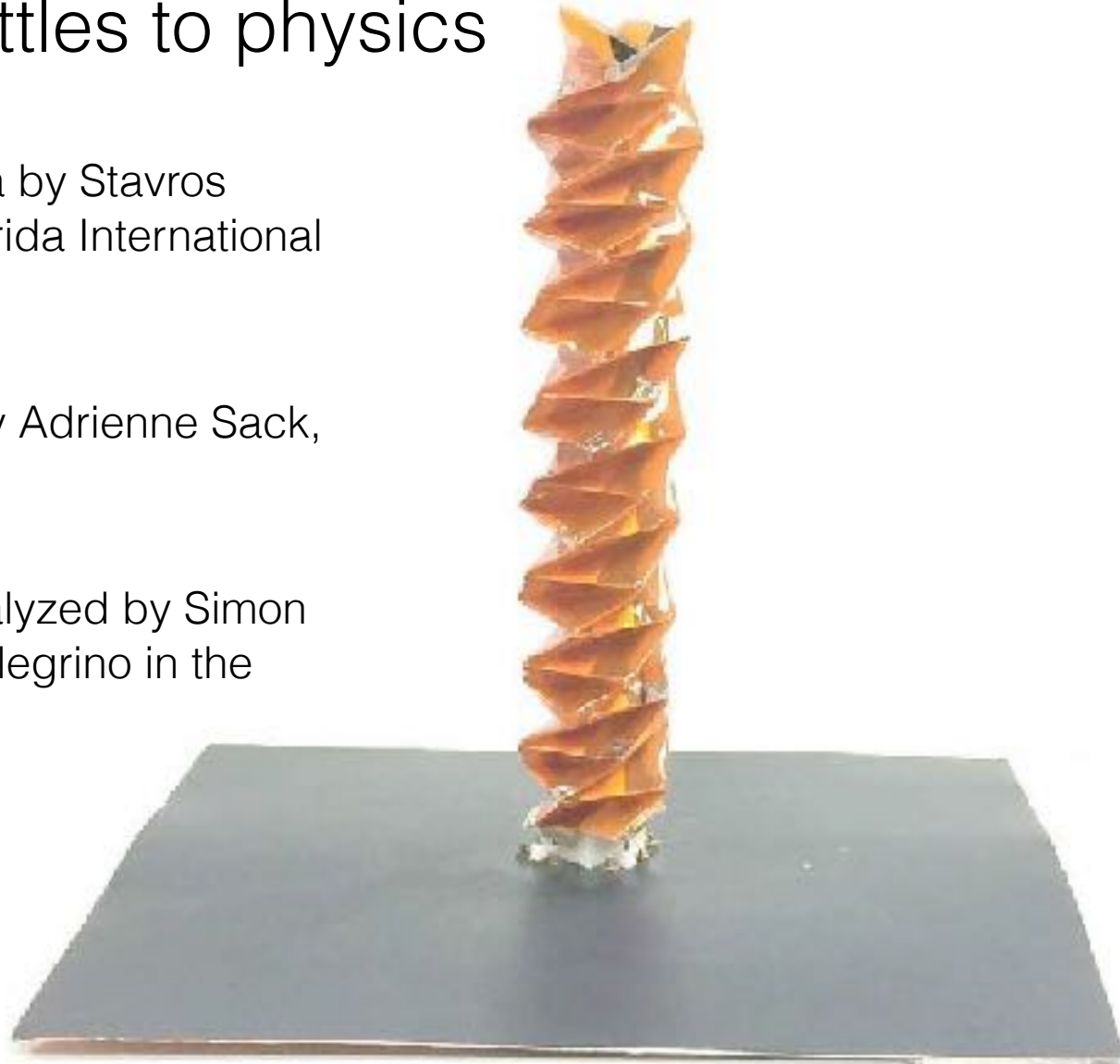
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From bottles to physics

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- —Microwave antenna by Stavros Georgakopoulos, Florida International University
- —Fashion designs by Adrienne Sack, Uyen Nguyen
- —Mathematically analyzed by Simon Guest and Sergio Pellegrino in the 1990s

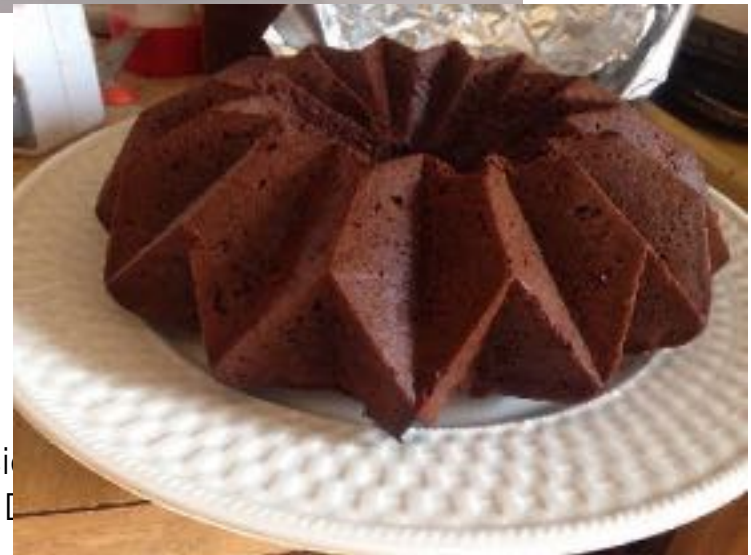
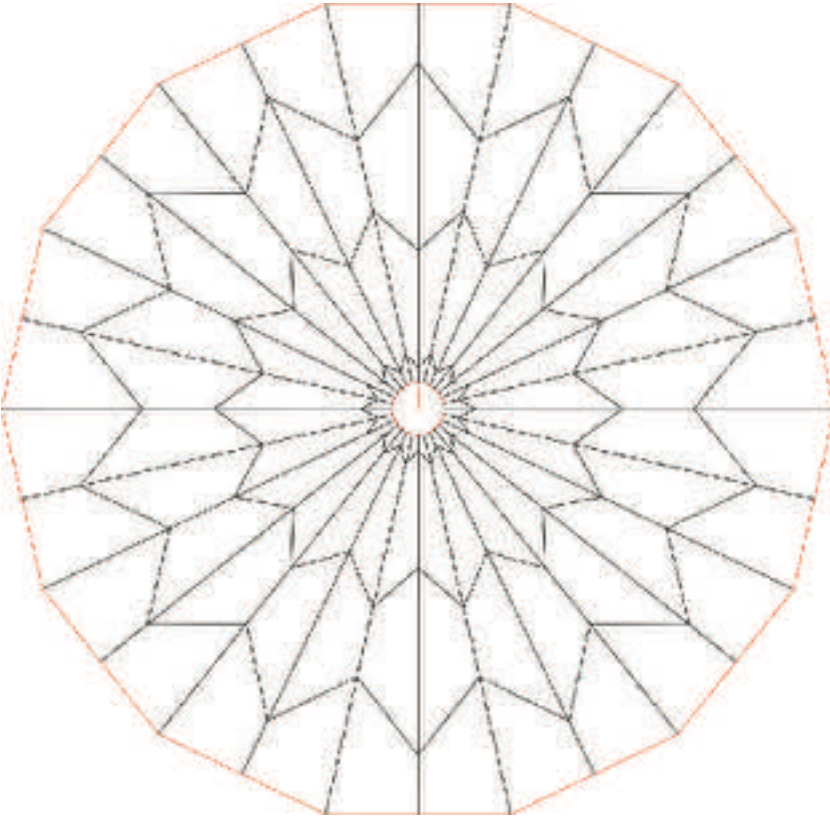


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...to food

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Courtesy of David Morgan,
Brigham Young University

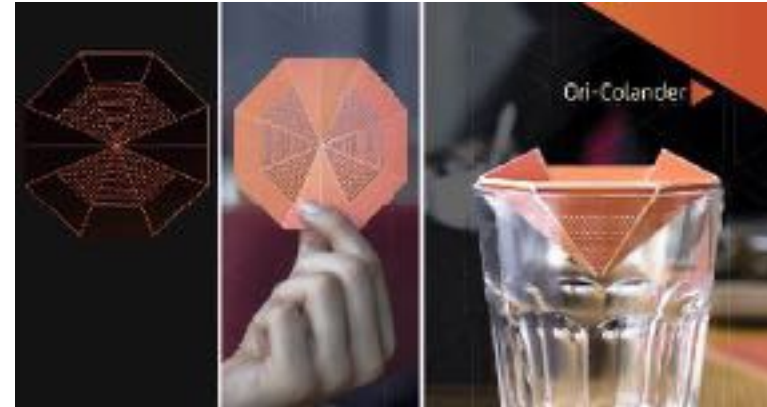
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Ori-Kit folding utensils

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- Fold-up measuring spoons, colander
- “Small for storage, large at destination”



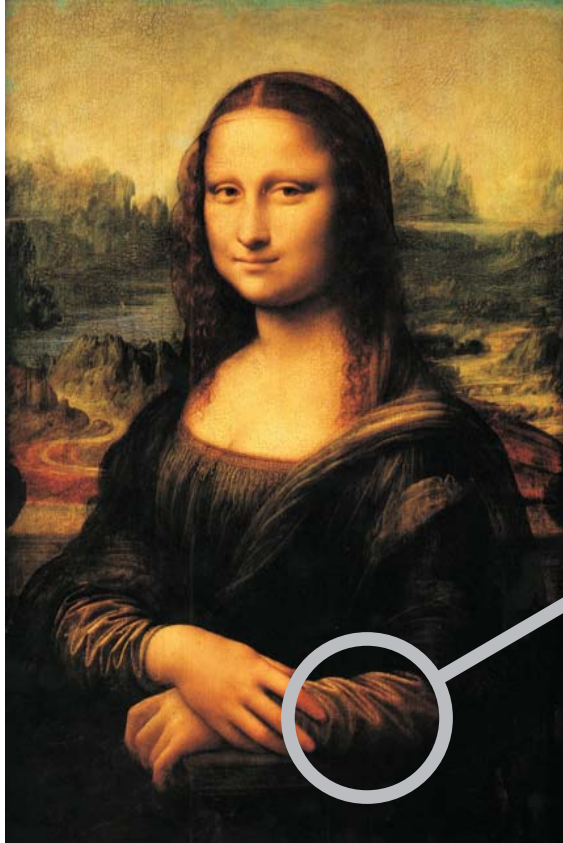
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Courtesy of CrowdCreate,
<http://crowdcreate.us/ori-kit>



Folded concepts are timeless

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ORIGAMI



Soft drink can design by Koryo Miura



Lamps

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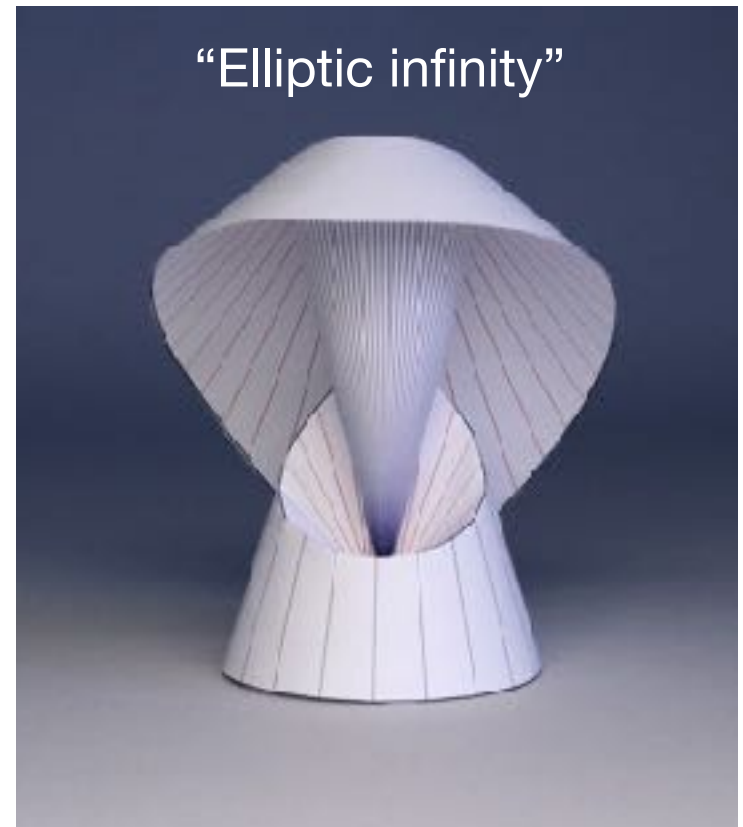
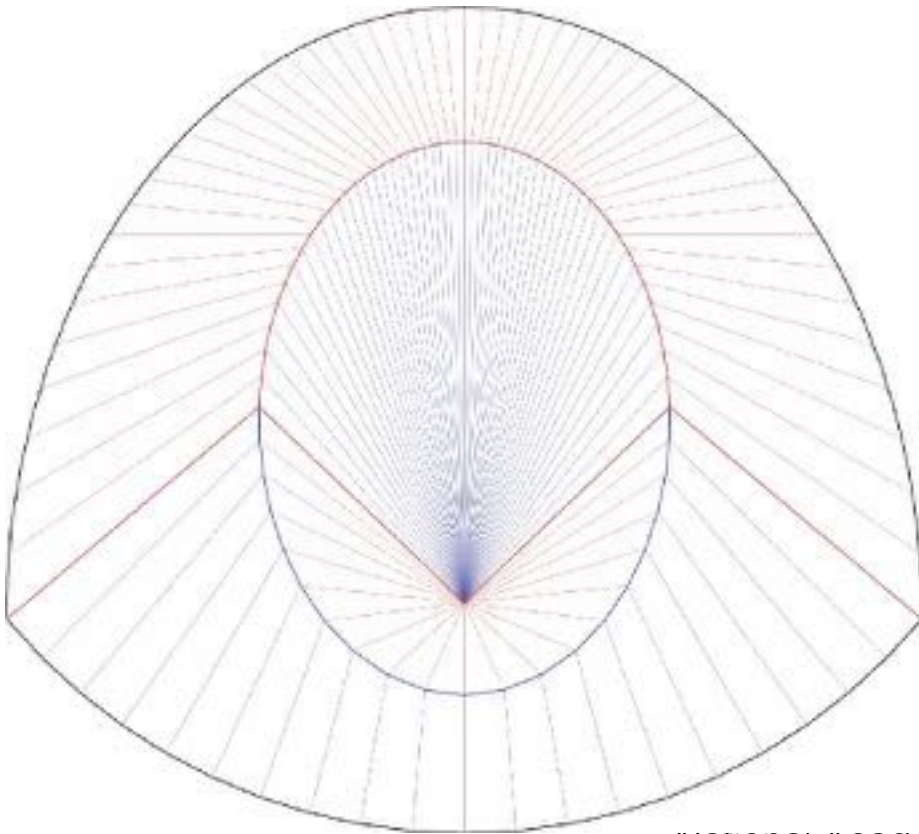
courtesy of Yuri and
Katrin Shumakov



Curved folding optics

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- Conic-section curved folding first explored by David Huffman
- Ruling lines refract like rays of light



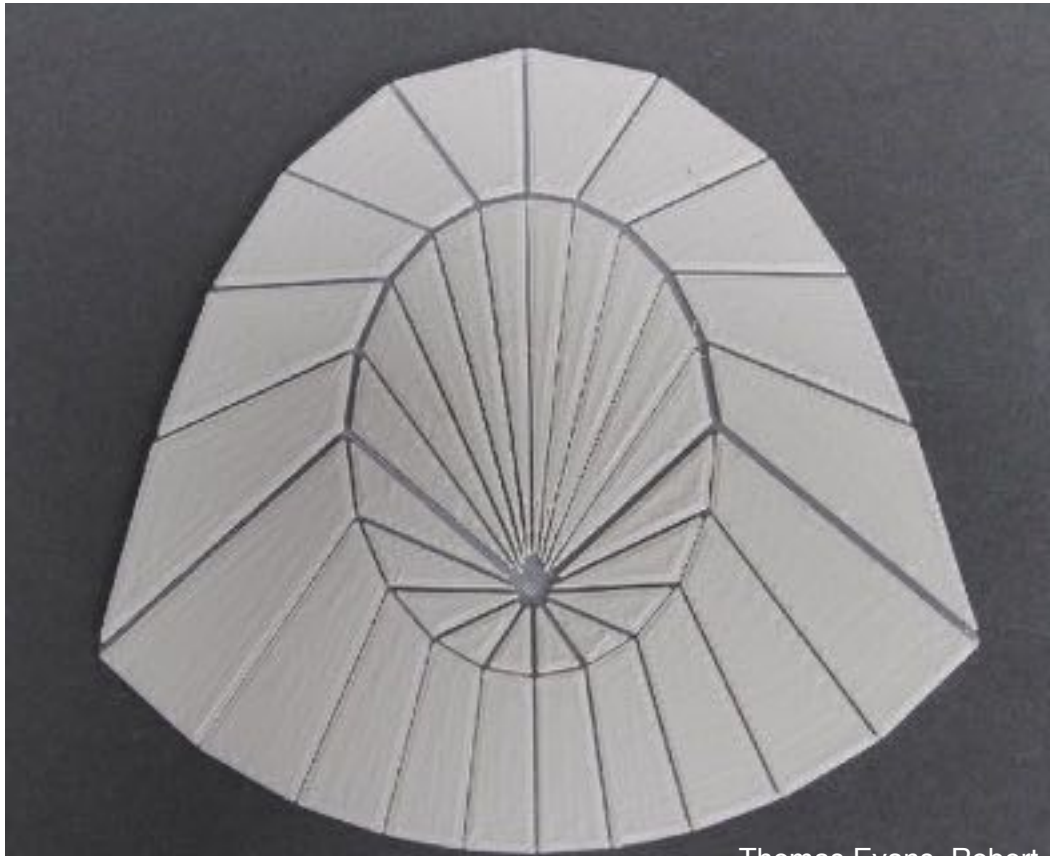
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Elliptic infinity

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- A discrete approximation of a curved-fold design



Thomas Evans, Robert J. Lang, Larry Howell, Spencer Magleby, BYU



The Origami Lamp

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ORIGAMI



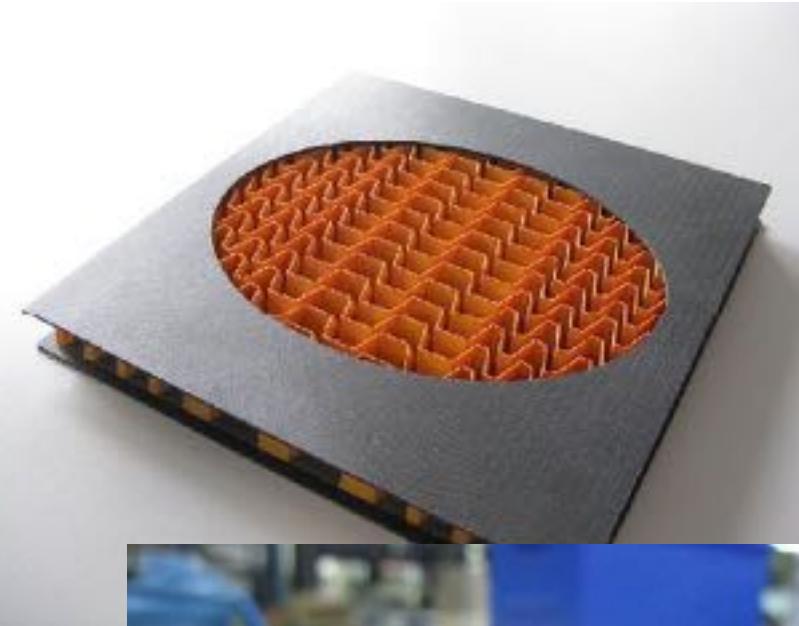
Video courtesy of Heron Elite, Inc.

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Foldcore Panels

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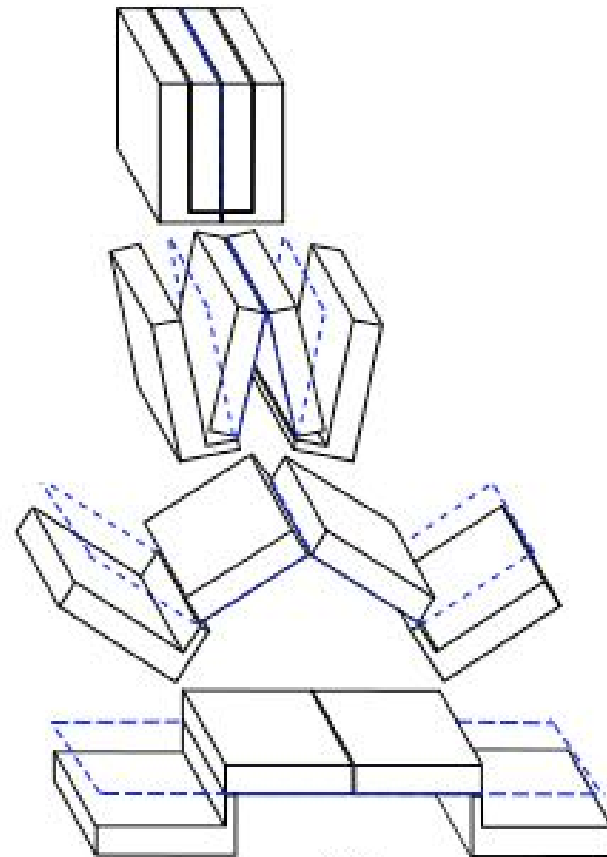
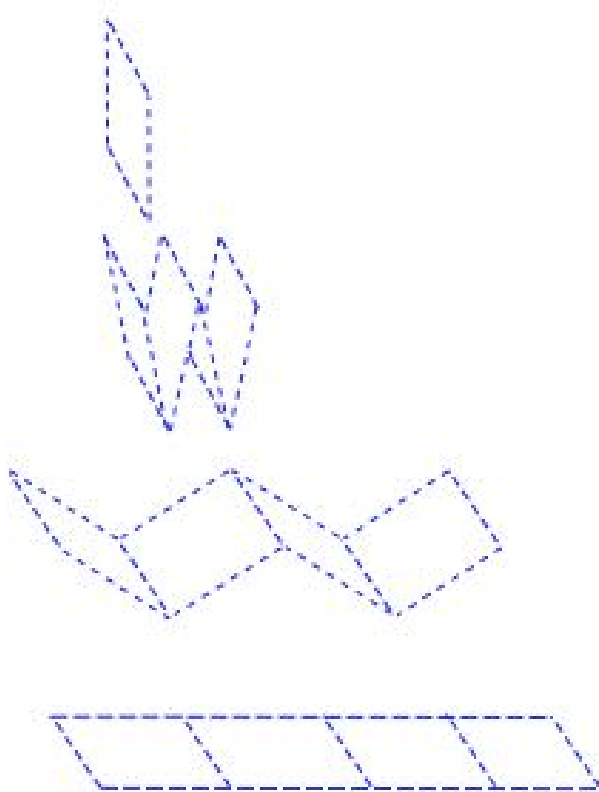


Images courtesy of Yves Klett,
Institute for Aircraft Design,
University of Stuttgart



Thick origami

- Paper thickness usually negligible, but real-world applications must account for it





Thick origami mechanisms

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BYU CMR Brigham Young University
Compliant Mechanisms Research

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images courtesy of CMR Group,
Brigham Young University



Kinematics

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- Current research at U. Tokyo, BYU, and Oxford extends origami to thick materials while preserving motion



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video courtesy of CMR Group,
Brigham Young University



Application of thick origami

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- Bulletproof barrier for law enforcement
- Begin with paper prototype
- Then develop “thick-origami” version



Imagery courtesy of CMR Group,
Brigham Young University, and PBS



Deployment

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ORIGAMI

- Multi-layer Kevlar



- Single-person deployable



Images courtesy of CMR Group,
Brigham Young University

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Ma



Testing

Video courtesy of CMR Group,
Brigham Young University

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Heart Implant

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ORIGAMI

- Developed by Paracor Medical, Inc.
- The implant unfolds from delivery tube
- “Small for the journey, large at the destination”

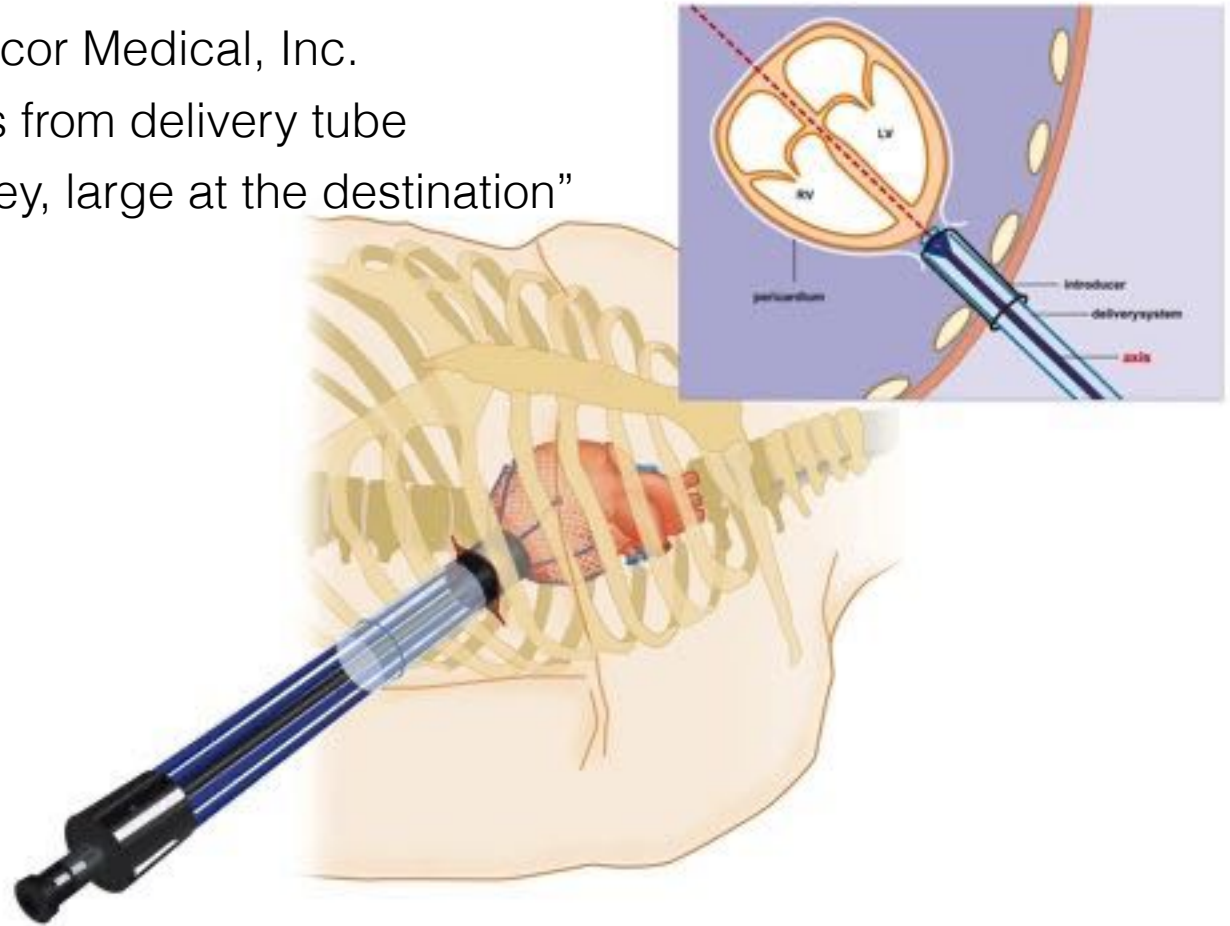


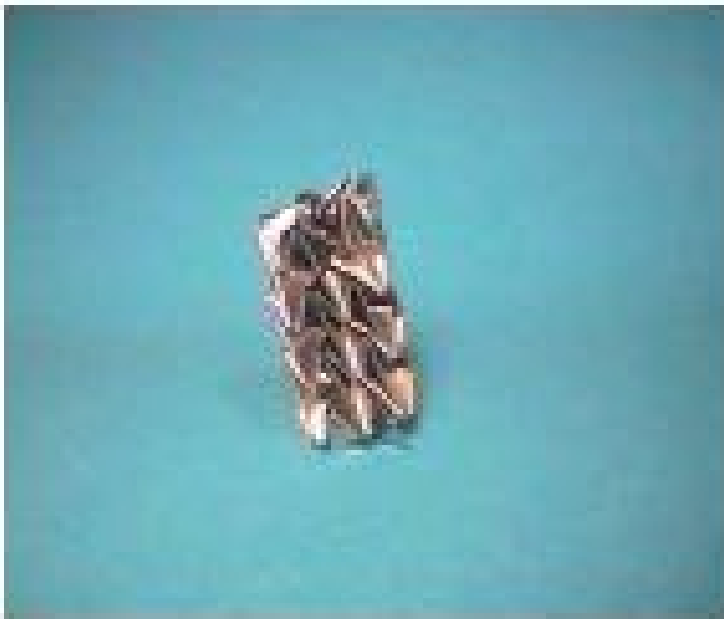
Image usage courtesy of
Paracor Medical, Inc.



Stents

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ORIGAMI

- Origami Stent graft developed by Zhong You (Oxford University) and Kaori Kuribayashi



An origami stent made from stain-less steel. Its diameter expands from 12 mm to 23 mm.



Artificial liver

ROBERT J. LANG
ORIGAMI

- Concept: seed a sheet with liver cells,
- then fold into “lobule” groupings

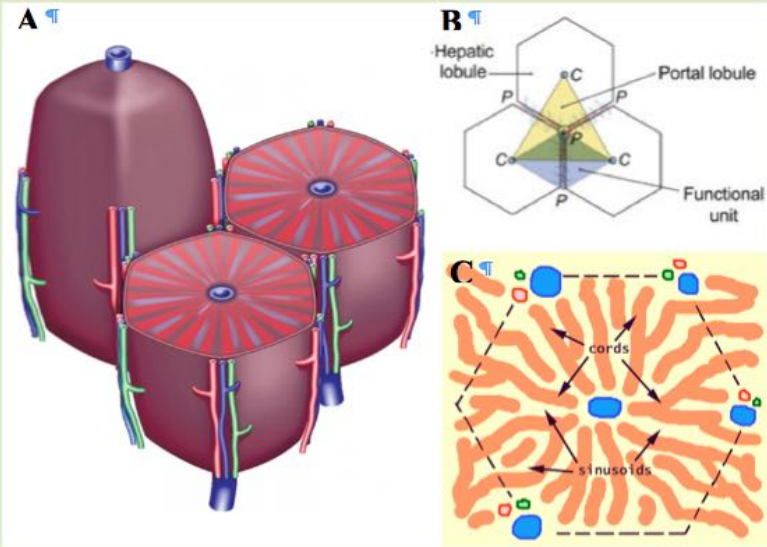


Figure 4. (A) Schematic 3D rendering of arrayed liver lobules [1], (B) hepatic lobule, portal lobule, and functional unit as alternate subunits [1], and (C) schematic structure of a single lobule showing hepatic cords (orange), sinusoids (yellow), vasculature (blue and red), and bile ducts (green) [1].



Carol Livermore et al, Northeastern University, MIT, San Jose State University
NSF EFRI-ODISSEI project

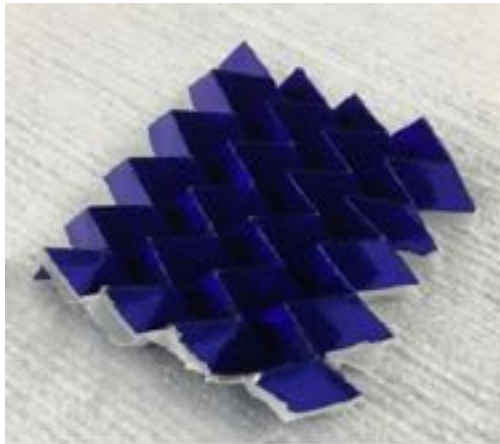
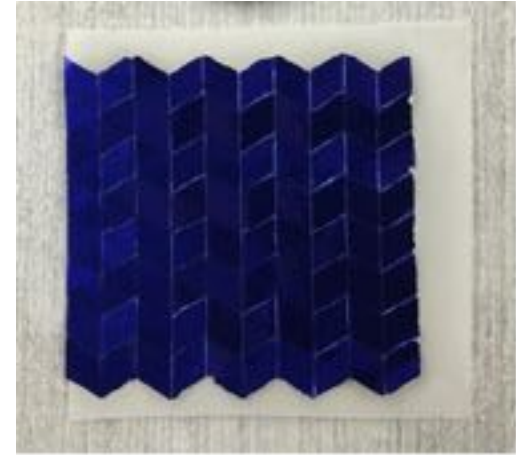


Miura-folding parallel channels

ROBERT J. LANG
ORIGAMI



1. Insert nanoporous membrane sheet between two laser-patterned foils



2. Fold the structure into Miura fold along patterned hinges



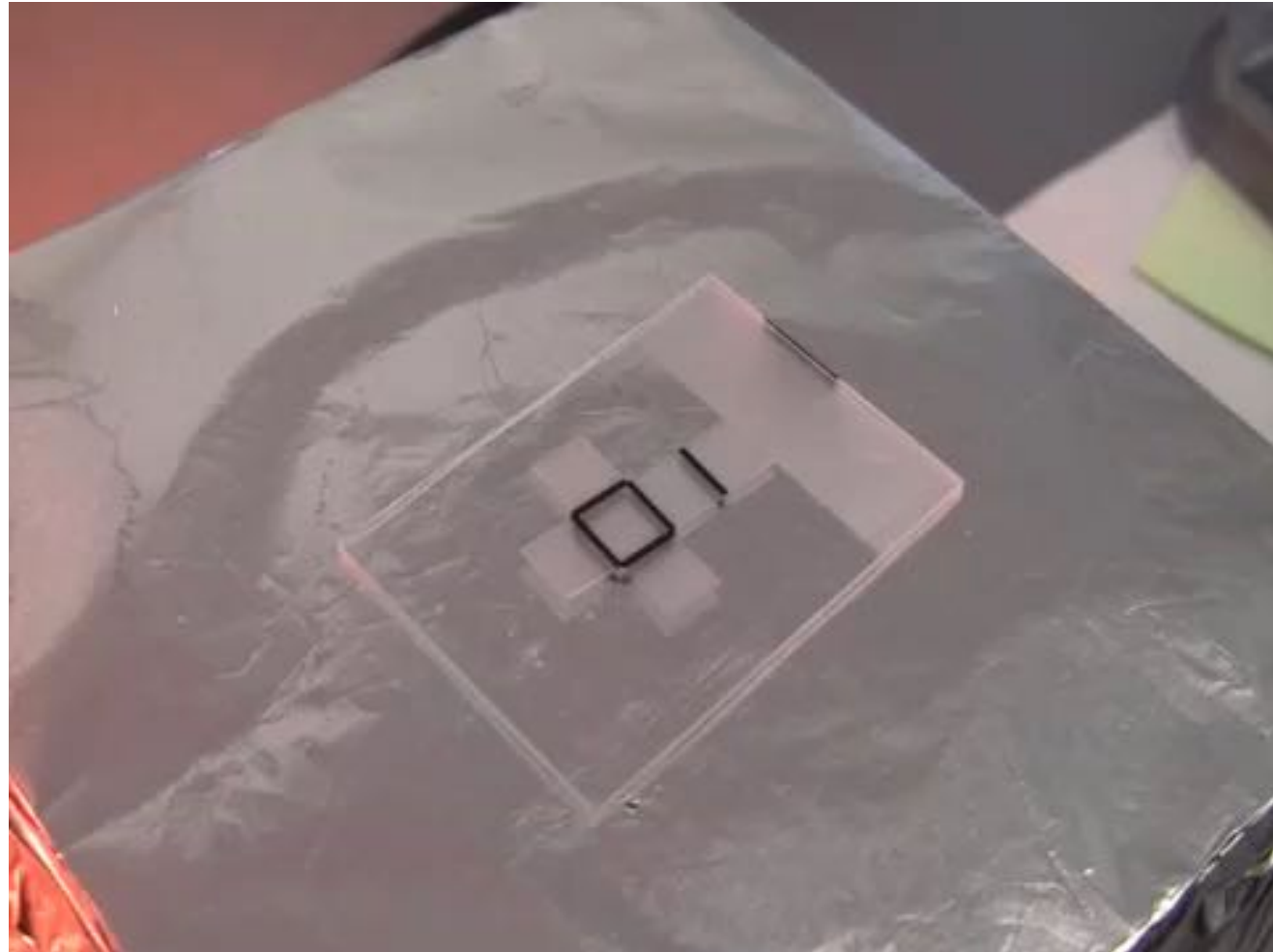
3. Release the nanoporous membrane



Actuation

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ORIGAMI

- Self-folding using local light absorption, Dickey et al., NC State University



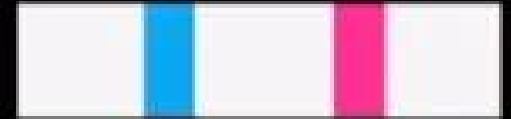
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Order by color

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This concept works for
other color schemes



384x

640x

Courtesy of Michael Dickey, NC State



Magnetic actuation

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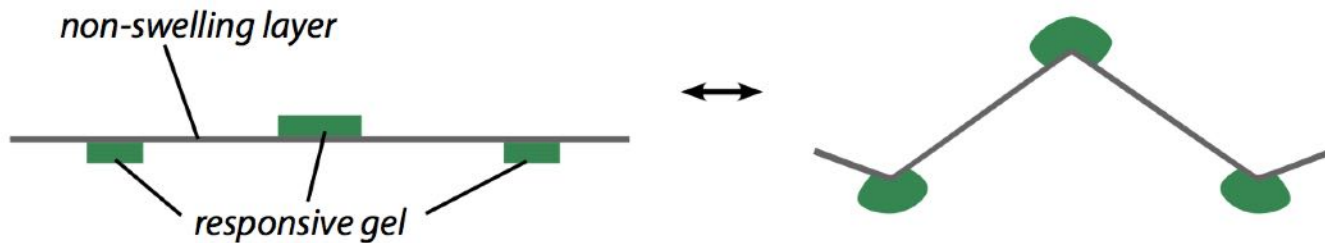
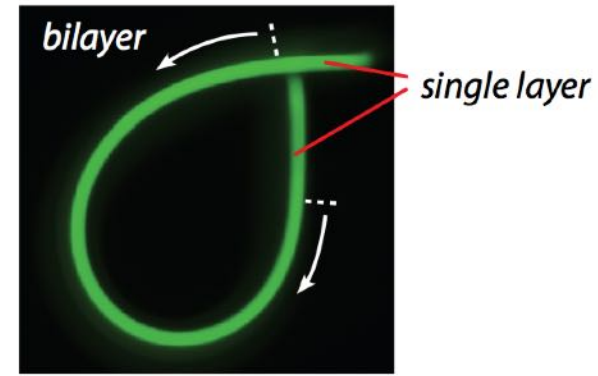
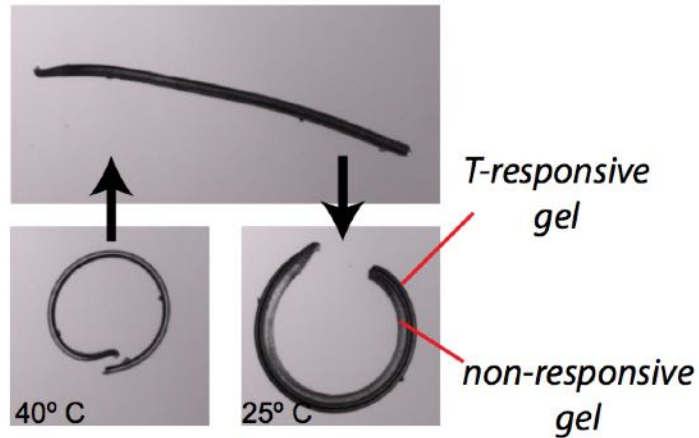


Courtesy Mary Frecker, Penn State



Hydrogel programmed folding

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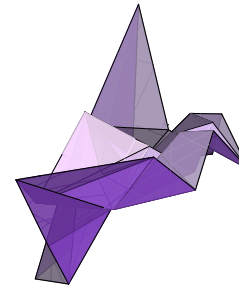
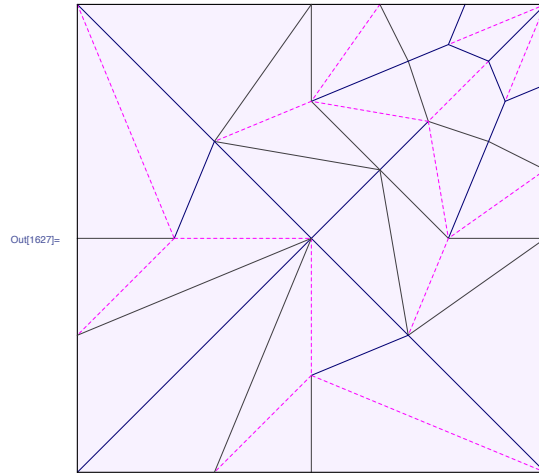


Ryan Hayward, Chris Santangelo (UMass), Itai Cohen (Cornell), Tom Hull (WNEU)
NSF EFRI-ODISSEI funded project

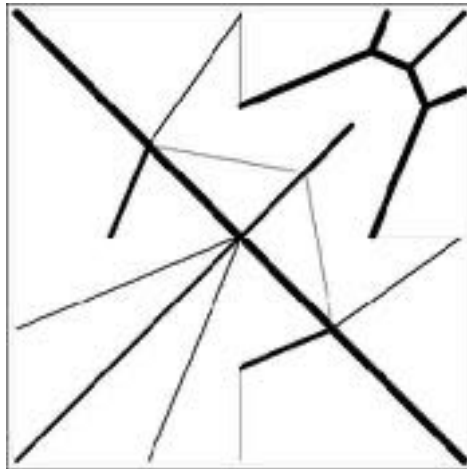


Programmed folds

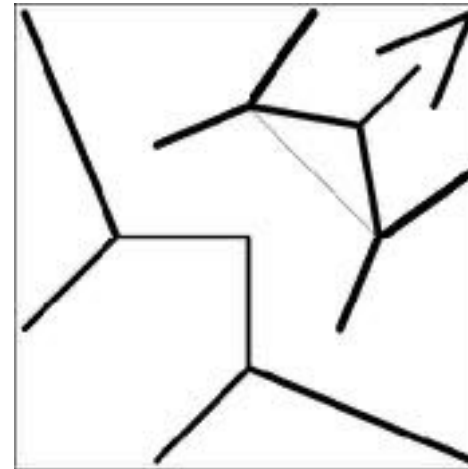
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mountains



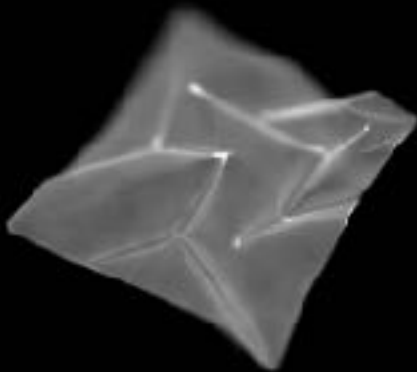
valleys





Look, no hands

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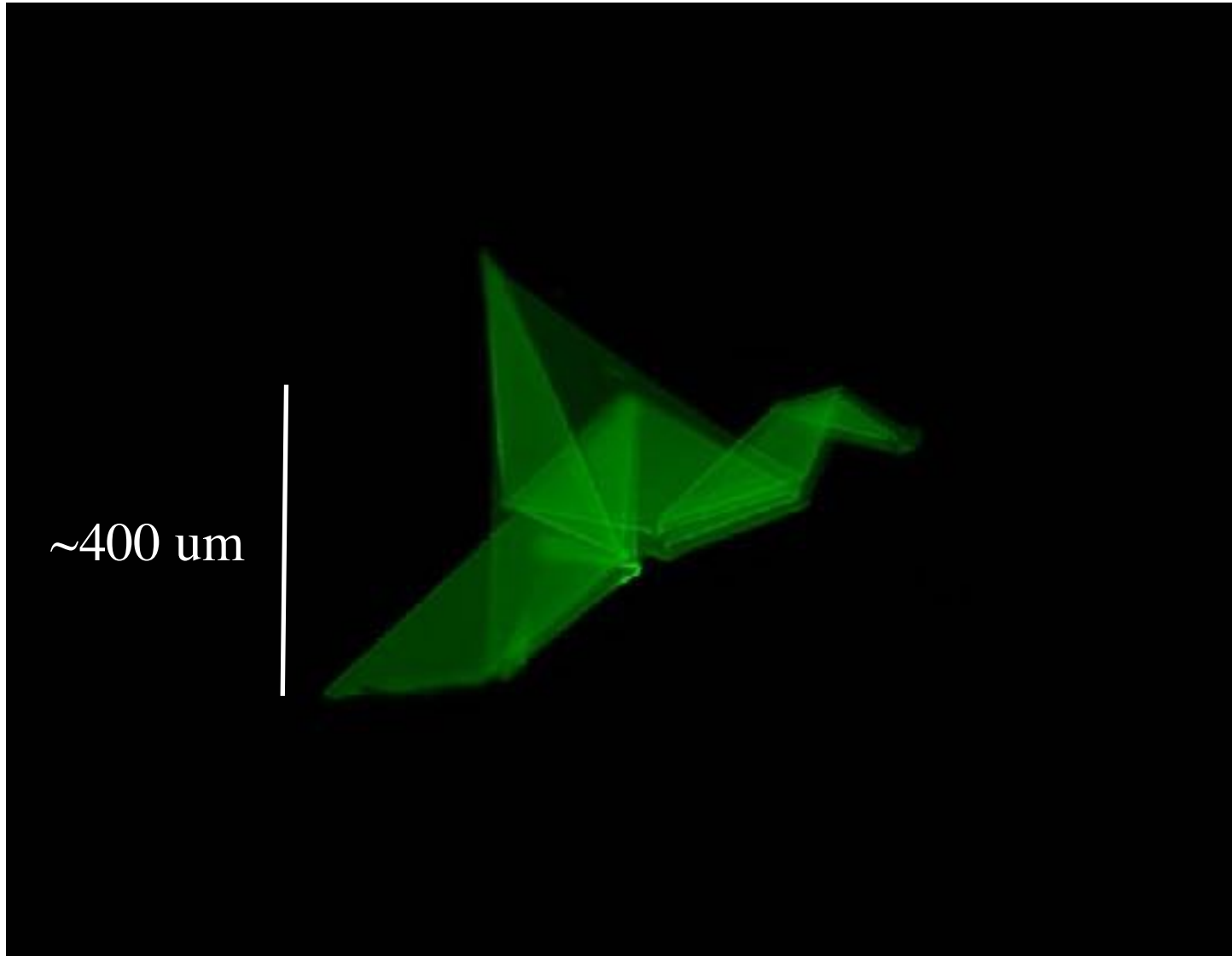
Ryan Hayward, Chris Santangelo, Jun-hee Na (UMass), Itai Cohen (Cornell), Tom Hull (WNEU)
NSF EFRI-ODISSEI funded project

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World's smallest flapping bird

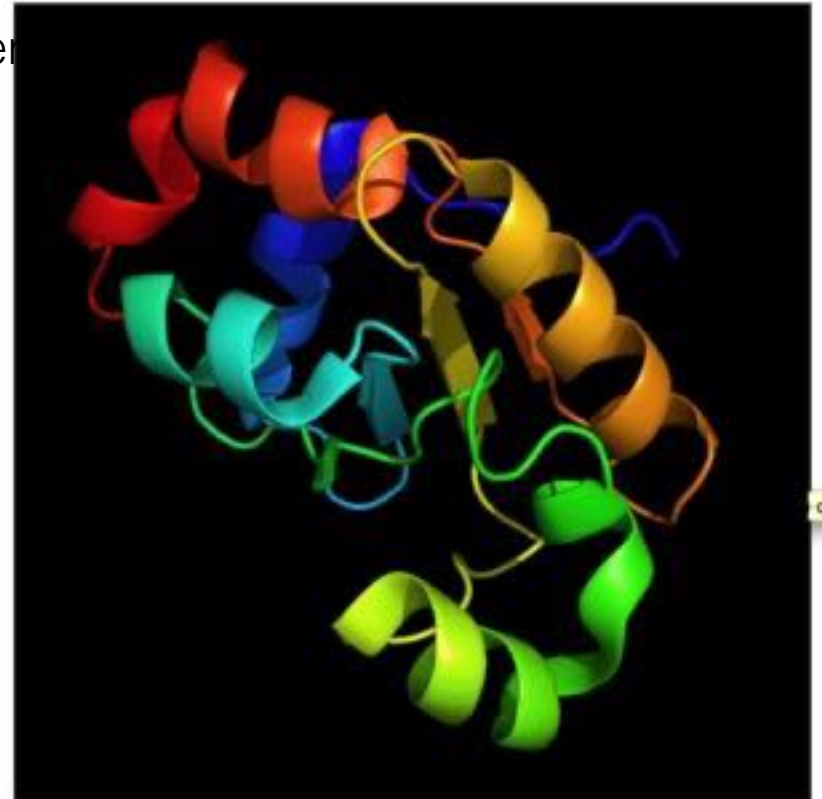
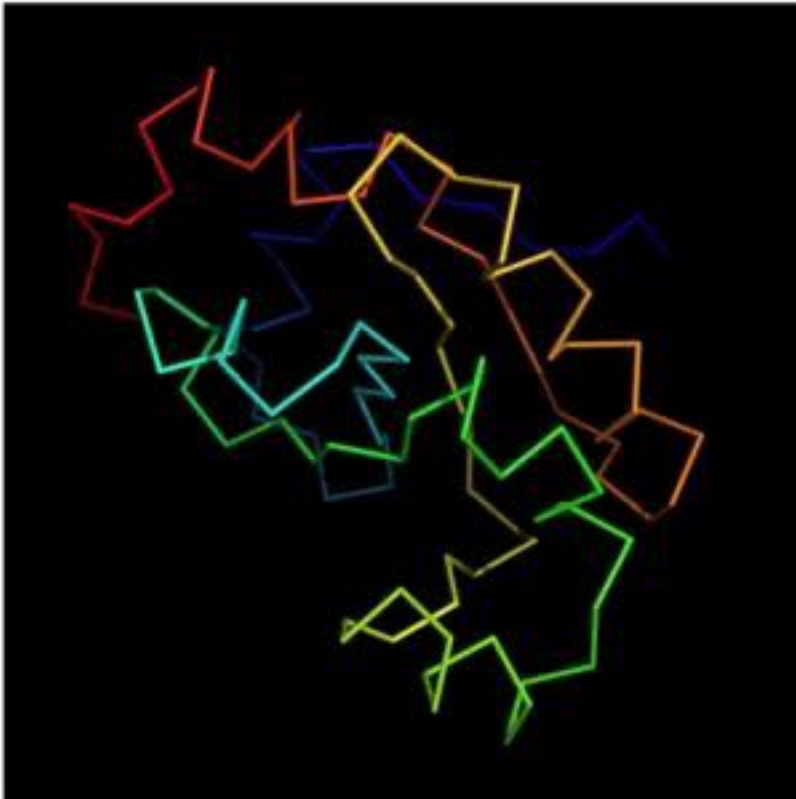
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Protein Folding

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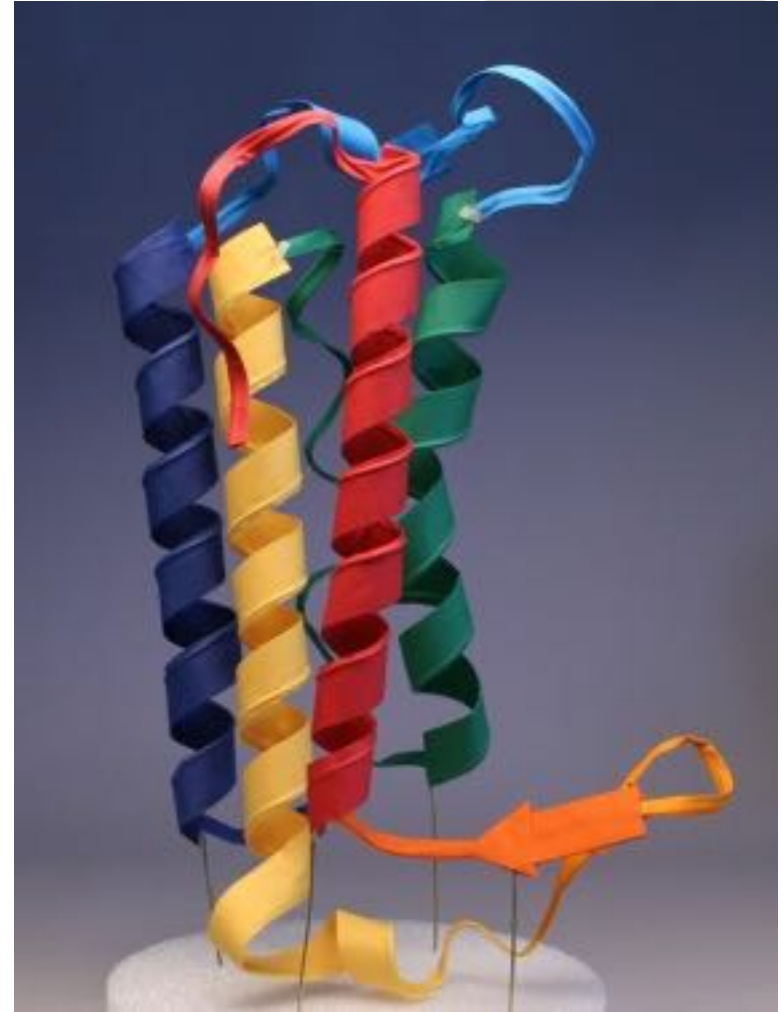
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Folds = Function

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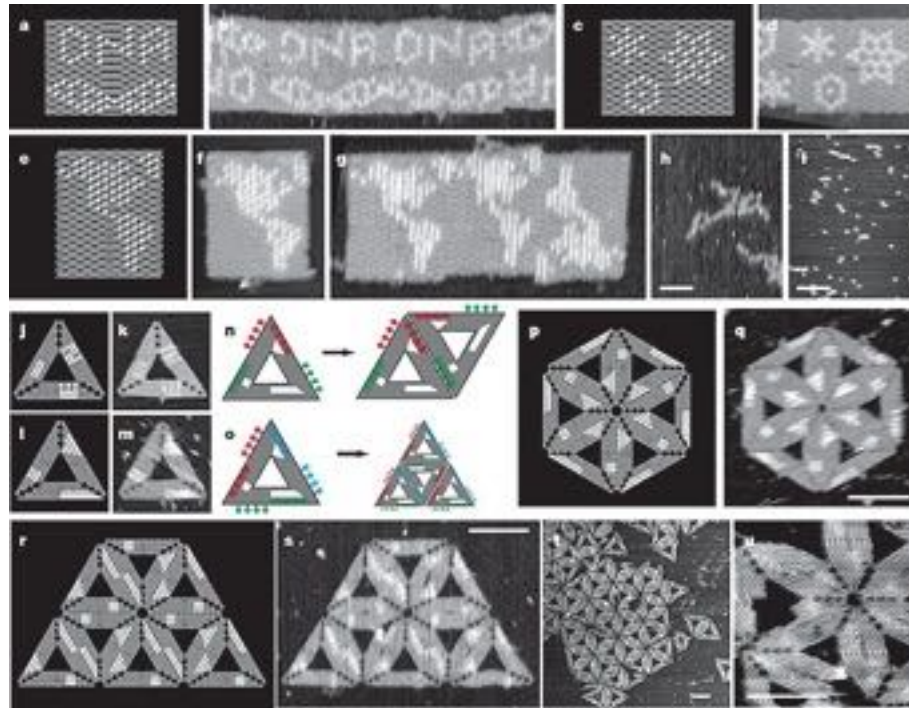
- The Grand Question of medicine and biology:
- How does a protein chain fold up?
- Fundamental laws of folding apply at any scale



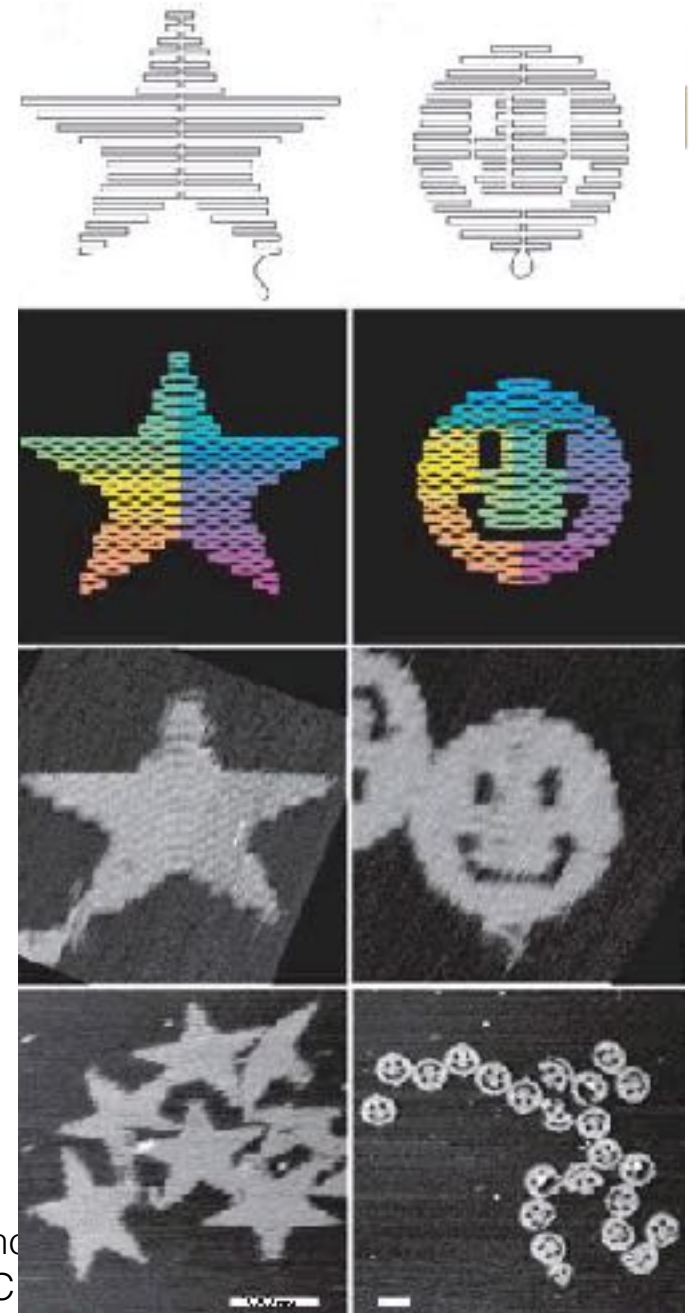


Folding DNA

- Paul Rothemund at Caltech developed techniques to fold DNA into origami shapes



Paul Rothemund, "Folding DNA to create nanoscale shapes and patterns," *Nature*, National Academies of Science, 2006
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DNA Origami for Leukemia

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- DNA origami cloaks anti-cancer drug (daunorubicin)
- Cancer cells swallow the “pill”, unfold the DNA, and die

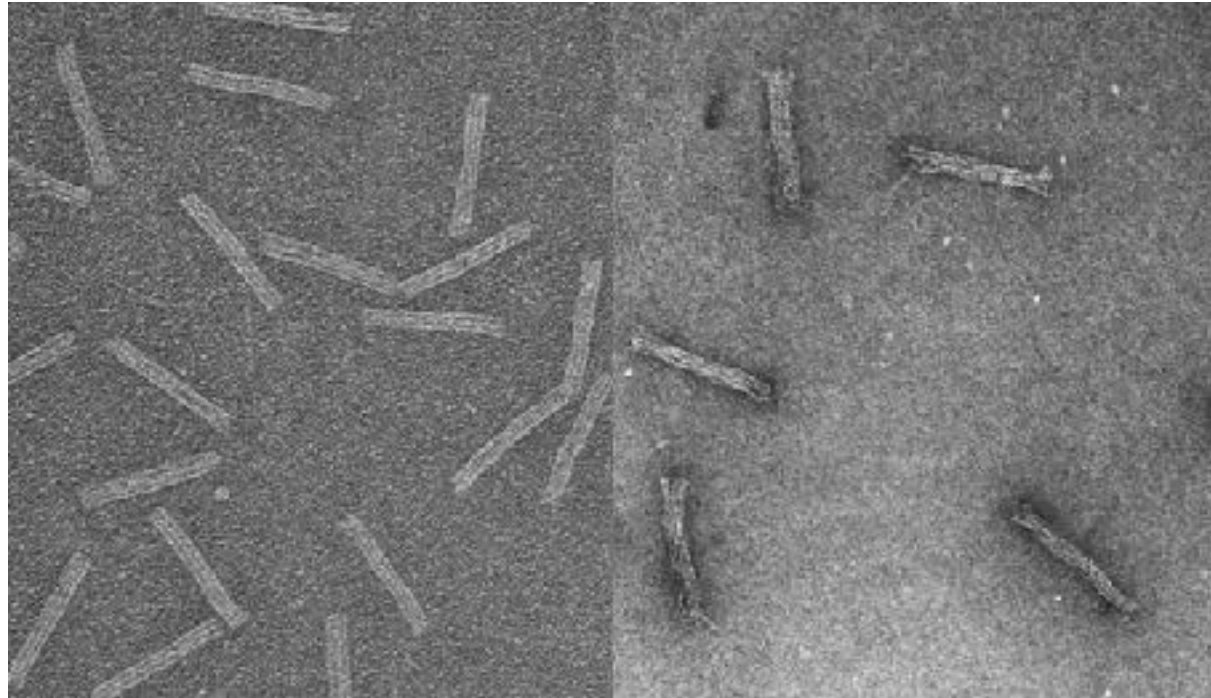
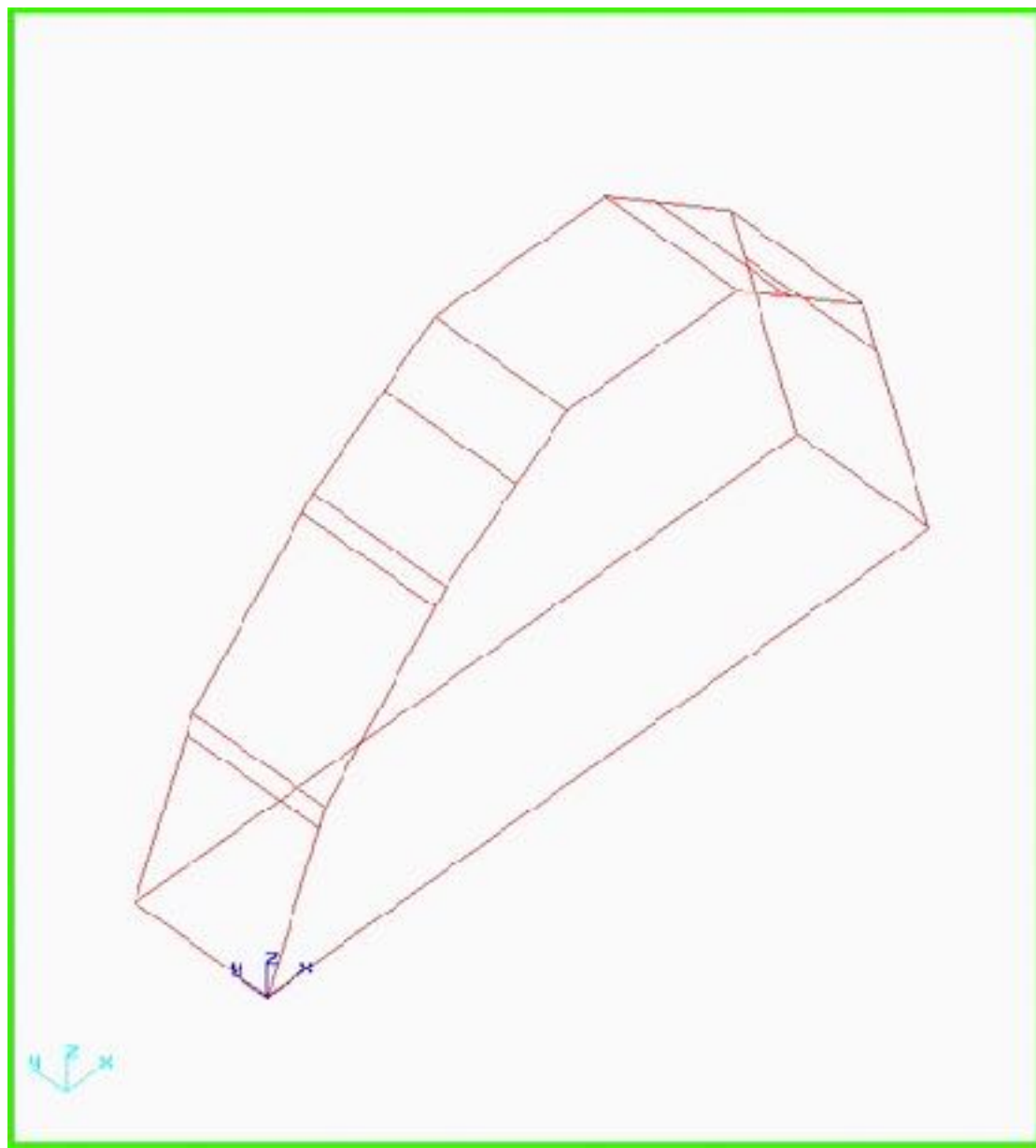


Image courtesy of John Byrd & Carlos Castro, Ohio State University (*Small*, March 2, 2016)



Airbags

- Origami algorithms used in simulation



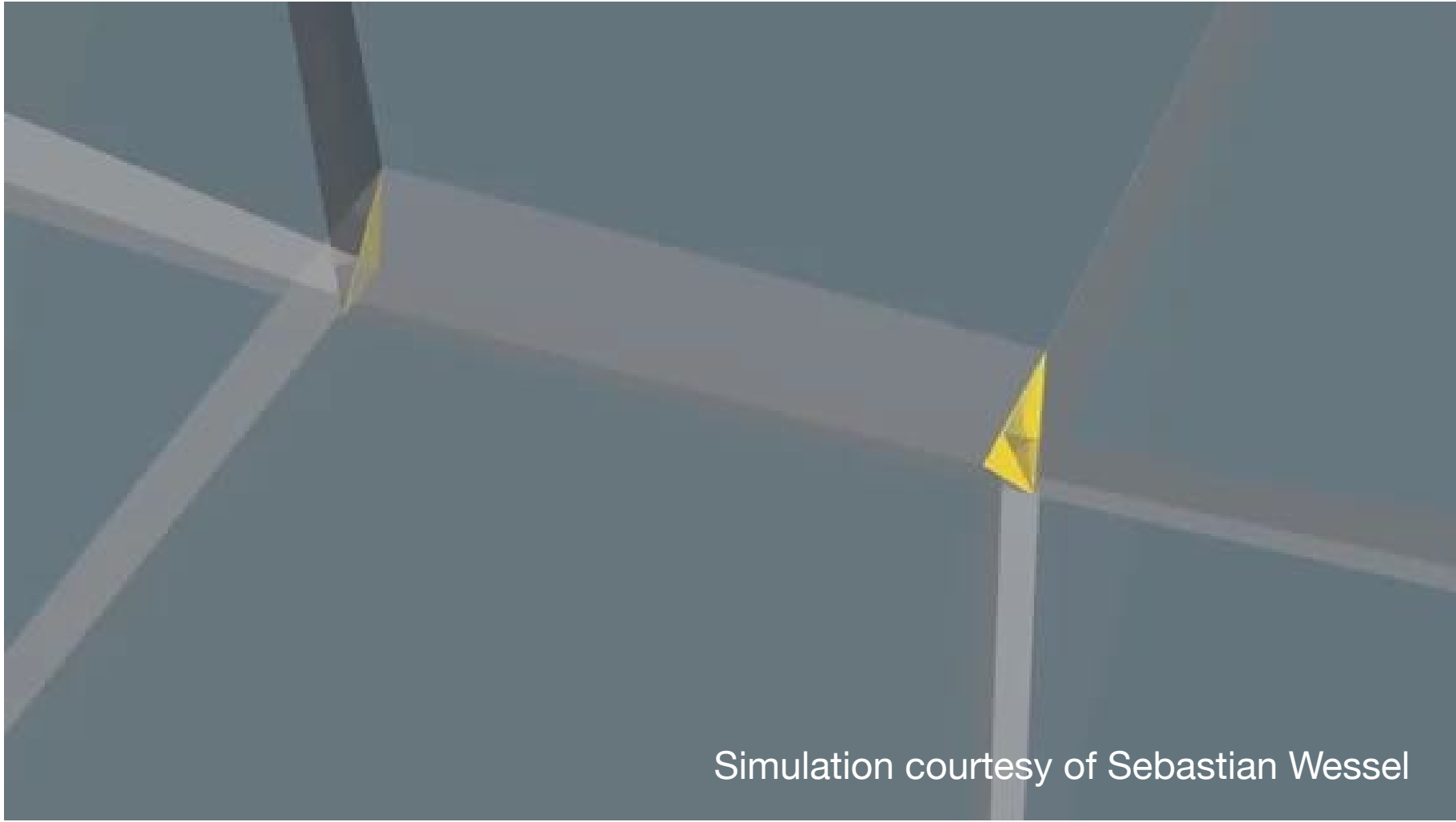
Animation courtesy EASi Engineering GmbH



Origami in higher dimensions

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- Simulations of dark matter reveal origami folding of 3D “sheets”



Simulation courtesy of Sebastian Wessel

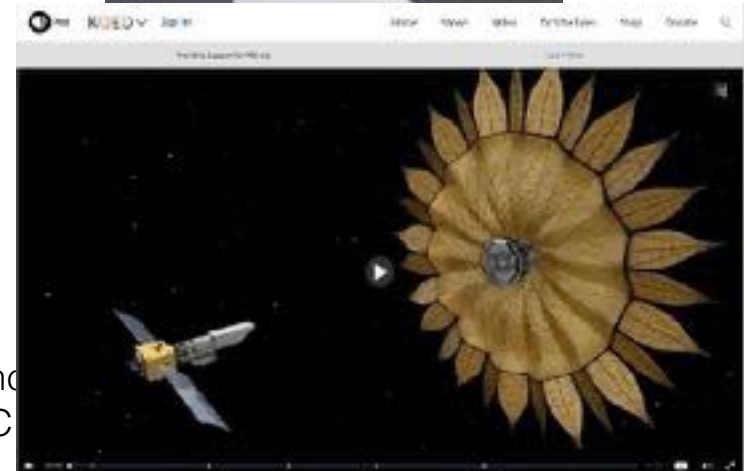


Simulation courtesy of Miguel Aragon-Calvo



Resources

- Further information may be found at
 - <http://www.langorigami.com>
- “Between the Folds,” a Peabody-award-winning origami documentary
 - <http://www.betweenthefolds.com>
- “The Origami Revolution”
 - PBS NOVA, streaming at <http://www.pbs.org/video/2365955827/>





From the everyday...

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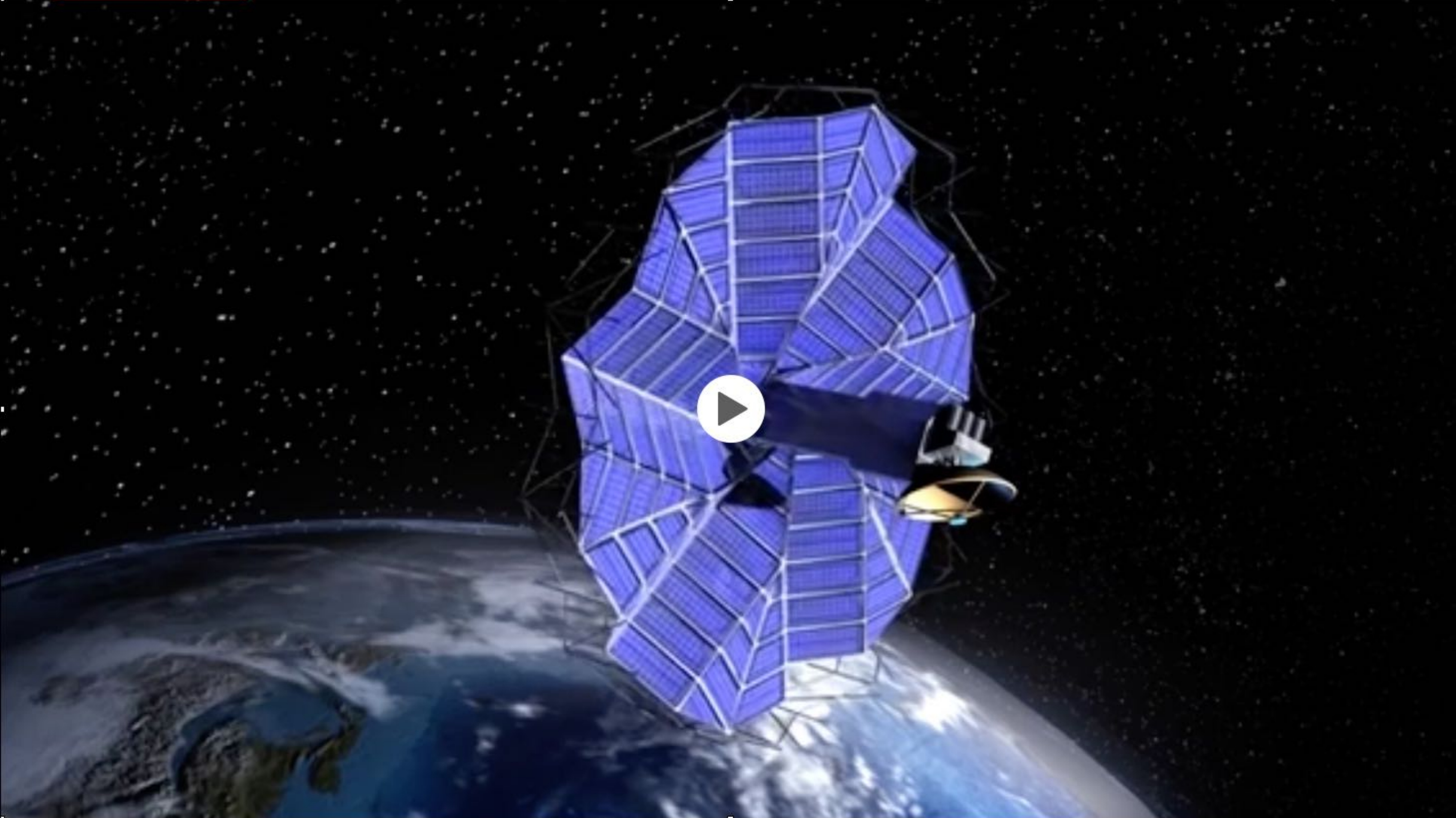
- “TrailerTail” deployable flaps -- cut wind resistance





To the future...

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"Flying Peace," by Kevin Box and Robert J. Lang, White Rock, NM