

# Communicate Without Errors

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- ▶ Channel Capacity
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# Channel

## Definition (channel)

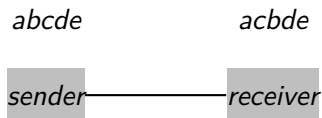
A channel has a sender and a receiver.

# Channel

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A message is a finite sequence of characters. The sender sends a message to the receiver.

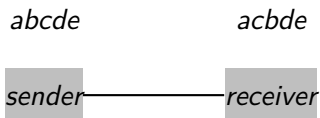


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The receiver receives message and decode it.

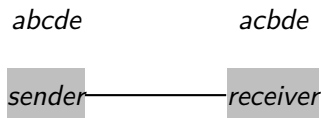


# Channel

## Definition (channel)

A channel has a sender and a receiver.

A message is a finite sequence of characters. The sender sends a message to the receiver.



The receiver receives message and decode it.

However, in the procedure of send and receive, the channel may introduce some errors. For instance, here, character *b* is decoded into *c*.

# Channel

## Definition (confusable)

Given two characters  $a$ ,  $b$ . If  $a$  and  $b$  have chance to be decoded into a same character say  $c$ , we say  $a$  and  $b$  are confusable.

For a two messages of length  $n$ , say  $a_1 a_2 \dots a_n$ ,  $b_1 b_2 \dots b_n$  is confusable if and only if  $a_i$  and  $b_i$  are confusable for every  $i$ .

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## Definition (rate of channel)

The rate of channel actually represent how many distinct character can be send per unit time.

Given a channel that could send  $r$  distinct characters per unit time. And send message with length  $n$ , so the number of distinct messages the channel can send is  $r^n$ .

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Conversely, given a channel that could send  $m$  distinct messages with length  $n$ . And could be able to send only one character per unit time. The rate of channel is  $\sqrt[n]{m}$ .

Here, we do not care about how much characters. We only care about the number of all messages we can send.

# Channel

## Definition (zero error rate)

Given a channel which could transfer messages of length  $n$ .

We want to find the maximum set of messages  $M$  that no two of them is confusable.

$$\text{zero error rate} = \max_M \sqrt[n]{|M|} \quad (1)$$

# Channel

If given a set of characters  $S$ , and some of the characters could be confusable.

We want to find

$$\sup_n \{\text{zero error rate of channel with length } n \text{ and } S \text{ as characters}\} \quad (2)$$

And we call this the shannon Capacity and denoted by  $\Theta(S)$ . Clearly, shannon Capacity is actually a function of the set of characters. So, we want a more abstract way to represent the characters.

# Graph Representation Of Characters

## Definition (graph)

A graph  $G$  is a set of vertices with a set of edges connecting pairs of vertices.

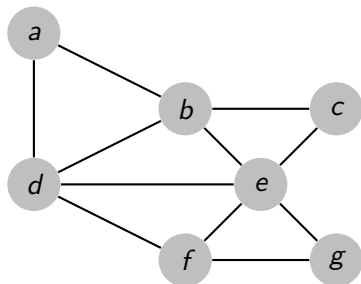


Figure: An example of a graph.

# Graph Representation Of Characters

## Definition

Given a channel that sending  $\{1, 2, \dots, n\}$  as characters. And some characters  $i$  and  $j$  could be confused with each other.

Then the graph representation of the characters is the graph with vertices  $\{1, 2, \dots, n\}$  and edges  $(i, j)$  if and only if  $i$  and  $j$  could be confused with each other.

Accordingly, there is the corresponding way that using graphs to represent a message zero error rate and Shannon Capacity.



# Product Graph

## Definition (graph product)

The product of two graphs can be considered as send a pair of characters  $(x, y)$  as one message. So, we have a channel that send messages of length 2.

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Recall that before, 2 messages is confusable means that they can be decoded into the same message, which means every characters the two channel use need to be confusable.

Given two graph  $G$  and  $H$ . The graph product  $G \times H$  is the graph with vertices  $V(G \times H) = V(G) \times V(H)$  in which  $(x, y)$  is adjacent to  $(x', y')$  in  $G \times H$  if and only if  $x$  is adjacent to  $x'$  in  $G$  and  $y$  is adjacent to  $y'$  in  $H$ .

# Product Graph

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A graph  $G$  product itself for  $n$  times will always be denoted by  $G^n$ . Which means we could use  $G^n$  to represent messages of a channel with length  $n$ .

$$\alpha(G)$$

### Definition ( $\alpha(G)$ )

The  $\alpha(G)$  represent the maximum number of characters or message that could not be confused with each other in graph  $G$ . If  $G$  represent a set of messages,  $\alpha(G)$  is just the zero error rate we have defined before.

# $\alpha(G)$

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The  $\alpha(G)$  represent the maximum number of characters or message that could not be confused with each other in graph  $G$ . If  $G$  represent a set of messages,  $\alpha(G)$  is just the zero error rate we have defined before.

Given a graph  $G$ . Given a subgraph  $H$  of  $G$ , such that every vertex of  $H$  is not connected in  $G$ . Then  $\alpha(G)$  is the maximum number of vertices of  $H$ .

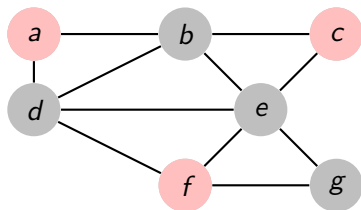


Figure: Example of  $\alpha(G)$ . Here  $\alpha(G) = 3$ .

# Shannon Capacity

## Definition (Shannon Capacity)

Recall that Shannon Capacity is

$$\sup_n \{ \text{zero error rate of channel with length } n \text{ and } S \text{ as characters} \} \quad (3)$$

Use the graph  $G$  to represent the set of characters, the Shannon capacity  $\Theta(G)$  is defined by

$$\Theta(G) = \sup_n \sqrt[n]{\alpha(G^n)} \quad (4)$$

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## Lower Bound of $\Theta(C_5)$

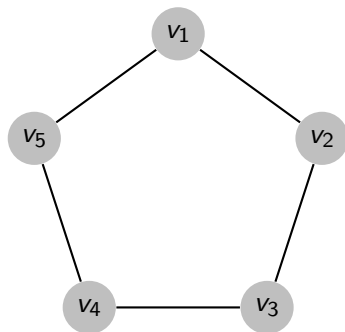


Figure:  $C_5$

The  $\alpha(C_5)$  is clearly equal to 2.



## Lower Bound of $\Theta(C_5)$

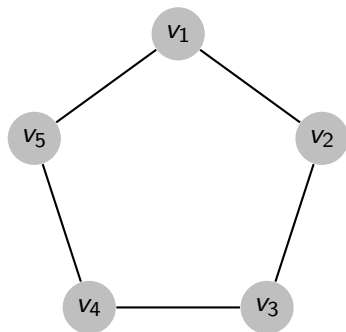


Figure:  $C_5$

The  $\alpha(C_5)$  is clearly equal to 2.

We want to show that  $\alpha((C_5)^2) \geq 5$ .

Thus  $\Theta(C_5) \geq \sqrt{\alpha((C_5)^2)} \geq \sqrt{5}$

## Lower Bound of $\Theta(C_5)$



Figure:  $(C_5)^2$

## Lower Bound of $\Theta(C_5)$

It is messy to draw edges in the graph of  $(C_5)^2$ . So we use the following graph to give some idea of  $(C_5)^2$ . But it is clear that every point is adjacent to the 8 points around it.

Point  $v_{ij}$  represent the vertex  $(v_i, v_j)$  in  $(C_5)^2$ .

The green points are the same with the corresponding red points, we use it just for the convenience of visualization.

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We will choose five points  $v_{11}$ ,  $v_{23}$ ,  $v_{35}$ ,  $v_{42}$ ,  $v_{54}$ , and show that they are mutually not adjacent.

## Lower Bound of $\Theta(C_5)$



Figure:  $(C_5)^2$

# Alpha Function of Product Graph

## Lemma

$$\alpha(G)\alpha(H) \leq \alpha(G \times H)$$

# Alpha Function of Product Graph

## Lemma

$$\alpha(G)\alpha(H) \leq \alpha(G \times H)$$

## Proof.

Given graph  $G$  and  $H$ . Let  $G'$  and  $H'$  be subgraph of  $G$  and  $H$  such that no vertex of  $G'$  or  $H'$  is adjacent in  $G$  or  $H$ , respectively. Then  $G' \times H'$  is a subgraph of  $G \times H$  such that no vertex of  $G' \times H'$  is adjacent in  $G \times H$ . □

# Orthonormal Representation

Here we have the third way to defined a set of characters.

## Definition (Orthonormal Representation)

Given a graph  $G$  with vertices  $1, 2, \dots, n$ , the orthonormal representation of  $G$  is a set of unit vectors  $\{v_1, v_2, \dots, v_n\}$  such that  $v_i$  and  $v_j$  are orthogonal if and only if  $i$  and  $j$  are not adjacent in  $G$ .



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This existence of the orthonormal representation can be proved by induction.

# Tensor Product

## Definition (tensor product)

Given two vectors  $v = (v_1, \dots, v_n)$  and  $w = (w_1, \dots, w_n)$ , the tensor product  $v \circ w$  is defined by

$$v \circ w = (v_1 w_1, \dots, v_1 w_n, v_2 w_1, \dots, v_2 w_n, \dots, v_n w_1, \dots, v_n w_n) \quad (5)$$

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## Lemma

*The inner product of tensor products can be computed by,*

$$\langle v \circ w, v' \circ w' \rangle = \langle v, v' \rangle \langle w, w' \rangle \quad (6)$$

# Product of Orthonormal Representation

This is the product of graph in the sense of orthonormal representation.

## Lemma

*Given a graph  $G$  with vertices  $1, 2, \dots, n$ , and a graph  $H$  with vertices  $1, 2, \dots, m$ . Then vectors  $\{v_i \circ w_j\}$  is an orthonormal representation of  $G \times H$ .*

# Theta Function

Given a graph  $G$ , the  $\theta(G)$  is defined by

$$\theta(G) = \inf_{\{v_1, v_2, \dots, v_n\}, c} \max_i \frac{1}{\langle c, v_i \rangle^2} \quad (7)$$

where  $\{v_1, v_2, \dots, v_n\}$  is an orthonormal representation of  $G$ , and  $c$  is any unit vector does not orthogonal to  $v_i$ .

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where  $\{v_1, v_2, \dots, v_n\}$  is an orthonormal representation of  $G$ , and  $c$  is any unit vector does not orthogonal to  $v_i$ .

## Lemma

*There always exist such an  $c$  and orthonormal representation  $\{v_1, v_2, \dots, v_n\}$  such that*

$$\theta(G) = \max_i \frac{1}{\langle c, v_i \rangle^2} \quad (8)$$

This could be proved by proving the set of all possible cases of  $\{v_1, v_2, \dots, v_n, c\}$  is compact. And the function  $\max \frac{1}{\langle c, v_i \rangle^2}$  is continuous.

# Theta Function of Product Graph

## Lemma

*Given graph  $G$  and  $H$ , then*

$$\theta(G \times H) \leq \theta(G)\theta(H) \quad (9)$$

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## Lemma

*Given graph  $G$  and  $H$ , then*

$$\theta(G \times H) \leq \theta(G)\theta(H) \quad (9)$$

## Proof.

Let  $\{v_1, v_2, \dots, v_n\}$  and  $\{w_1, w_2, \dots, w_m\}$  be orthonormal representation of  $G$  and  $H$  and  $c_v$  and  $c_w$  such that

$$\max \left\{ \frac{1}{\langle c_v, v_i \rangle^2} : i = 1, 2, \dots, n \right\} = \theta(G) \quad (10)$$

and

$$\max \left\{ \frac{1}{\langle c_w, w_i \rangle^2} : i = 1, 2, \dots, m \right\} = \theta(H) \quad (11)$$





Proof.

Then

$$\theta(G \times H) \leq \max \left\{ \frac{1}{\langle c_v \circ c_w, v_i \circ w_j \rangle^2} \right\} \quad (12)$$

$$= \max \left\{ \frac{1}{\langle c_v, v_i \rangle^2 \langle c_w, w_j \rangle^2} \right\} \quad (13)$$

$$= \max \left\{ \frac{1}{\langle c_v, v_i \rangle^2} \right\} \max \left\{ \frac{1}{\langle c_w, w_j \rangle^2} \right\} \quad (14)$$

$$= \theta(G)\theta(H) \quad (15)$$

$$(16)$$



# Relation of Theta Function and Alpha Function

Lemma

$$\theta(G) \geq \alpha(G) \quad (17)$$

# Relation of Theta Function and Alpha Function

## Lemma

$$\theta(G) \geq \alpha(G) \quad (17)$$

## Proof.

Let  $\{1, 2, \dots, k\}$  be the set of vertices of  $G$  such that every point is not adjacency in  $G$ . And  $k = \alpha(G)$

Let  $\{v_1, v_2, \dots, v_n\}$  be an orthonormal representation of  $G$  and  $c$  such that

$$\max \left\{ \frac{1}{\langle c, v_i \rangle^2} \right\} = \theta(G) \quad (18)$$

Then

$$1 = c^2 \geq \sum_{i=1}^k \langle c, v_i \rangle^2 \geq \frac{k}{\theta(G)} \quad (19)$$

# Relation of Theta Function and Shannon Capacity

## Theorem

*Given a graph  $G$ , then*

$$\theta(G) \geq \Theta(G) \quad (20)$$

# Relation of Theta Function and Shannon Capacity

## Theorem

*Given a graph  $G$ , then*

$$\theta(G) \geq \Theta(G) \quad (20)$$

*Proof.*

$$\Theta(G) = \lim_n \sqrt[n]{\alpha(G^n)} \quad (21)$$

$$\leq \lim_n \sqrt[n]{\theta(G^n)} \quad (22)$$

$$\leq \lim_n \sqrt[n]{\theta(G)^n} \quad (23)$$

$$= \theta(G) \quad (24)$$



The final result we want to prove today,

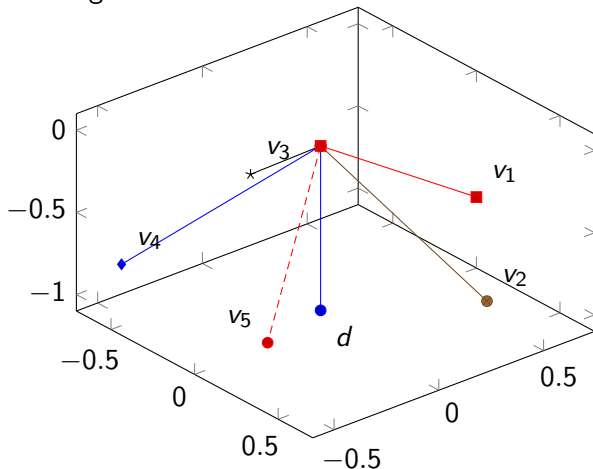
$$\Theta(C_5) \leq \theta(C_5) \leq \sqrt{5} \quad (25)$$

## Theorem

$$\theta(C_n) \leq \sqrt{5} \quad (26)$$

## Proof.

Consider an umbrella that has a handle and 5 ribs that all have unit length. And also its handle is a unit vector.





### Proof.

Here, angles between two consecutive ribs are same.

Let  $v$  be a rib. And let  $w$  be one of the rib that have the largest angle with  $v$ . Then, we let the angle between  $v$  and  $w$  be  $\pi/2$ .

Then, the 5 ribs of such an umbrella form an orthonormal representation of  $C_5$ .

Let  $d$  be the vector represent the handle, and  $v_1, v_2, \dots, v_5$  be the 5 ribs. And let  $\gamma$  be the angle between the handle and any rib.

So, by some calculation, we get

$$\theta(C_5) \leq \max_{\langle d, v_i \rangle} \frac{1}{\langle d, v_i \rangle^2} \quad (27)$$

$$= \left( \frac{1}{\cos(\gamma)} \right)^2 \quad (28)$$

$$= \sqrt{5} \quad (29)$$



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# Conclusion

- ▶ We have proved that  $\Theta(C_5) = \sqrt{5}$
- ▶ We could actually prove that  $\Theta(C_n)$  is equal to  $n \frac{\cos(\pi/n)}{1+\cos(\pi/n)}$ .

# Open Questions

- ▶ Although  $\Theta(C_n)$  is equal to  $n \frac{\cos(\pi/n)}{1+\cos(\pi/n)}$ , but we still don't know the exact value of  $\Theta(C_n)$ . Even for  $n = 7$
- ▶ Is there any good lower bound for  $\Theta(C_n)$ ?
- ▶ Is there any patterns for  $n$  such that  $\Theta(C_n)$  is hard to compute?

# Discussion

In the real world cases, we always have some kind of relay between the sender and receiver. So the new channel is kind of composite of two channel. Can we compute Shannon Capacity these channels independently and then combine them together to get the Shannon Capacity of the new Channel?

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- ▶ On the Shannon Capacity of a Graph by Laszlo Lovasz
- ▶ The zero error capacity of a noisy channel by Claude Shannon