The Mathematics of Origami

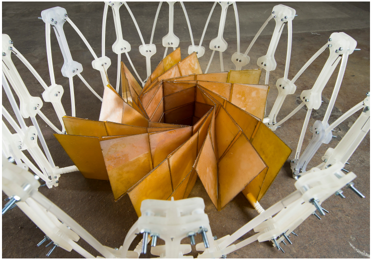
Thomas Bertschinger, Joseph Slote, Claire Spencer,
& Samuel Vinitsky

Carleton College

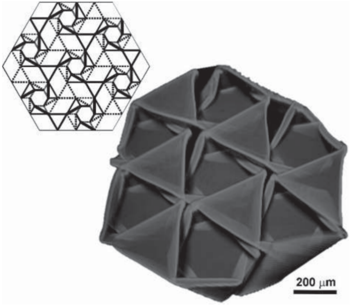
February 23, 2016

Why Study Origami?

Why Study Origami?



http://www.nasa.gov/jpl/news/origami-style-solar-power-20140814



Jun-Hee Na, Hayward Research Group, UMass Amherst

Overview

- Origami Constructions
- The Basics of Foldability
- Map Folding: An Open Problem
- Combinatorics of Origami

Axioms of Origami

General

i. Brief History

ii. Independence

Axioms of Origami

Seven Axioms of Origami

i. Given two points p_1 and p_2, we can fold a line connecting them.
ii. Given two points p_1 and p_2, we can fold p_1 onto p_2.
iii. Given two lines l_1 and l_2, we can fold line l_1 onto l_2.
iv. Given a point p_1 and a line l_1, we can make a fold perpendicular to l_1 passing through the point p_1.

Axioms of Origami

Seven Axioms of Origami

v. Given two points p_1 and p_2 and a line l_1, we can make a fold that places p_1 onto l_1 and passes through the point p_2.

vi. Given two points p_1 and p_2 and two lines l_1 and l_2, we can make a fold that places p1 onto line l_1 and places p_2 onto line l_2.

vii. Given a point p_1 and two lines l_1 and l_2, we can make a fold perpendicular to l_2 that places p_1 onto line l_1.

Axioms of Origami

Seven Axioms of Origami

i. The first six axioms allow all quadratic and cubic equations with rational coefficients to be solved.
ii. They also allow two of the three problems of antiquity, the trisection of an angle and the doubling of the cube, to be constructed.

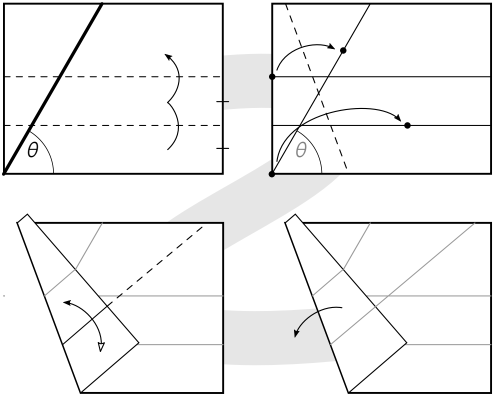
Greek Problems of Antiquity

Problems of Antiquity

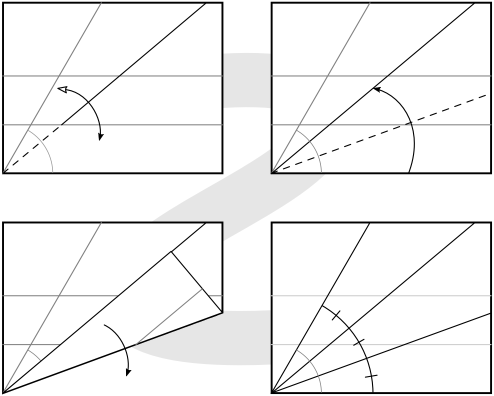
These were a trio of geometric problems whose solutions were attempted solely through the use of compass and straight-edge.

i. Angle Trisection
ii. Cube Duplication
iii. Circle Squaring

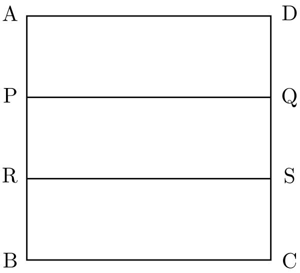
Angle Trisection

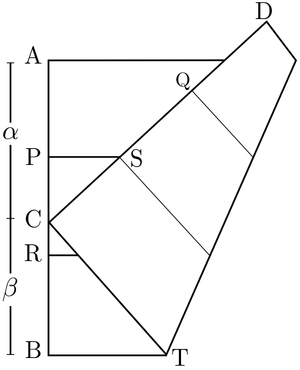


Angle Trisection



Cube Duplication





i. $\frac{\alpha}{\beta} = \sqrt[3]{2}$

ii. Thus, a cube with a side length α will have twice the volume of a cube with side length β.

Squaring the Circle

i. Impossible

ii. π

Constructibility

Initial Definitions

- We begin with two points p_0 and p_1 and define the distance between them to be 1.
- Line
- Point
- Number

Constructibility

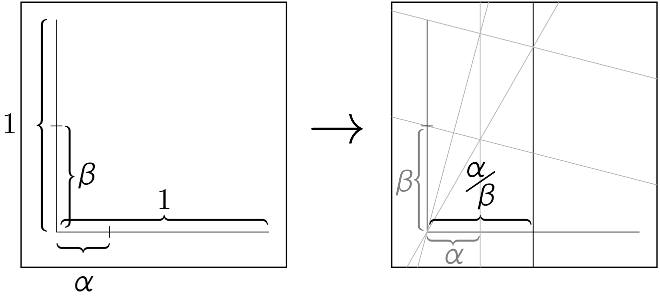
Constructible Numbers

Given two constructible numbers α and β, we can construct:

i. $\alpha + \beta$
ii. $\alpha - \beta$
iii. $\alpha\beta$
iv. $\frac{\alpha}{\beta}$

Constructibility

Given two constructible numbers α and β, we can construct $\frac{\alpha}{\beta}$, their ratio.



Constructibility

Constructible Numbers

i. Since the set of constructible numbers is closed under addition, subtraction, multiplication, and division, it can be concluded that the set of constructible numbers form a field.
ii. Ultimately, the field of origami constructible numbers are closed under taking both square roots and cube roots.
iii. The construction of the square root of any constructible number implies the field of origami constructible numbers contains the field of compass and straightedge constructible numbers.

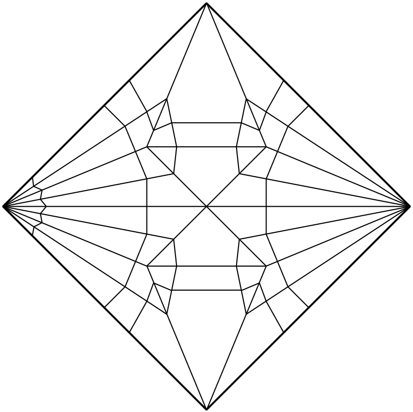
Future Work

i. Efficiency
ii. Optimality

Foldability

Foldability

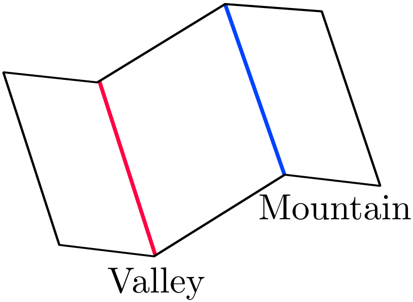
An example of a crease pattern:



Foldability

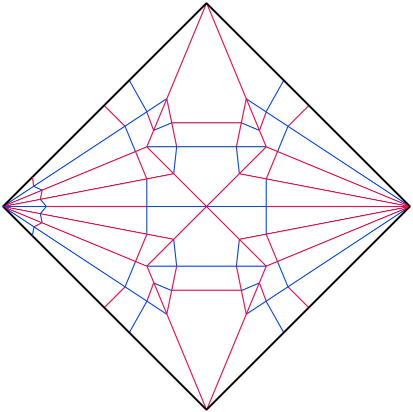
Crease Assignments

A crease pattern doesn't contain all the information about a model, however.



Foldability

The crease pattern with mountain-valley assignment:



Foldability

Two questions

For a given crease pattern,

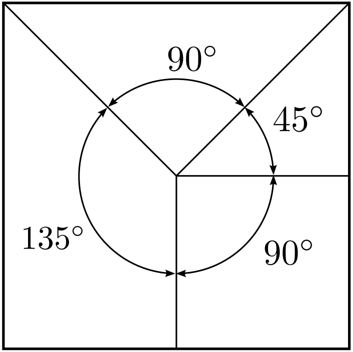
i. how can we fold it up?

ii. can it be folded flat?

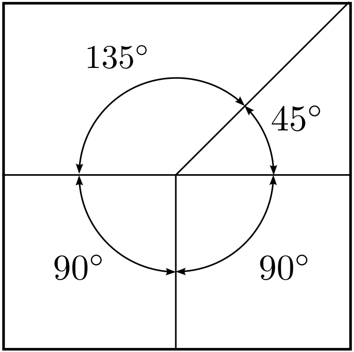
Flat-Foldability Conditions

Kawasaki's Theorem (1989)

The alternate angles around a vertex must sum to 180°.



(a)



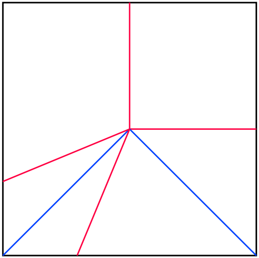
(b)

Flat-Foldability Conditions

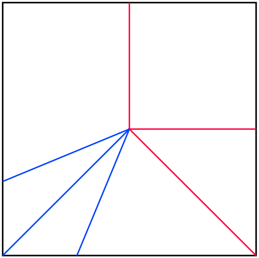
Maekawa's Theorem (1986)

Let M be the number of mountain folds and V the number of valley folds; then

$$M - V = \pm 2.$$



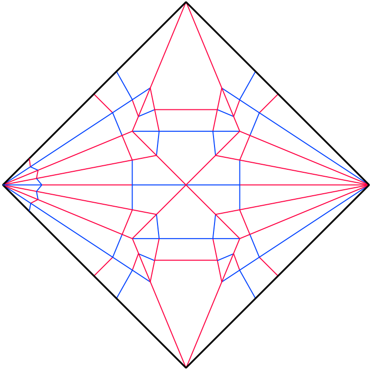
(a)



(b)

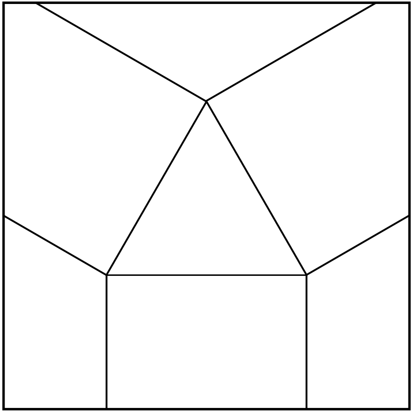
More Complicated Crease Patterns

How can we determine flat foldability for a more complicated pattern?



More Complicated Crease Patterns

Here's a crease pattern that can't fold flat!

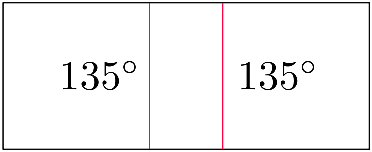


Foldings

How can we capture the notion of a folded paper?

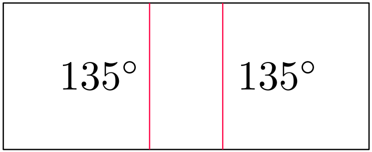
Foldings

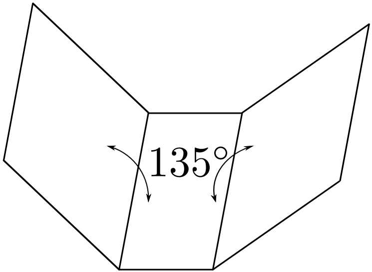
How can we capture the notion of a folded paper?



Foldings

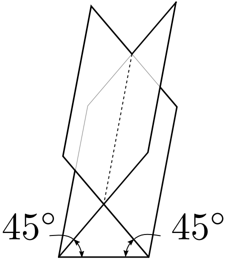
How can we capture the notion of a folded paper?





An Invalid Folding

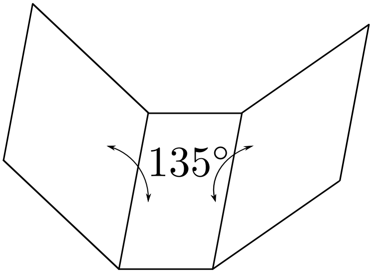
This folding has self-intersection.

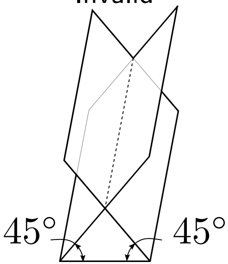


Valid Foldings

A valid folding is one that doesn't cause any self-intersecton.

Valid





Topology and Origami

Drawing pictures on Crease Patterns

Question

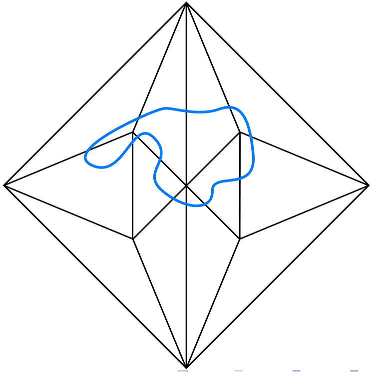
If we draw something on the flat piece of paper before folding it up, what can happen when we fold it?

Drawing pictures on Crease Patterns

Question

If we draw something on the flat piece of paper before folding it up, what can happen when we fold it?

We'll see what happens when we draw Jordan curves on the crease patterns, like the picture on the right.

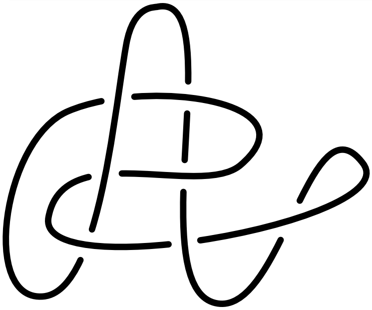


Knot Theory 101

What is a knot?

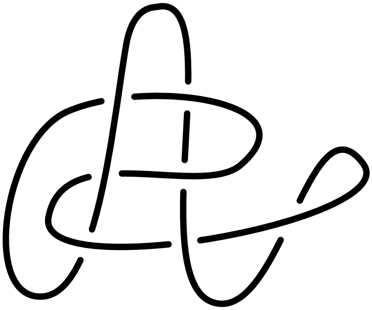
Knot Theory 101

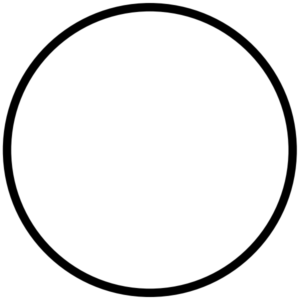
What is a knot?



Knot Theory 101

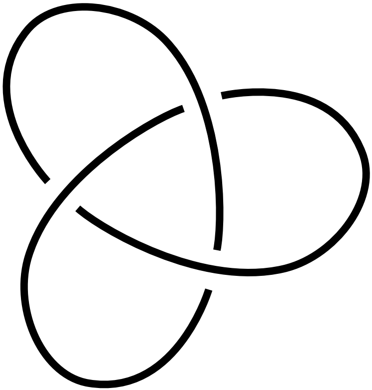
What is a knot?





Knot Theory 101

This is the *trefoil knot*. We can't "untangle" it, no matter how hard we try.



Connecting Topology and Origami

Theorem (Bertschinger and Slote 2016)

A folding of a crease pattern is valid if and only if every Jordan curve embedded in the paper before folding is mapped to the unknot after folding.

Connecting Topology and Origami

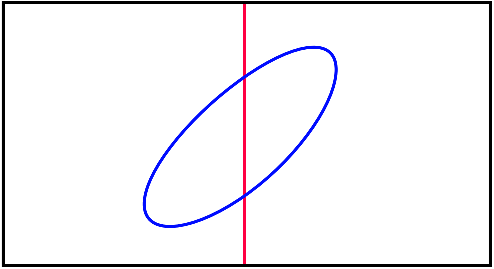
$\Longrightarrow$

This direction is fairly intuitive.

Connecting Topology and Origami

$\Longrightarrow$

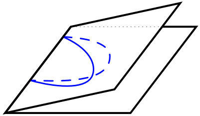
This direction is fairly intuitive.



Connecting Topology and Origami

$\Longrightarrow$

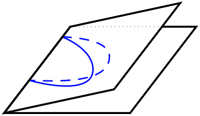
This direction is fairly intuitive.

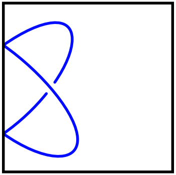


Connecting Topology and Origami

$\Longrightarrow$

This direction is fairly intuitive.

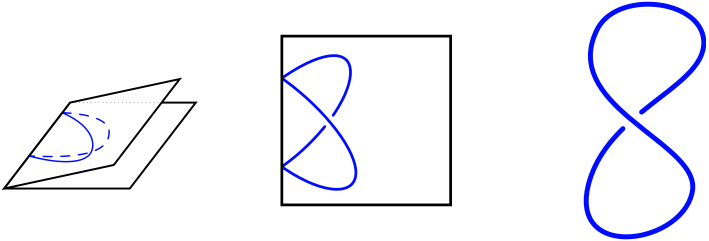




Connecting Topology and Origami

$\Longrightarrow$

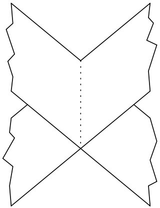
This direction is fairly intuitive.



Connecting Topology and Origami

$\Longleftarrow$

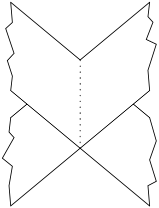
Invalid folding means intersection.

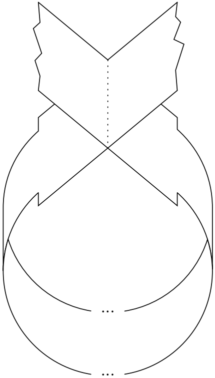


Connecting Topology and Origami

$\Longleftarrow$

We can connect up the paper like this.

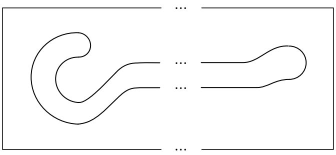


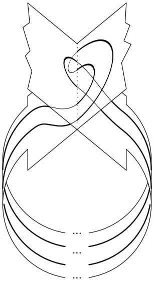


Connecting Topology and Origami

$\Longleftarrow$

We can draw a curve like this.

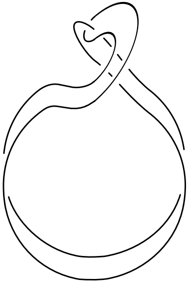




Connecting Topology and Origami

$\Longleftarrow$

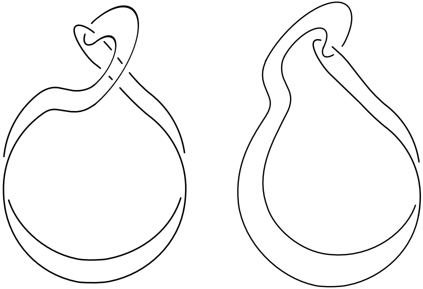
Is it a knot?



Connecting Topology and Origami

⟸

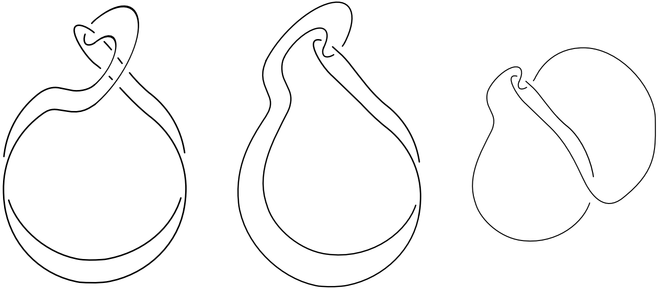
Is it a knot?



Connecting Topology and Origami

$\Longleftarrow$

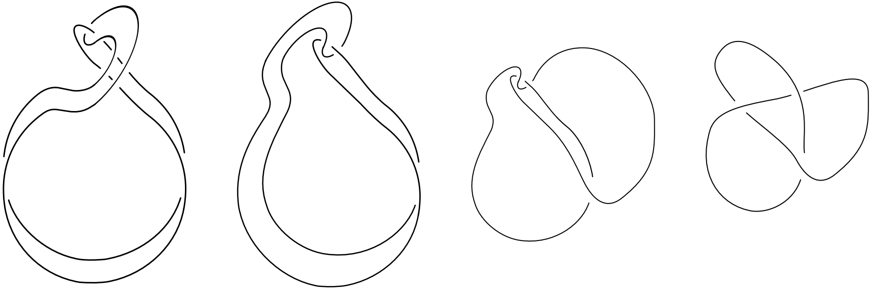
Is it a knot?



Connecting Topology and Origami

⟸

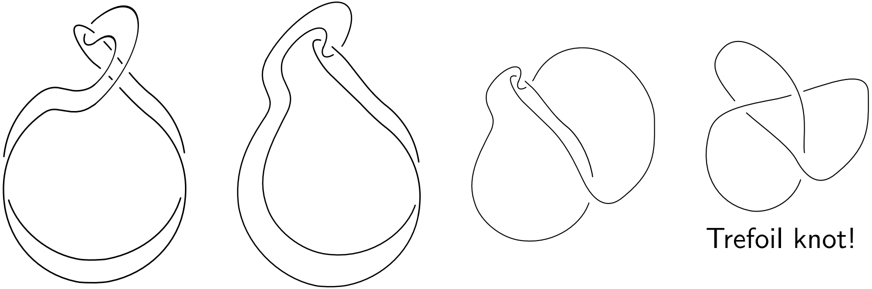
Is it a knot?



Connecting Topology and Origami

⟸

Is it a knot?



Trefoil knot!

Connecting Topology and Origami

Now what?

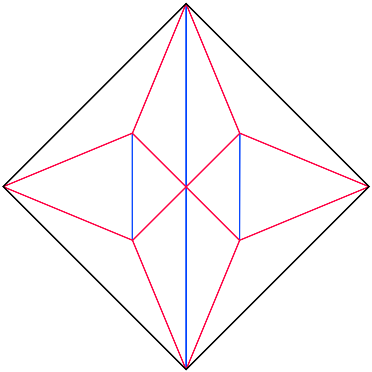
- Describe a characteristic for crease patterns
- Finding ways to describe the complexity of a crease pattern or a folding (e.g. the number of self-intersections)

Computational Questions

Determining flat-foldability

Goal:

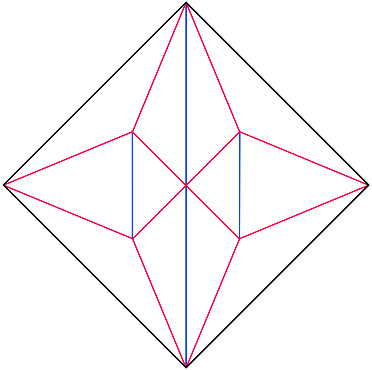
Given a crease pattern, determine if it is flat-foldable.

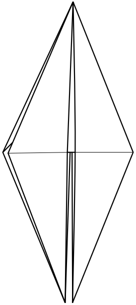


Determining flat-foldability

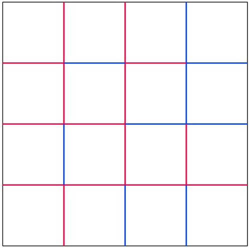
Goal:

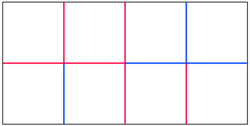
Given a crease pattern, determine if it is flat-foldable.



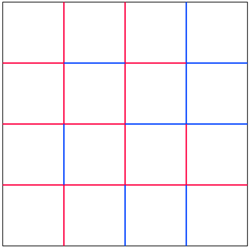


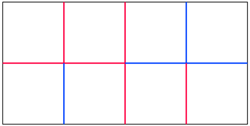
Introduction to Maps

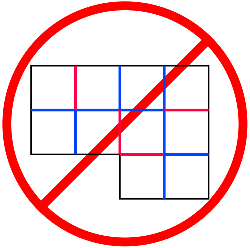


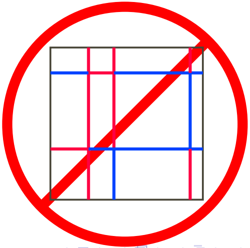


Introduction to Maps

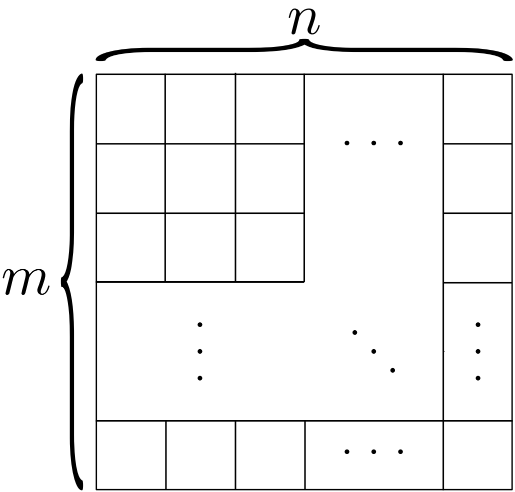








Introduction to Maps



Map Folding: An Open Problem

Open Problem:

How hard is it to determine whether or not a map is flat-foldable?

Map Folding: An Open Problem

Open Problem:

How hard is it to determine whether or not a map is flat-foldable?

Easier Problem:

How hard is it to determine whether or not a map is *flat-folded*?

Map Folding: An Open Problem

Open Problem:

How hard is it to determine whether or not a map is flat-foldable?

Easier Problem:

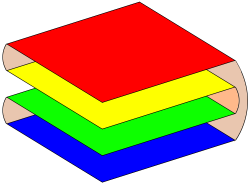
How hard is it to determine whether or not a map is *flat-folded*?

(Reminder: Flat-foldability is a property of maps, flat-folded-ness is a property of specific foldings.)

Linear Orderings

Question:

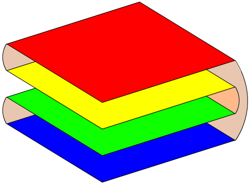
How can we represent a folded form?



Linear Orderings

Question:

How can we represent a folded form?

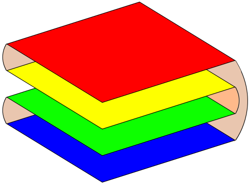


red $\rightarrow$ yellow $\rightarrow$ green $\rightarrow$ blue

Linear Orderings

Question:

How can we represent a folded form?



red $\rightarrow$ yellow $\rightarrow$ green $\rightarrow$ blue

Note:

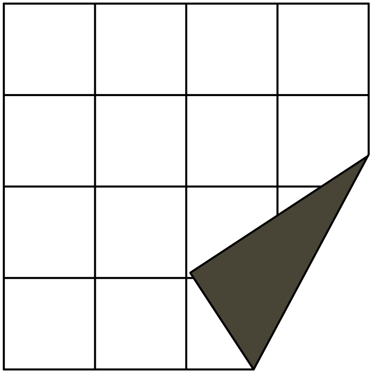
Each linear ordering corresponds with exactly one folded form.

Linear Orderings

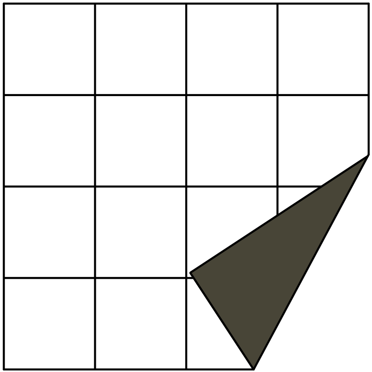
Question:

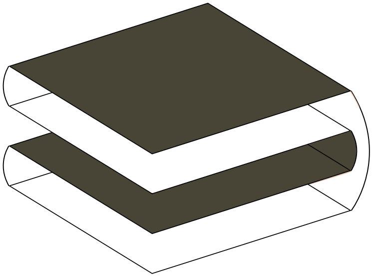
How can we tell if a linear ordering is realizable by a given crease pattern?

Checkerboard Pattern



Checkerboard Pattern





Checkerboard Pattern

Goal:

Label each face as being light-side or dark-side up in *any* folding.

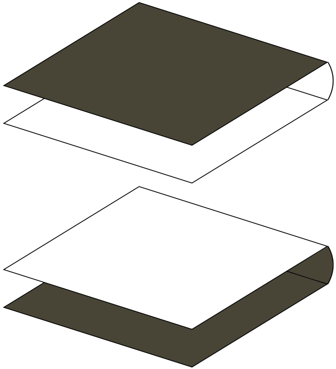
	?	?	?
?	?	?	?
?	?	?	?
?	?	?	?

Checkerboard Pattern

Goal:

Label each face as being light-side or dark-side up in *any* folding.

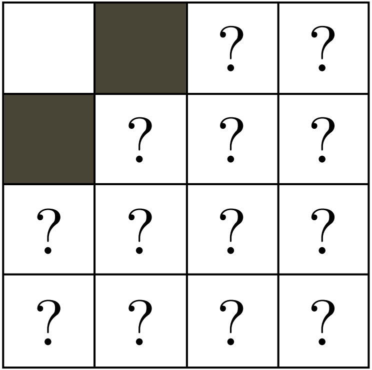
	?	?	?
?	?	?	?
?	?	?	?
?	?	?	?

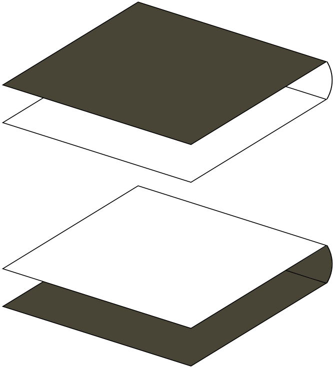


Checkerboard Pattern

Goal:

Label each face as being light-side or dark-side up in *any* folding.

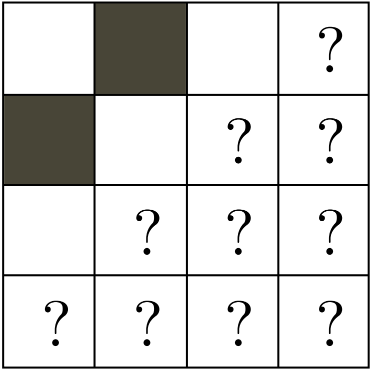


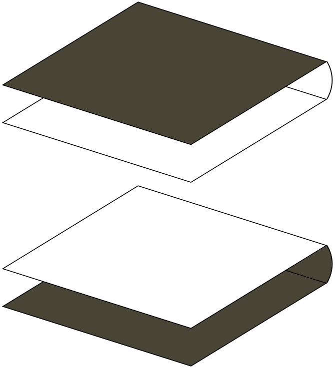


Checkerboard Pattern

Goal:

Label each face as being light-side or dark-side up in *any* folding.

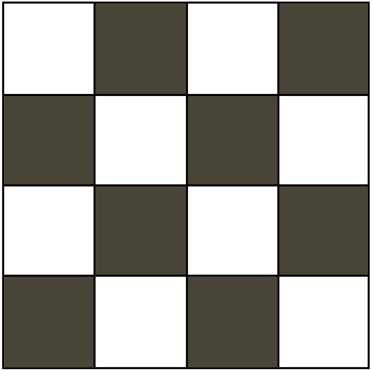


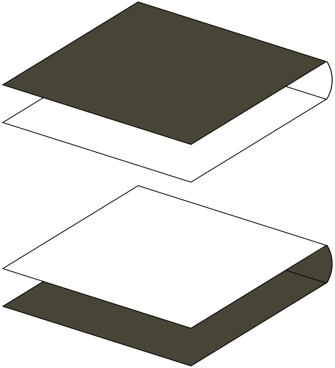


Checkerboard Pattern

Goal:

Label each face as being light-side or dark-side up in *any* folding.





Partial Ordering

Definition:

A *partial ordering* P on a set S is a set of ordered pairs of elements of S that orders some of the elements of S.

Partial Ordering

Definition:

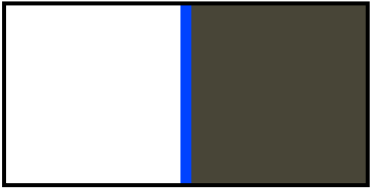
A *partial ordering* P on a set S is a set of ordered pairs of elements of S that orders some of the elements of S.

We will denote an ordered pair as $a \to b$ ("a covers b")

Partial Ordering

Goal:

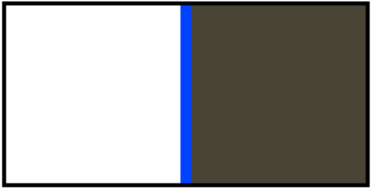
Use checkerboard pattern and crease assignments to tell, for each pair of adjacent faces, which face comes first in *all* linear orderings.

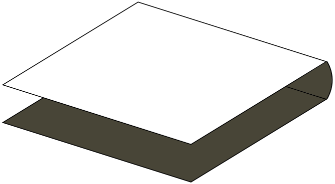


Partial Ordering

Goal:

Use checkerboard pattern and crease assignments to tell, for each pair of adjacent faces, which face comes first in *all* linear orderings.

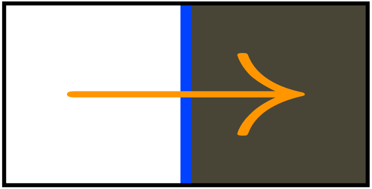


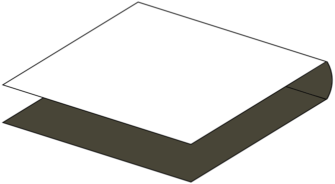


Partial Ordering

Goal:

Use checkerboard pattern and crease assignments to tell, for each pair of adjacent faces, which face comes first in *all* linear orderings.

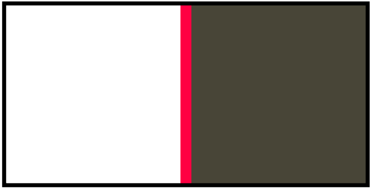




Partial Ordering

Goal:

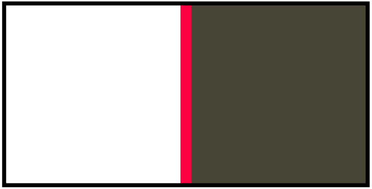
Use checkerboard pattern and crease assignments to tell, for each pair of adjacent faces, which face comes first in *all* linear orderings.

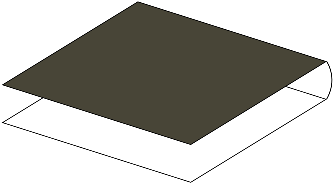


Partial Ordering

Goal:

Use checkerboard pattern and crease assignments to tell, for each pair of adjacent faces, which face comes first in *all* linear orderings.

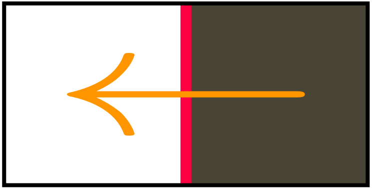


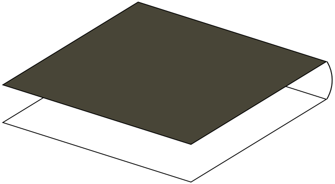


Partial Ordering

Goal:

Use checkerboard pattern and crease assignments to tell, for each pair of adjacent faces, which face comes first in *all* linear orderings.

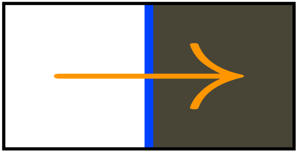


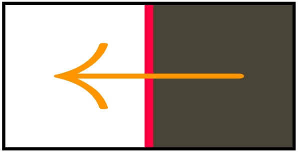


Partial Ordering

Goal:

Use checkerboard pattern and crease assignments to tell, for each pair of adjacent faces, which face comes first in *all* linear orderings.

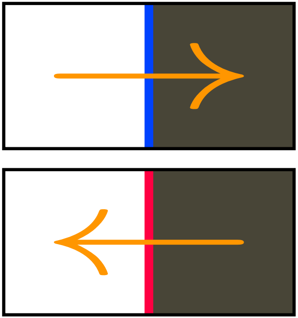


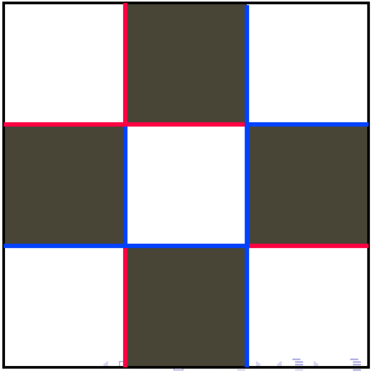


Partial Ordering

Goal:

Use checkerboard pattern and crease assignments to tell, for each pair of adjacent faces, which face comes first in *all* linear orderings.

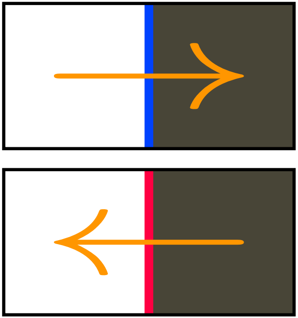


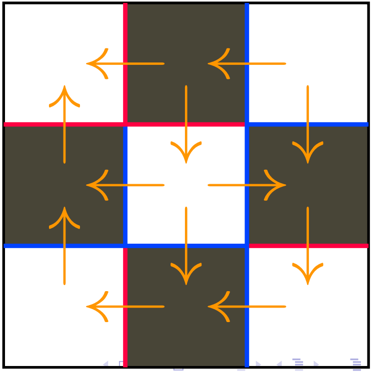


Partial Ordering

Goal:

Use checkerboard pattern and crease assignments to tell, for each pair of adjacent faces, which face comes first in *all* linear orderings.





Linear Orderings

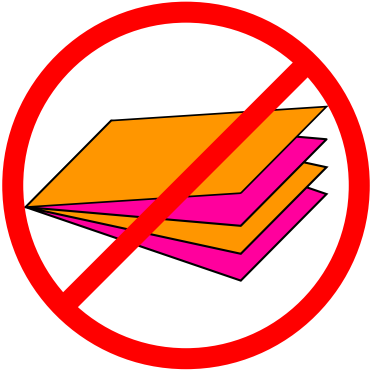
Is satisfying this partial ordering enough to ensure foldability?

Linear Orderings

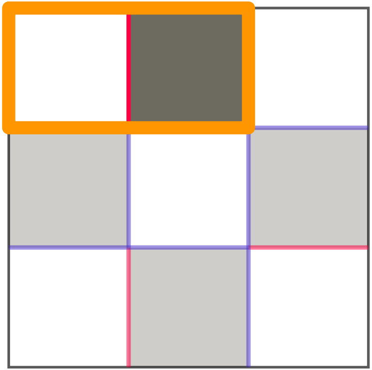
Is satisfying this partial ordering enough to ensure foldability? **No!**

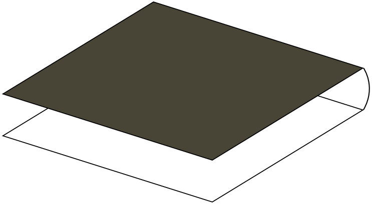
Linear Orderings

Is satisfying this partial ordering enough to ensure foldability? **No!**

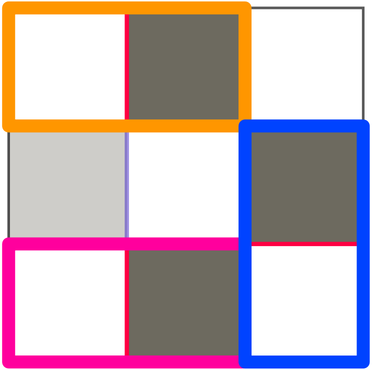


Butterflies

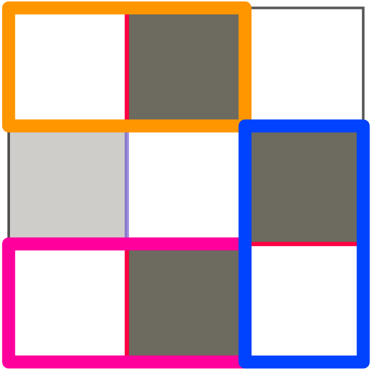


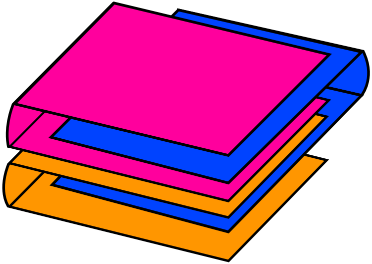


Butterflies



Butterflies

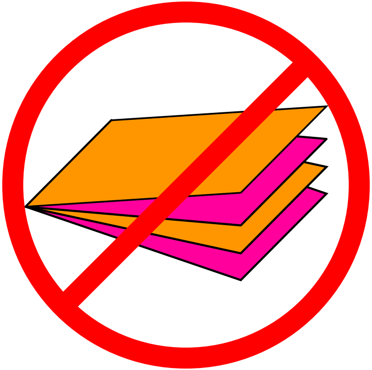




Butterfly Condition

Goal:

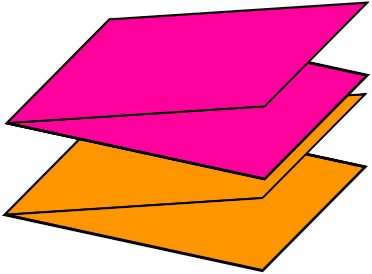
Enumerate the realizable configurations of twin butterfly pairs.



Butterfly Condition

Goal:

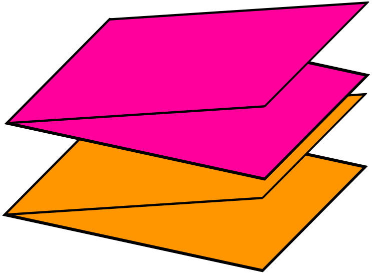
Enumerate the realizable configurations of twin butterfly pairs.

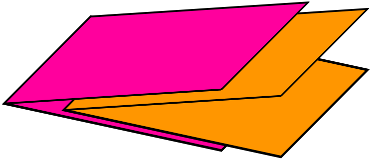


Butterfly Condition

Goal:

Enumerate the realizable configurations of twin butterfly pairs.





Linear Orderings: Conditions for Validity

Theorem: (Nishat and Whitesides 2013)

A linear ordering $\mathcal{L}$ of faces is flat-foldable if and only if (*i*) $\mathcal{L}$ satisfies the partial ordering given by the map and (*ii*) every pair of twin butterflies stacks or nests in $\mathcal{L}$.

Linear Orderings: Conditions for Validity

Theorem: (Nishat and Whitesides 2013)

A linear ordering $\mathcal{L}$ of faces is flat-foldable if and only if (*i*) $\mathcal{L}$ satisfies the partial ordering given by the map and (*ii*) every pair of twin butterflies stacks or nests in $\mathcal{L}$.

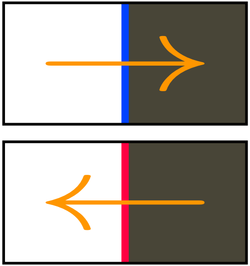
Proof: [$\Longrightarrow$] We have already proven this direction.

Linear Orderings: Conditions for Validity

Theorem: (Nishat and Whitesides 2013)

A linear ordering $\mathcal{L}$ of faces is flat-foldable if and only if (*i*) $\mathcal{L}$ satisfies the partial ordering given by the map and (*ii*) every pair of twin butterflies stacks or nests in $\mathcal{L}$.

Proof: [$\Longrightarrow$] We have already proven this direction.

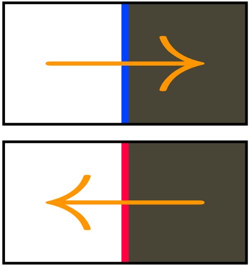


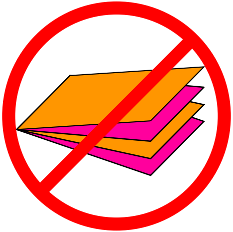
Linear Orderings: Conditions for Validity

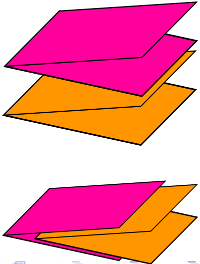
Theorem: (Nishat and Whitesides 2013)

A linear ordering $\mathcal{L}$ of faces is flat-foldable if and only if (i) $\mathcal{L}$ satisfies the partial ordering given by the map and (ii) every pair of twin butterflies stacks or nests in $\mathcal{L}$.

Proof: $[\implies]$ We have already proven this direction.







Linear Orderings: Conditions for Validity

Theorem: (Nishat and Whitesides 2013)

A linear ordering $\mathcal{L}$ of faces is flat-foldable if and only if (i) $\mathcal{L}$ satisfies the partial ordering given by the map and (ii) every pair of twin butterflies stacks or nests in $\mathcal{L}$.

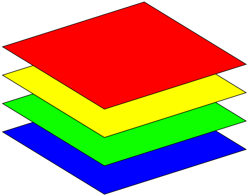
Proof: [$\Longleftarrow$] Let's prove this direction now.

Linear Orderings: Conditions for Validity

Theorem: (Nishat and Whitesides 2013)

A linear ordering $\mathcal{L}$ of faces is flat-foldable if and only if (i) $\mathcal{L}$ satisfies the partial ordering given by the map and (ii) every pair of twin butterflies stacks or nests in $\mathcal{L}$.

Proof: $[\Longleftarrow]$ Let's prove this direction now.

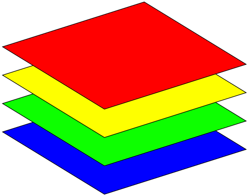


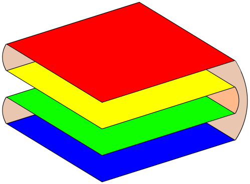
Linear Orderings: Conditions for Validity

Theorem: (Nishat and Whitesides 2013)

A linear ordering $\mathcal{L}$ of faces is flat-foldable if and only if (i) $\mathcal{L}$ satisfies the partial ordering given by the map and (ii) every pair of twin butterflies stacks or nests in $\mathcal{L}$.

Proof: [$\Longleftarrow$] Let's prove this direction now.





Computational Complexity of Validity Testing

Algorithm for determining whether or not a linear ordering is valid:

Computational Complexity of Validity Testing

Algorithm for determining whether or not a linear ordering is valid:

1. Check that the linear ordering satisfies the partial ordering given by the map.

Computational Complexity of Validity Testing

Algorithm for determining whether or not a linear ordering is valid:

1. Check that the linear ordering satisfies the partial ordering given by the map.
2. Check that every pair of twin butterflies stacks or nests.

Computational Complexity of Validity Testing

Algorithm for determining whether or not a linear ordering is valid:

1. Check that the linear ordering satisfies the partial ordering given by the map.
2. Check that every pair of twin butterflies stacks or nests.

This can be done in $\mathcal{O}(mn)$ (linear) time, which is super fast!

Computational Complexity of Validity Testing

Algorithm for determining whether or not a linear ordering is valid:

1. Check that the linear ordering satisfies the partial ordering given by the map.
2. Check that every pair of twin butterflies stacks or nests.

This can be done in $\mathcal{O}(mn)$ (linear) time, which is super fast!

Summary: If someone says "This map can be flat-folded, here is the folding," we can quickly test whether or not they were correct.

Goal:

Given a crease pattern, determine if it is flat-foldable.

Goal:

Given a crease pattern, determine if it is flat-foldable.

Result:

Given a linear order, we can determine if it is flat-folded really fast.

Goal:

Given a crease pattern, determine if it is flat-foldable.

Result:

Given a linear order, we can determine if it is flat-folded really fast.

Leveraging this into a solution:

Goal:

Given a crease pattern, determine if it is flat-foldable.

Result:

Given a linear order, we can determine if it is flat-folded really fast.

Leveraging this into a solution:

Given a crease pattern, check every linear ordering.

Goal:

Given a crease pattern, determine if it is flat-foldable.

Result:

Given a linear order, we can determine if it is flat-folded really fast.

Leveraging this into a solution:

Given a crease pattern, check every linear ordering.

If any of them are valid, then it is flat-foldable.

Goal:

Given a crease pattern, determine if it is flat-foldable.

Result:

Given a linear order, we can determine if it is flat-folded really fast.

Leveraging this into a solution:

Given a crease pattern, check every linear ordering.

If any of them are valid, then it is flat-foldable.

If none of them are valid, then it is not flat-foldable.

Goal:

Given a crease pattern, determine if it is flat-foldable.

Result:

Given a linear order, we can determine if it is flat-folded really fast.

Leveraging this into a solution:

Given a crease pattern, check every linear ordering.

If any of them are valid, then it is flat-foldable.

If none of them are valid, then it is not flat-foldable.

Theorem: (Vinitsky 2016)

$\textsc{Map Flat Foldability} \in \mathsf{NP}$

Counting Problems

Counting Problems in Origami

- How many ways can we fold an $m \times n$ map?
- How many $m \times n$ map crease patterns can be folded, period?

Counting Problems in Origami

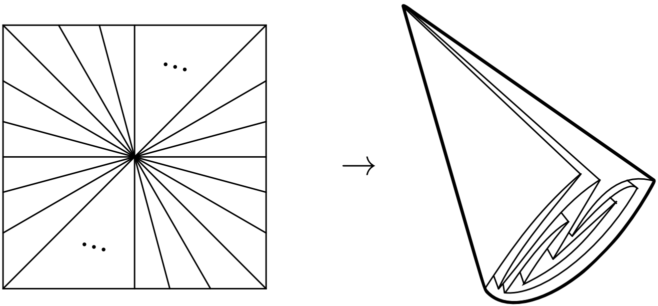
- How many ways can we fold an $m \times n$ map?
  - How many ways can we fold a $1 \times n$ map?
- How many $m \times n$ map crease patterns can be folded, period?

Counting Problems in Origami

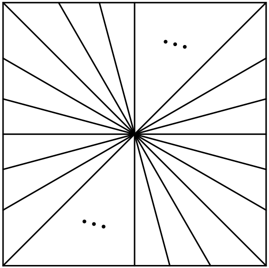
- How many ways can we fold an $m \times n$ map?
  - How many ways can we fold a $1 \times n$ map?
- How many $m \times n$ map crease patterns can be folded, period?
  - How many $1 \times n$ map crease patterns have a valid folding?

Star Patterns

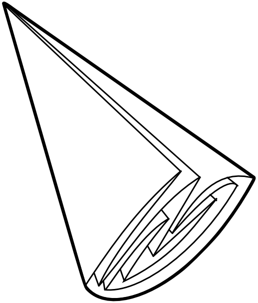
Star Patterns



Star Patterns



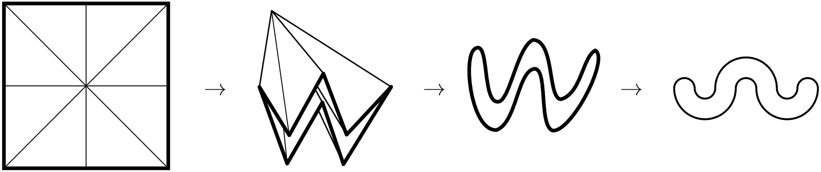
$\rightarrow$



Question: How many foldings are generated by star patterns with $2n$ creases?

Representing foldings of Star Patterns

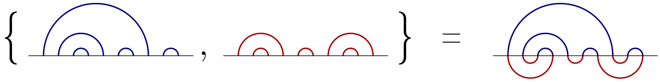
Representing foldings of Star Patterns



Meanders

Definition (Closed Meanders)

A *closed meander* of order n has two collections of n arches such that when they are placed opposite each other on a line, they form a Jordan curve.

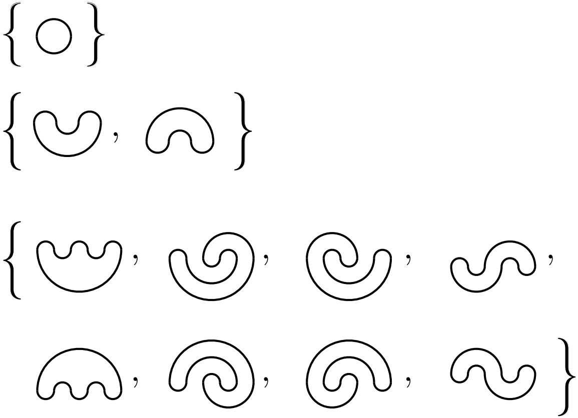


Examples of Meanders

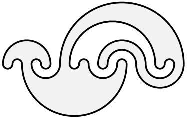
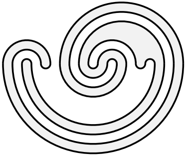
$n = 1$

$n = 2$

$n = 3$



Examples of Meanders

$n = 10$ { ... ,  ,  , ... }

Examples of Meanders

Order n	**# Meanders** M_n
1	1
2	2
3	8
4	42
5	262
$\vdots$	$\vdots$

Table : The sequence of Meandric Numbers

Examples of Meanders

Order n	**# Meanders** M_n
1	1
2	2
3	8
4	42
5	262
$\vdots$	$\vdots$
10	
$\vdots$	$\vdots$

Table : The sequence of Meandric Numbers

Examples of Meanders

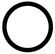
Order n	**# Meanders** M_n
1	1
2	2
3	8
4	42
5	262
⋮	⋮
10	8,152,860
⋮	⋮

Table : The sequence of Meandric Numbers

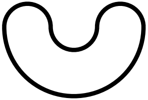
Our Method

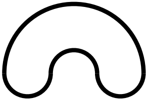
Game Plan

$$n = 1$$

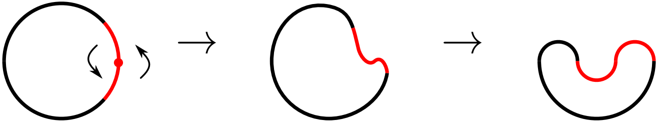


$$n = 2$$

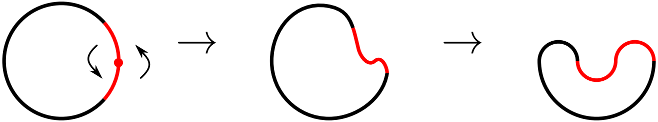




Game Plan

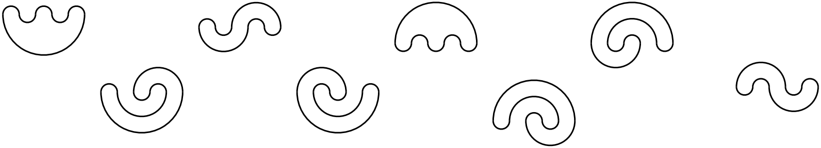


Game Plan

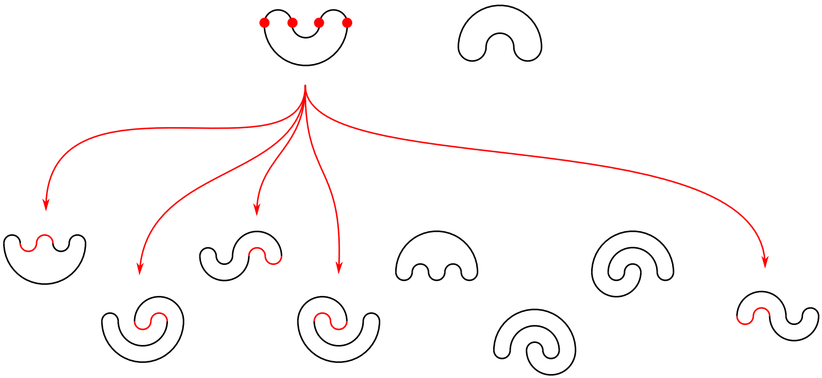


Idea: Produce larger meanders by adding "twists" to smaller meanders

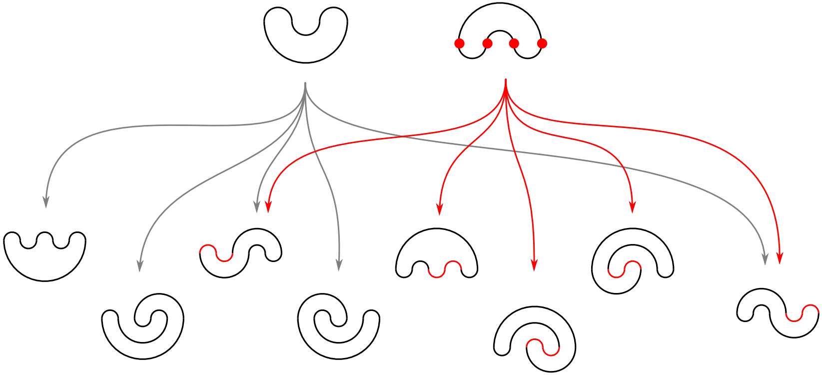
Will it work?



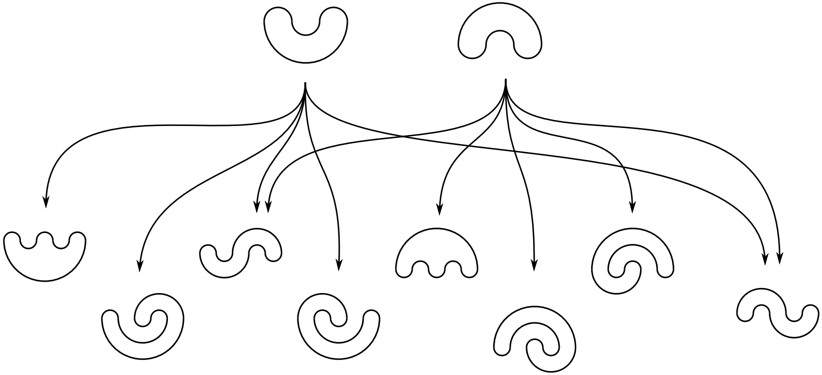
Will it work?



Will it work?



Will it work?



Will it work?

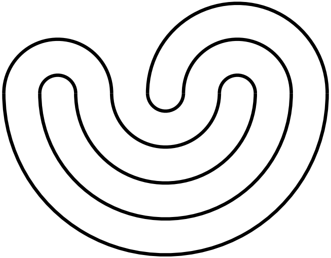
Question: Can we get all meanders by repeatedly doing this?

Will it work?

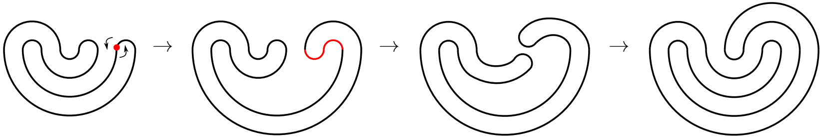
Question: Can we get all meanders by repeatedly doing this?
Answer:

Will it work?

Question: Can we get all meanders by repeatedly doing this?
Answer: Sadly we cannot:



Will it work?



Meanders

Theorem (Slote 2016)

Every meander of order n can be produced from some meander of order $n-1$ with a single twist and at most one shuffle.

Two issues to address:

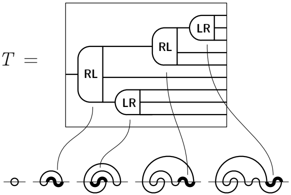
1. Different twists yield the same meander (double counting)
2. Shuffling is necessary but further increases double counting

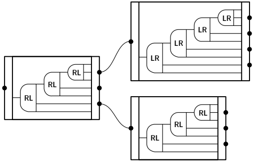
Simple Meanders

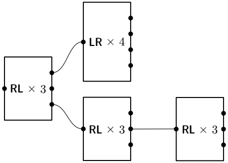
Definition (Simple Meander)

A *simple meander* is a meander of order n that can be constructed without shuffling.

Another picture

$T =$ 





Simple Meanders

Theorem (Slote 2016)

Let $\mathbb{P}(k,n) = \{(x_1, x_2, \ldots, x_n) : \sum x_i = k \text{ and } x_i \geq 0 \forall i\}$. *Then*

$$r(n) = \sum_{i=1}^{n} \sum_{P \in \mathbb{P}(i,n+1)} \prod_{k=1}^{n+1} r(P_k)$$

$$H(n) = \sum_{i=1}^{n} r(i) \sum_{P \in \mathbb{P}(i,n)} \prod_{k=1}^{n} H(P_k)$$

$$M_n^s = 2H(n)$$

Thank You!

Make sure to stop by our exhibit in the Gould Library!

Opening Spring Term 2016

References

Rahnuma Islam Nishat and Sue Whitesides
Map Folding
Canadian Conference on Computational Geometry (2013), p. 49-52

Robert J. Lang
Huzita-Justin Axioms
Robert J. Lang Origami

Shepherd Engle
Origami, Algebra, and the Cubic (2012)

References

Thomas C. Hull
The Combinatorics of Flat Folds: A Survey
Origami³ (2002)

Thomas C. Hull, Sarah-Marie Belcastro
Modelling the folding of paper into three dimensions using affine transformations
Linear Algebra and its Applications vol. 348 (2002), p. 273-282