Science Dialogue at Okazaki High School

Aaron Chan

Graduate School of Mathematics, Nagoya University

December 14, 2018

A bit on my background

Name: Aaron Chan

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Sweden ($>$ 1 year)

A bit on my background

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$\rightsquigarrow$ so I speak English in a mix of Cantonese accent, contemporary Received Pronunciation ($\approx$ "proper" British English), and Multicultural London accent.

A bit on Hong Kong

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Well-known for.... may be this guy:

Photo source: imdb.com

A bit on Hong Kong

or view like this:

Photo source: fodors.com

A bit on UK

Well-known for.... may be these:

Photo source: buckinghampalace.com

A bit on UK

Photo source: visitlondon.com

A bit on UK

Photo source: The Beatles - Abbey Road

A bit on UK

Photo source: Queen - Bohemian Rhapsody

A bit on UK

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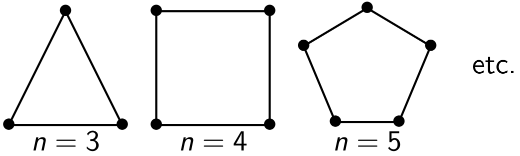
- etc. etc.

Break

Any question?

Triangulating polygons

Consider a (convex) polygon with $n \geq 3$ sides (=**edges**).



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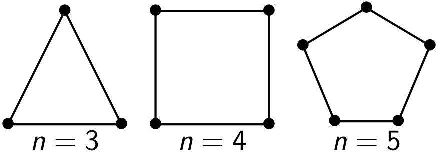
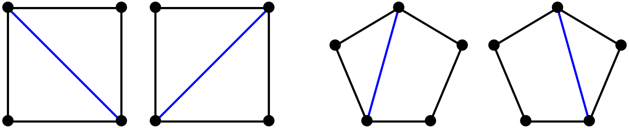


etc.

If we draw a straight line between two corners (**vertices**) of an n-gon, then it can be divided into "smaller polygons".



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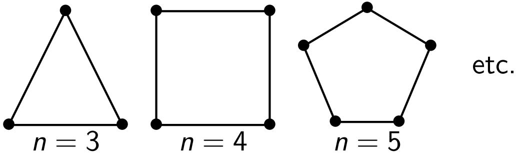

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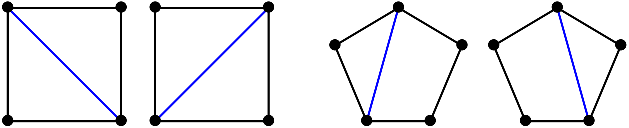
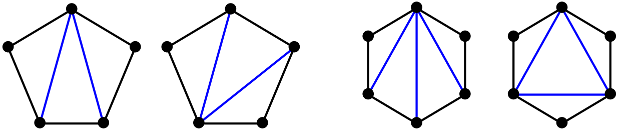


We can keep on dividing the smaller polygons into even smaller polygons. At the end, we can see that a polygon is divided into pieces of triangles.

Triangulating polygons

A **triangulation** of a polygon = a division of the said polygon into triangles in the way we just described.



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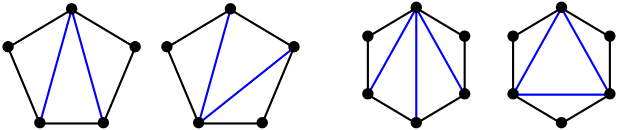

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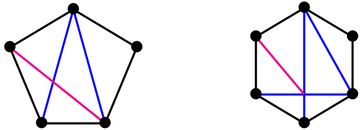

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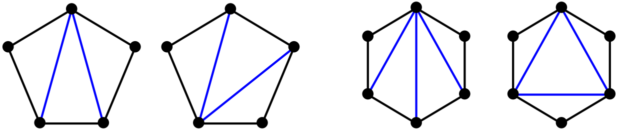

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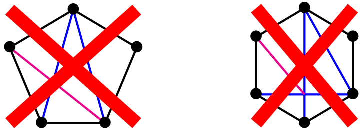

Play Time!

TASK

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TASK Discuss, in groups of 3 or 4:

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1. Find all triangulations of a 5-gon (pentagon).

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1. Find all triangulations of a 5-gon (pentagon).
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3. When are two triangulations "almost the same"?

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4. (Optional) How many blue lines are in a triangulation?

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Discussion time: $5 \sim 10$ min.

Play Time!

TASK Discuss, in groups of 3 or 4:

1. Find all triangulations of a 5-gon (pentagon).
   Hint: There are 5 of them.
2. Find all triangulations of a 6-gon (hexagon).
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TASK Discuss, in groups of 3 or 4:

1. Find all triangulations of a 5-gon (pentagon).
   Hint: There are 5 of them.
2. Find all triangulations of a 6-gon (hexagon).
   Hint: There are 14 of them.
3. When are two triangulations "almost the same"?

4. (Optional) How many blue lines are in a triangulation?

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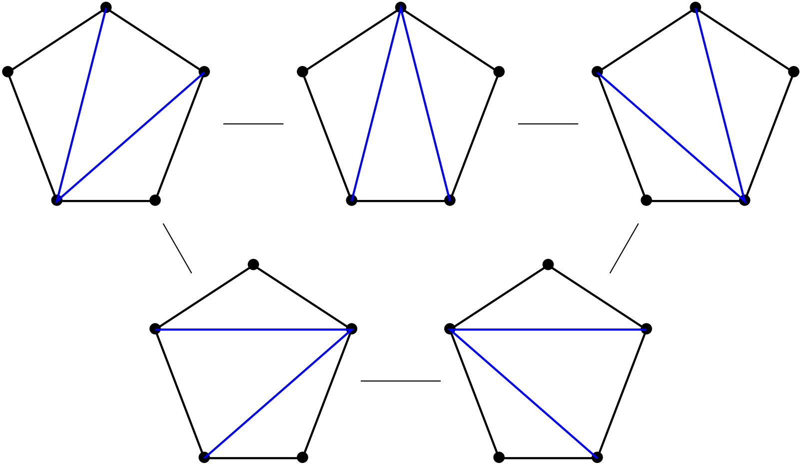
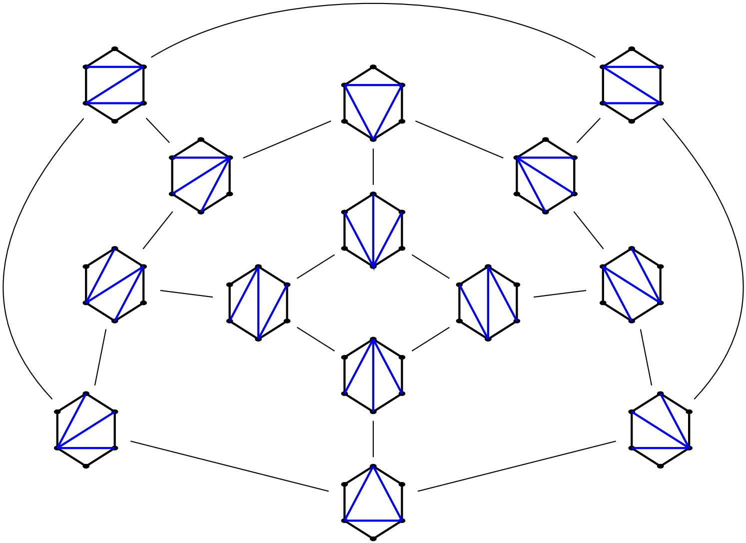
Triangulations of a 5-gon



Triangulations of a 6-gon



How do we know we have got all of them?

In the pictures before, we drew a line between two different triangulation if they are **differ by only one blue line**(=**arc**)

(= they are "almost the same").

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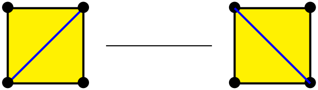

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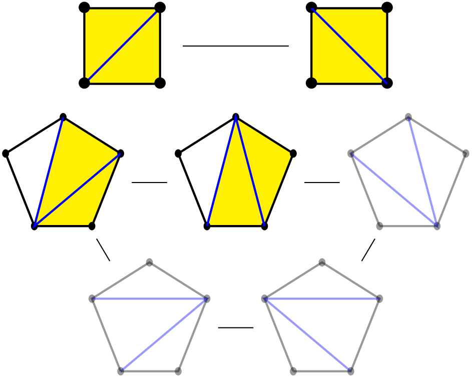

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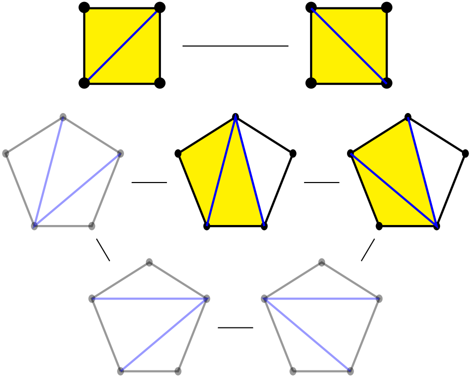

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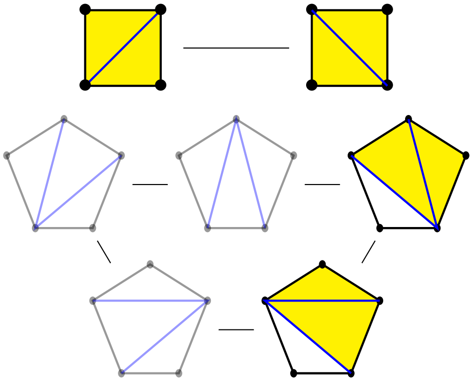

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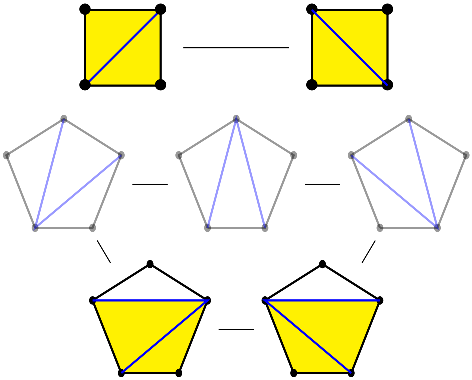

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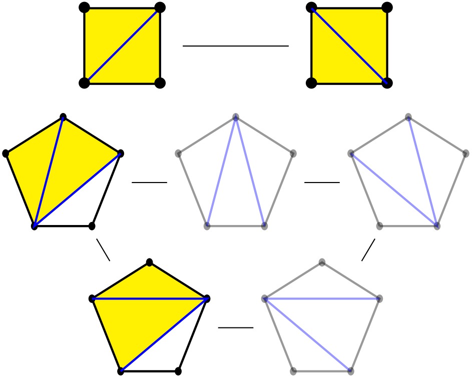

Flip of triangulations

Two triangulations A, B are almost the same $\Rightarrow$ we can obtain A from B by **flipping one arc**, vice versa.

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Observing from the cases of square, pentagon, and hexagon, it is natural to expect the following results.

Expectation

1. For any triangulation of an n-gon, there are the same number (precisely, $n-3$) of arcs.
2. Starting from any triangulation of an n-gon, we can obtain any other triangulation by *repeatedly flipping arcs*.

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2. Starting from <u>any</u> triangulation of an n-gon, we can obtain <u>any</u> other triangulation by *repeatedly flipping arcs*.

For the first expectation: EXERCISE for the keen audience.

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For the second problem...
Well, let us start with an "easy triangulation".

Flip of triangulations

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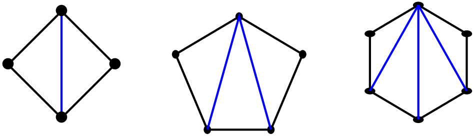
The **fan triangulation**:



etc.

where every arc touches the (!)fixed(!) vertex of the polygon.

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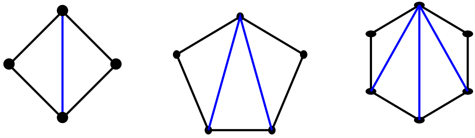

etc.

where every arc touches the (!)<u>fixed</u>(!) vertex of the polygon.

Let's try this "easier" problem:

Can we always "any triangulation $\overset{\text{flip flip flip}}{\rightsquigarrow}$ fan"?

Play time again!

TASK Discuss, in groups of 3 or 4:

- an algorithm/strategy to flip from any triangulation to a fan.

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If you prefer an (...may be...) easier problem, try to prove that:

- any triangulation of an n-gon has precisely $n - 3$ arcs.

Some guide

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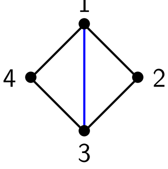
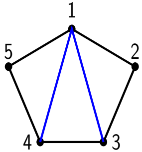
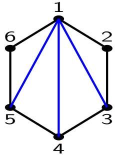
2. Label the vertices by $1, 2, \ldots, n$ clockwise.







Then fan triangulation = all arcs touching the vertex 1.

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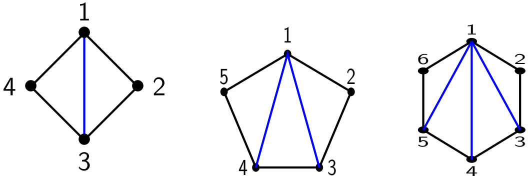

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3. $\rightsquigarrow$ the number of arcs touching vertex 1 "measures" how close a triangulation is from being a fan!

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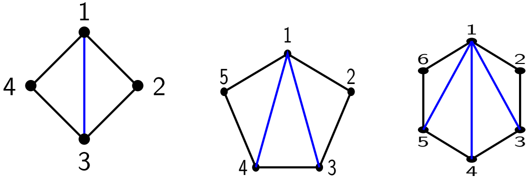

Then fan triangulation = all arcs touching the vertex 1.

3. $\rightsquigarrow$ the number of arcs touching vertex 1 "measures" how close a triangulation is from being a fan!

More hint:

- Any arc divides a polygon into two smaller polygons $\rightsquigarrow$ use **induction** (帰納法) on n

Flip towards the fan

Start with any triangulation, look at vertex 1.

Flip towards the fan

Start with any triangulation, look at vertex 1.

If all arcs touch the vertex 1, then we are done!

Flip towards the fan

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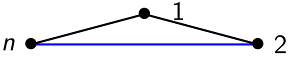
If there is no arc touching vertex 1:

Start with any triangulation, look at vertex 1.

If there is no arc touching vertex 1:

- There must be a triangle:



which is inside some square (with vertices $1, 2, n, k$ some k).

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  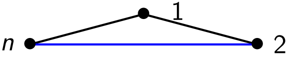

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- Flip the arc 

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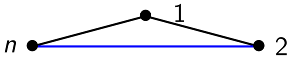

  which is inside some square (with vertices $1, 2, n, k$ some k).
- Flip the arc 

- There is now 1 arc touching vertex 1! (closer to fan!)

Flip towards the fan

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If there is an arc $(1, k)$ touching vertex 1 and vertex k:

Flip towards the fan

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If there is an arc $(1, k)$ touching vertex 1 and vertex k:

- note that $k \neq 1, 2, n$.

Flip towards the fan

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If there is an arc $(1, k)$ touching vertex 1 and vertex k:

- note that $k \neq 1, 2, n$.
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- note that $k \neq 1, 2, n$.
- Arc $(1, k)$ divides the n-gon into a k-gon and an $(n - k + 1)$-gon
- Observe we have triangulations on both smaller polygons.

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- Apply induction hypothesis:

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- Observe we have triangulations on both smaller polygons.
- Apply induction hypothesis: We can flip the triangulation in each of the smaller polygons to a fan.

Flip towards the fan

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- Now all arcs touch vertex 1,

Flip towards the fan

Start with any triangulation, look at vertex 1.

If there is an arc $(1, k)$ touching vertex 1 and vertex k:

- note that $k \neq 1, 2, n$.
- Arc $(1, k)$ divides the n-gon into a k-gon and an $(n - k + 1)$-gon
- Observe we have triangulations on both smaller polygons.
- Apply induction hypothesis: We can flip the triangulation in each of the smaller polygons to a fan.
- Now all arcs touch vertex 1, so a fan in the big n-gon!

Example

Give me any random triangulation and let us work together on the blackboard.

Final Step

Now we have:

$$\text{any triangulation} \overset{\text{flip}}{} \overset{\text{flip}}{\rightsquigarrow} \overset{\text{flip}}{} \text{fan triangulation}$$

Final Step

Now we have:

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Because flipping an arc is a reversible operation (flip an arc twice = do nothing), so we also have:

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JOB DONE!

How many triangulations for an n-gon?

Let C_n be the number of triangulations for an $(n+2)$-gon.

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Due to time constraint, we will not discuss why this is the correct formula, Google it if you are interested!

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Of course, also read Wikipedia on Catalan combinatorics.

Finally...

Thank you for having me here.

Any further questions? (can be on anything, maths or not)

Extra: More examples of Catalan combinatorics

(1) Handshake around a round table:
If you have $2n$ people sitting around a round table,
each of you are required to shake hand with one other person sitting around the table,
and none of the handshake shall crosses each other.
Count the number of all possible such handshake, then you will get the Catalan number C_n.

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(2) Ballot sequence:
Imagine a queue with $2n$ people, n girls and n boys.
The queue must obey the following rule:
Number of (girls from person 1 to person k) $\geq$ Number of (boys from person 1 to person k)
for any $k = 1, 2, \ldots, 2n$.
Such a queue is called a ballot sequence.
Number of ballot sequences with $2n$ people is, again, C_n.

Extra: Why I become a maths researcher?

Chapter 1

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- started to find sciences are more interesting and beautiful (elegant) than I thought
- decided to study Mathematics + Computer Science for university

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So I thought...may be I should do mathematics (=playing games) as my job?

Have a very Merry Christmas

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Have a very Merry Christmas and a Happy New Year!!