

# Title

D. Zack Garza

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### 0.1 Exercises

#### Problem 1.

Let  $C$  denote the Cantor set.

1. Show that  $C$  contains point that is not an endpoint of one of the removed intervals.
2. Show that  $C$  is nowhere dense, meager, and has measure zero.
3. Show that  $C$  is uncountable.

#### Solution 1.

1. First we will characterize the endpoints of the removed intervals. Let  $C_n$  be the  $n$ th stage of the deletion process that is used to define the Cantor set; then what remains is a union of intervals:

$$C_n = [0, \frac{1}{3^n}] \cup [\frac{2}{3^n}, \frac{3}{3^n}] \cup \cdots \cup [\frac{3^n - 1}{3^n}, 1],$$

and so the endpoints are precisely the numbers of the form  $\frac{k}{3^n}$  where  $0 \leq k \leq 3^n$ . Moreover, any endpoint appearing in  $C_n$  is never removed in any later step, and so all endpoints remaining in  $C$  are of this form where we allow  $0 \leq n < \infty$ .

Thus, our goal is to produce a number  $x \in [0, 1]$  such that  $x \neq \frac{k}{3^n}$  for any  $k$  or  $n$ , but also satisfies  $x \in C$ . So we will need a general characterization of all of the points in  $C$ .

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Lemma: If  $x \in C$ , then one can find a ternary expansion for which all of the digits are either 0 or 2, i.e.

$$x = \sum_{k=1}^{\infty} a_k 3^{-k} \quad \text{where } a_k \in \{0, 2\}.$$

Proof: By induction on the index  $k$  in  $a_k$ , first consider note that if  $x \in C$  then  $x \in C_1 = [0, 1] \setminus [\frac{1}{3}, \frac{2}{3}] = [0, \frac{1}{3}] \cup [\frac{2}{3}, 1]$ . So if  $x \in C_1$ , then  $x \notin (\frac{1}{3}, \frac{2}{3})$ . But note that  $a_1$  is computed in the following way:

$$a_1 = \begin{cases} 0 & 0 \leq x < \frac{1}{3}, \\ 1 & \frac{1}{3} \leq x < \frac{2}{3}, \\ 2 & \frac{2}{3} \leq x < 1. \end{cases}$$

Since the interval  $(\frac{1}{3}, \frac{2}{3})$  is deleted in  $C_1$ , we find that  $a_1 = 1 \iff x = \frac{1}{3}$ . In this case, however, we claim that we can find a ternary expansion of  $x$  that does not contain a 1. We first write

$$x = \frac{1}{3} = \sum_{k=1}^{\infty} a_k 3^{-k} \quad \text{where } a_1 = 1, a_{k>1} = 0,$$

and then define

$$x' = \sum_{k=1}^{\infty} b_k 3^{-k} \quad \text{where } b_1 = 0, b_{k>1} = 2.$$

The claim now is that  $x = x'$ , which follows from the fact that this is a geometric sum that can be written in closed form:

$$\begin{aligned} x' &= \sum_{k=2}^{\infty} (2) 3^{-k} \\ &= \left( \sum_{k=0}^{\infty} (2) 3^{-k} \right) - 2 - 2(3^{-1}) \\ &= 2 \left( \sum_{k=0}^{\infty} 3^{-k} \right) - 2 - 2(3^{-1}) \\ &= 2 \left( \frac{1}{1 - \frac{1}{3}} \right) - 2 - 2(3^{-1}) \\ &= 2 \left( \frac{3}{2} \right) - 2 - 2(3^{-1}) \\ &= 1 - \frac{2}{3} \\ &= \frac{1}{3} = x. \end{aligned}$$

In short, we have  $\frac{1}{3} = (0.1)_3 = (0.222\cdots)_3$  as ternary expansions, and a similar proof shows that such an expansion without 1s can be found for any endpoint.

For the inductive step, consider  $a_n$ : the claim is that if  $a_n = 1$ , then  $x \notin C_{n+1}$  – that is, it is contained in one of the intervals deleted at the  $n + 1$ st stage. Writing the deleted interval at this stage as  $(a, b)$ , we find that  $a_n = 1$  if and only if  $x \in [a, b)$ . Since  $x \in C$ , the only way  $a_n$  can be 1 is if  $x$  was in fact the endpoint  $a$  (since no previous digit was a 1, by hypothesis). However, as shown above, every such endpoint has a ternary expansion containing no 1s.  $\square$

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Therefore, if we can produce an  $x$  that satisfies  $x \neq \frac{k}{3^n}$  for any  $k, n$  **and**  $x$  has no 1s in its ternary expansion, we will have an  $x \in C$  that is not an endpoint.

So take

$$x = (0.\overline{02})_3 = (0.020202\cdots)_3.$$

This evidently has no 1s in its ternary expansion, and if we sum the corresponding geometric series, we find  $x = \frac{1}{4}$ . This is not of the form  $\frac{k}{3^n}$  for any  $k, n$ , and thus fulfills both conditions.

2. We first show that  $C$  is nowhere dense by showing that the interior of its closure is empty, i.e.  $(\overline{C})^\circ = \emptyset$ .

To do so, we note that  $C$  is itself closed and so  $C = \overline{C}$ . To see why this is, consider  $C^c$ ; we'll show that it is open. By construction,  $C_1^c$  is the open interval  $(\frac{1}{3}, \frac{2}{3})$  that is deleted, and similarly  $C_n^c$  is the finite union of the open intervals that are deleted at the  $n$ th stage. But then

$$C^c = \left(\bigcap C_n\right)^c = \bigcup C_n^c$$

is an infinite union of open sets, which is also open. So  $C$  is closed.

It is also the case that  $C$  has empty interior, so  $C^\circ = \emptyset$ . Towards a contradiction, suppose  $x \in C$  is an interior point; then there is some neighborhood  $N_\varepsilon(x) \subset C$ . Since we are on the real line, we can write this as an interval  $(x - \varepsilon, x + \varepsilon)$ , which has length  $2\varepsilon > 0$ . Moreover, we have the containment

$$(x - \varepsilon, x + \varepsilon) \subset C \subset C_n$$

for every  $n$ .

Claim: The length of  $C_n$  is  $(\frac{2}{3})^n$  where we define  $C_0 = [0, 1]$ . Letting  $L_n$  be the length of  $C_n$ , one easy way to see that this is the case is to note that  $L_n$  satisfies the recurrence relation

$$L_{n+1} = \frac{2}{3}L_n,$$

since an interval of length  $\frac{1}{3}L_n$  is removed at each stage. With the initial conditions  $L_0 = 1$ , it can be checked that  $L_n = (\frac{2}{3})^n$  solves this relation.

Now, since  $x \in C = \bigcap C_n$ , it is in every  $C_n$ . So we can choose  $n$  large enough such that

$$\left(\frac{2}{3}\right)^n \leq 2\varepsilon.$$

Letting  $\mu(X)$  denote the length of an interval, we always have  $C \subseteq C_n$  and so  $\mu(C) \leq \mu(C_n)$ .

Using the subadditivity of measures, we now have

$$\begin{aligned} (x - \varepsilon, x + \varepsilon) &\subset C \subset C_n \\ \implies \mu(x - \varepsilon, x + \varepsilon) &\leq \mu(C) \leq \mu(C_n) \\ &\implies 2\varepsilon \leq \left(\frac{2}{3}\right)^n, \end{aligned}$$

a contradiction. So  $C$  has no interior points.

But this means that

$$(\overline{C})^\circ = C^\circ = \emptyset,$$

and so  $C$  is nowhere dense.

To see that  $\mu(C) = 0$ , we can use the fact that for any sets, measures are additive over disjoint sets and we have

$$\mu(A) + \mu(X \setminus A) = \mu(X) \implies \mu(X \setminus A) = \mu(X) - \mu(A).$$

Here we will take  $X = [0, 1]$ , so  $\mu(X) = 1$ , and  $A = C$  the Cantor set.

By tracing through the construction of the Cantor set, letting  $B_n$  be the length of the interval that is removed at each stage, we can deduce

$$\begin{aligned} B_1 &= \frac{1}{3} \\ B_2 &= \frac{2}{9} \\ &\dots \\ B_n &= \frac{2^n}{3^{n+1}}. \end{aligned}$$

We can identify  $B_n = \mu(C_n^c)$ , and using the fact that  $C_n^c \cap C_{>n}^c = \emptyset$  and the fact that measures are additive over disjoint sets, we can compute

$$\begin{aligned} \mu(C) &= 1 - \mu(C^c) \\ &= 1 - \mu\left(\left(\bigcap_{n=0}^{\infty} C_n\right)^c\right) \\ &= 1 - \mu\left(\bigcup_{n=0}^{\infty} C_n^c\right) \\ &= 1 - \sum_{n=0}^{\infty} \mu(C_n^c) \\ &= 1 - \sum_{n=0}^{\infty} \frac{2^n}{3^{n+1}} \\ &= 1 - \frac{1}{3} \sum_{n=0}^{\infty} \left(\frac{2}{3}\right)^n \\ &= 1 - \frac{1}{3} \left(\frac{1}{1 - \frac{2}{3}}\right) \\ &= 1 - \frac{1}{3}(3) = 0, \end{aligned}$$

which is what we wanted to show.  $\square$

3. Let  $y \in [0, 1]$  be arbitrary, we will construct an element  $x \in C$  such that  $y = f(x)$ . We first note that every number has a binary expansion, and we can write

$$y = \sum_{k=1}^{\infty} y_k 2^{-k} \quad \text{where } y_k \in \{0, 1\}.$$

Now we construct

$$x = \sum_{k=1}^{\infty} a_k 3^{-k} \quad \text{where } a_k = 2y_k \implies a_k \in \{0, 2\}.$$

By the characterization given in part (1), we see that  $x \in C$  because it has no 1s in its ternary expansion. Moreover, under  $f$ , we have  $a_k \mapsto \frac{1}{2}a_k = \frac{1}{2}(2a_k) = a_k$ , and so  $f(x) = y$  by construction.