

# Title

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Monday 27<sup>th</sup> July, 2020

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## 1 Spring 2017

### 1.1 1

Concepts used:

- Definition:  $A$  is *nowhere dense*  $\iff$  every interval  $I$  contains a subinterval  $S \subseteq A^c$ .

### Solution

- Claim:  $K$  is **compact**.
  - It suffices to show that  $K^c := [0, 1] \setminus K$  is open; Then  $K$  will be a closed and bounded subset of  $\mathbb{R}$  and thus compact by Heine-Borel.
  - Strategy: write  $K^c$  as the union of open balls (since these form a basis for the Euclidean topology on  $\mathbb{R}$ ).
    - \* Do this by showing every point  $x \in K^c$  is an interior point, i.e.  $x$  admits a neighborhood  $N_x$  such that  $N_x \subseteq K^c$ .
  - Identify  $K^c$  as the set of real numbers in  $[0, 1]$  whose decimal expansion **does** contain a 4.
    - \* We will show that there exists a neighborhood small enough such that all points in it contain a 4 in their decimal expansions.

– Let  $x \in K^c$ , suppose a 4 occurs as the  $k$ th digit, and write

$$x = 0.d_1d_2\cdots d_{k-1}4d_{k+1}\cdots = \left(\sum_{j=1}^k d_j 10^{-j}\right) + (4 \cdot 10^{-k}) + \left(\sum_{j=k+1}^{\infty} d_j 10^{-j}\right).$$

– Set  $r_x < 10^{-k}$  and let  $y \in [0, 1] \cap B_{r_x}(x)$  be arbitrary.

– Thus  $|x - y| < r_x < 10^{-k}$ , and the first  $k$  digits of  $x$  and  $y$  must agree:

\* Write  $y = \sum_{j=1}^{\infty} c_j 10^{-j}$ , this means that for all  $j \leq k$  we have  $d_j = c_j$ , and in particular  $d_k = 4 = c_k$ , so  $y$  has a 4 in its decimal expansion.

– But then  $K^c = \bigcup_x B_{r_x}(x)$  is a union of open sets and thus open.

• Claim:  $K$  is nowhere dense and  $m(K) = 0$ :

Since  $K$  is closed, we'll show that  $K$  can not properly contain any interval, so  $(\overline{K})^\circ = \emptyset$ .

As in the construction of the Cantor set, let

- $K_1$  denote  $[0, 1]$  with 1 interval  $[0.4, 0.5]$  of length  $\frac{1}{10}$  deleted
- $K_2$  denote  $K_1$  with 9 intervals  $[0.04, 0.05], [0.14, 0.15], \dots [0.94, 0.95]$  length  $\frac{1}{100}$  deleted
- $K_n$  denote  $K_{n-1}$  with  $9^{n-1}$  such intervals of length  $10^{-n}$  deleted.

Then  $K = \bigcap K_n$ , and

$$m(K) = 1 - m(K^c) = 1 - \sum_{j=0}^{\infty} \frac{9^j}{10^{j+1}} = 1 - \frac{1}{10} \left( \frac{1}{1 - \frac{9}{10}} \right) = 0,$$

and since any interval has strictly positive measure,  $K$  can not contain any interval.

• Claim:  $K$  has no isolated points:

A point  $x \in K$  is isolated iff there is an open ball  $B_r(x)$  containing  $x$  such that  $B_r(x) \cap K = \{x\}$ , so every point in this ball has a 4 in its decimal expansion.

Note that  $m(K_n) = \left(\frac{9}{10}\right)^n \rightarrow 0$  and that the endpoints of intervals are never removed and are thus elements of  $K$ . Then for every  $\varepsilon$ , we can choose  $n$  such that  $\left(\frac{9}{10}\right)^n < \varepsilon$ ; then there is an endpoint of a removed interval  $e_n$  satisfying  $|x - e_n| \leq \left(\frac{9}{10}\right)^n < \varepsilon$ .

So every ball containing  $x$  contains some endpoint of a removed interval, and thus an element of  $K$ . ■

## 1.2 2

$$\lambda \ll \mu \iff E \in \mathcal{M}, \mu(E) = 0 \implies \lambda(E) = 0.$$

**1.2.1 a**

By Radon-Nikodym, if  $\lambda \ll \mu$  then  $d\lambda = f d\mu$ , which would yield

$$\int g d\lambda = \int gf d\mu.$$

So let  $E$  be measurable and suppose  $\mu(E) = 0$ . Then

$$\lambda(E) := \int_E f d\mu = \lim_n \left\{ \varphi_n := \sum_j c_j \mu(E_j) \right\},$$

where we take a sequence of simple functions increasing to  $f$ .

But since each  $E_j \subseteq E$ , we must have  $\mu(E_j) = 0$  for any such  $E_j$ , so every such  $\varphi_n$  must be zero and thus  $\lambda(E) = 0$ .

**1.2.2 b**

By Radon-Nikodym, there exists a positive  $f$  such that

$$\int g dm = \int gf d\mu,$$

where we can take  $g(x) = x^2$ , then the LHS is zero by assumption and thus so is the RHS.

Note that  $gf$  is positive.

Define  $A_k = \left\{ x \in X \mid gf\chi_E > \frac{1}{k} \right\}$ , then by Chebyshev

$$\mu(A_k) \leq k \int_E gf d\mu = 0,$$

which holds for every  $k$ .

Then noting that  $A_k \searrow A := \{x \in E \mid x^2 > 0\}$ , and  $gf$  is positive, we have

$$x \in E \iff gf\chi_E(x) > 0 \iff x \in A,$$

so  $E = A$  and  $\mu(E) = \mu(A)$ .

But since  $m \ll \mu$  by construction, we can conclude that  $m(E) = 0$ .

■

**1.3 3****1.3.1 a**

Letting  $x_n := \frac{1}{n}$ , we have

$$\sum_{k=1}^{\infty} |f_k(x)| \geq |f_n(x_n)| = |ae^{-ax} - be^{-bx}| := M.$$

In particular,  $\sup_x |f_n(x)| \not\rightarrow 0$ , so the terms do not go to zero and the sum can not converge.

**1.3.2 b**

?

**1.4 4**

Switching to polar coordinates and integrating over a half-circle contained in  $I^2$ , we have

$$\int_{I^2} f \geq \int_0^\pi \int_0^1 \frac{\cos(\theta) \sin(\theta)}{r^2} dr d\theta = \infty,$$

so  $f$  is not integrable.

**1.5 5**

See <https://math.stackexchange.com/questions/507263/prove-that-c1a-b-with-the-c1-norm-is-a-banach-space>

This is clearly a norm, which we'll write  $\|\cdot\|_u$

Let  $f_n$  be a Cauchy sequence and define a candidate limit  $f(x) = \lim_n f_n(x)$ .

Then noting that  $\|f_n\|_\infty, \|f'_n\|_\infty \leq \|f_n\|_u < \infty$ , both  $f_n, f'_n$  are Cauchy sequences in  $C^0([a, b], \|\cdot\|_\infty)$ , which is a Banach space.

So  $f_n \rightarrow f$  uniformly, and  $f'_n \rightarrow g$  uniformly for some  $g$ , and moreover  $f, g \in C^0([a, b])$ .

We thus have

$$\begin{aligned} f_n(x) - f_n(a) &\xrightarrow{u} f(x) - f(a) \\ \int_a^x f'_n &\xrightarrow{u} \int_a^x g, \end{aligned}$$

and by the FTC, the left-hand sides are equal, and by uniqueness of limits so are the right-hand sides, so  $f' = g$ .

Since  $f, f' \in C^0([a, b])$ , they are bounded, and so  $\|f\|_u < \infty$ . This means that  $\|f_n - f\|_u \rightarrow 0$ , so  $f_n$  converges to  $f$ , which is in the same space.

■