STATS310A - Lecture 5

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Contents

1 Applying Borel Cantelli

Recall, $l_n(\omega)$ = length of the head run starting at n. That is $l_n(\omega) = k$ if and only if $d_n(\omega) = d_{n+1}(\omega) = \ldots = d_{n+k-1}(\omega) = 1$ and $d_{n+k} = 0$. Last time we saw

$$P(\omega : l_n(\omega) > (1+\varepsilon)\log_2(n) \ i.o) = 0.$$

We will now see

$$P(w : l_n(w) > \log_2(n) \ i.o.) = 1.$$

The problem is that the events $\{l_n \geq r_n\}$ are not independent. The trick is to use subsequences.

Proposition 1. *Let r_n be a weekly increasing subsequence such that $r_n > 0$ and $\sum_{n=1}^\infty \frac{2^{-r_n}}{r_n} = \infty$ (for example $r_n = \log_2(n)$). Then $P(l_n \geq r_n \ i.o.) = 1$.*

Proof. Define a sequence n_k by $n_1 = 1$ and $n_{k+1} = n_k + r_{n_k}$ so that $n_{k+1} - n_k = r_{n_k}$. Define $A_k = \{l_{n_k} \geq r_{n_k}\}$. Then $A_k = \{\omega : d_i(\omega) = 1 \text{ for } n_k \leq i \leq n_{k+1} - 1\}$ since $n_k + r_{n_k} = n_{k+1}$. Thus the events $\{A_k\}_{k=1}^\infty$ are independent. Note also that $P(A_k) = \frac{1}{2^{r_{n_k}}}$. The second Borel Cantelli theorem tells us that if

$$\sum_{k=1}^\infty P(A_k) = \infty,$$

then $P(A_k \text{ } i.o.) = 1$. Note that

$$\begin{aligned}\sum_{k=1}^{\infty} P(A_k) &= \sum_{k=1}^{\infty} 2^{-r_{n_k}} \\ &= \sum_{k=1}^{\infty} 2^{-r_{n_k}} \frac{n_{k+1} - n_k}{r_{n_k}} \\ &= \sum_{k=1}^{\infty} \sum_{n=n_k}^{n_{k+1}-1} \frac{2^{-r_{n_k}}}{r_{n_k}} \\ &\geq \sum_{k=1}^{\infty} \sum_{n=n_k}^{n_{k+1}-1} \frac{2^{-r_n}}{r_n} \\ &= \sum_{n=1}^{\infty} \frac{2^{-r_n}}{r_n} \\ &= \infty. \end{aligned} \qquad \square$$

2 Homework

Read sections 10, 11 and 12. Do problems 10.3, 10.4, 11.2, 14.5 and two more.

3 Measure Theory

Let Ω be a set and $\mathcal{F}$ an algebra of subsets of Ω.

Definition 1. A *measure* on $(\Omega, \mathcal{F})$ is a function $\mu : \mathcal{F} \to [0, \infty]$ such that

(a) (Non-trivial) $\mu(\emptyset) = 0$.

(b) (Monotone) If $A, B \in \mathcal{F}$ and $A \subseteq B$, then $\mu(A) \leq \mu(B)$.

(c) (Countable additivity) If $\{A_i\}_{i=1}^{\infty}$ is a countable collection of disjoint subsets in $\mathcal{F}$ and $\bigcup_i A_i \in \mathcal{F}$, then

$$\mu\left(\bigcup_{i=1}^{\infty} A_i\right) = \sum_{i=1}^{\infty} \mu(A_i).$$

For example with $\Omega = \mathbb{R}$ and $\mathcal{F}$ equal to the collection of all subsets, then $\mu(\emptyset) = 0$ and $\mu(A) = \infty$ otherwise is a measure. Likewise $\mu(A) = \#$ of points in A, is also a measure of $(\Omega, \mathcal{F})$.

One might ask why we are doing this?

(a) We want to define probabilities via densities, that is we want to write

$$P(A) = \int_A f(\omega) d\mu(\omega),$$

where μ is a measure that is not necessarily a probability measure.

(b) It's free from the hard work we've already done.

A word of caution! For probabilities we had if $A \subseteq B$, then $P(B \setminus A) = P(B) - P(A)$. This is not true in general. For measures we hamy have $P(B) = P(A) = \infty$. For example if μ is Lesbegue measure, $B = (0, \infty)$ and $A = (x, \infty)$ for some $x \geq 0$, then $\mu(B \setminus A) = \mu((0, x]) = x$ but $\mu(B) = \mu(A) = \infty$.

Definition 2. A measure μ on $(\Omega, \mathcal{F})$ is *σ-finite* if there exists a countable collection $B_i \in \mathcal{F}$ s.t. $\bigcup_i B_i = \Omega$ and $\mu(B_i) < \infty$ for all i.

For example Lesebgue measure is σ-finite since we can set $B_i = (-i, i)$. The measure $\mu(A) = \#$ of points in A is not σ-finite on $\mathbb{R}$.

Theorem 1. *Suppose that we have two measure μ_1, μ_2 on $\sigma(\mathcal{P})$ where $\mathcal{P}$ is a π-system. If μ_1 and μ_2 agree on $\mathcal{P}$ and there exists a countable collection $B_i \in \mathcal{P}$ such that $\mu_1(B_i) = \mu_2(B_i) < \infty$ and $\Omega = \bigcup_i B_i$, then μ_1 and μ_2 agree on $\sigma(\mathcal{P})$.*

Proof. For $B \in \mathcal{P}$ with $\mu_1(B) < \infty$, define $L_B = \{A \in \sigma(\mathcal{P}) : \mu_1(A \cap B) = \mu_2(A \cap B)\}$. Then L_B is a λ-system and it contains $\mathcal{P}$ and thus by the π-λ theorem $\sigma(\mathcal{P}) = L_B$.

By assumption we have $\Omega = \bigcup_i B_i$ where $B_i \in \mathcal{P}$ and $\mu_1(B_i) < \infty$. Fix $A \in \sigma(\mathcal{P})$ and for $i = 1, 2$, note that, by the inclusion exclusion formula

$$\mu_i \left(\bigcup_{j=1}^n A \cap B_i \right) = \sum_{j=1}^n \mu_i(A \cap B_j) - \sum_{1 \leq j < k \leq n} \mu_i(A \cap B_j \cap B_k) + \dots.$$

Furthore more, finite interesections of $\{B_i\}_{i=1}^\infty$ are in $\mathcal{P}$ and have finite measure. Thus since $L_B = \sigma(\mathcal{P})$ for all $B \in \mathcal{P}$ with finite measure we have $\mu_1(A \cap B) = \mu_2(A \cap B)$ where B is any finite intersection of $\{B_i\}_{i=1}^\infty$. Thus

$$\mu_1 \left(\bigcup_{j=1}^n A \cap B_i \right) = \mu_2 \left(\bigcup_{j=1}^n A \cap B_i \right),$$

for all n. Letting $n \to \infty$ we see that $\mu_1(A) = \mu_2(A)$. $\square$

Note that σ-finiteness is needed. If $\mu_1(A) = \#$ of points in A and $\mu_2(A) = \infty$ if $A \neq \emptyset$, then $\mu_1 = \mu_2$ on all intervals but $\mu_1 \neq \mu_2$ on the Borel σ-algebra.

Definition 3. Let Ω be a set. An outer measure μ^* is a function defined on all subsets of Ω such that

(a) $\mu^*(A) \in [0, \infty]$

(b) $\mu^*(\emptyset) = 0$,

(c) $\mu^*(A) \leq \mu^*(B)$ if $A \subseteq B$, and

(d) $\mu^*\left(\bigcup_{i=1}^\infty A_i\right) \leq \sum_{i=1}^\infty \mu^*(A_i)$.

For example let Ω be any set and let $\mathcal{A}$ be any collection of subsets of Ω and let $\rho : \mathcal{A} \to [0, \infty]$ be any function such that $\rho(\emptyset) = 0$. Then

$$\mu^*(A) = \inf \left\{ \sum_{i=1}^\infty \rho(A_i) : A \subseteq \bigcup_{i=1}^\infty A_i, A_i \in \mathcal{A} \right\},$$

where $\inf \emptyset = \infty$ is an outer measure. This can be seen by using the usual $\varepsilon 2^{-i}$ trick to prove countable subadditivity.

A special case of this is Hausdorff measure when $M \subseteq \mathbb{R}^n$ is a crinkly manifold or a fractal or something similar. We define $\mathcal{A} = \{B_\varepsilon(x) : x \in \mathbb{R}^n, \varepsilon > 0\}$ where $B_\varepsilon(x)$ is a ball of radius ε centred at x. We then define $\rho_{n,\gamma}(B_\varepsilon(x)) = (2\varepsilon)^\gamma$ and call the resulting $\mu^*_{n,\gamma}$ the $\gamma-$Hausdorff measure on $\mathbb{R}^n$.

Theorem 2. *Let μ^* be an outer measure on all subsets of Ω and define*

$$\mathcal{M} = \{A \subseteq \Omega : \mu^*(E) = \mu^*(A \cap E) + \mu^*(A^c \cap E) \text{ for all } E \subseteq \Omega\},$$

then $\mathcal{M}$ is a σ-algebra and μ restricted to $\mathcal{M}$ is a measure.

Proof. Symbol for symbol, letter for letter, the same as the proof of the Caratheodory extension theorem. $\square$

4 Distribution functions

"People at microsoft research" were putting probabilities on $\mathbb{R}^n$ using distribution functions in a funny way.

If $\mathbb{P}$ is a probability measure on $\mathbb{R}^n$ we can define a function $F : \mathbb{R}^n \to [0,1]$ by $F(x) = \mathbb{P}(A_x)$ where $A_x = \{y : y_i \leq x_i, \text{ for } i = 1, \ldots, n\}$. We call $F(x)$ the distribution function (DF) generated by $\mathbb{P}$. A distribution function satisfies the following

- $\lim_{x \to +\infty} F(x) = 1$.
- $\lim_{x \to -\infty} F(x) = 0$.
- F is monotone in each coordinate.
- F is right continuous. If $x_n \searrow x$, then $F(x_n) \searrow F(x)$.

But not every F that satisfies the above is a DF. At microsoft they had the idea to take define on $\mathbb{R}^3$

$$MS(x, y, z) = F(x, y, z)G(x, y)H(x),$$

where F, G and H were all distribution functions. One can ask is MS a distribution function? A function $F : \mathbb{R}^2 \to [0,1]$ is a distribution function if and only if

(a) $\lim_{x \to +\infty} F(x) = 1$.

(b) $\lim_{x \to -\infty} F(x) = 0$.

(c) F is monotone in each coordinate.

(d) F is right continuous. If $x_n \searrow x$, then $F(x_n) \searrow F(x)$.

(e) For all $(x_1, y_1), (x_2, y_2)$ such that $x_1 \leq x_2$ and $y_1 \leq y_2$, we have

$$F(x_2, y_2) - F(x_2, y_1) - F(x_1, y_2) + F(x_1, y_1) \geq 0.$$

This property requires that the probability of every rectangle is non-negative.

Furthermore, if F satisfies (a)-(e), then there is a unique probability measure $\mathbb{P}$ on $\mathbb{R}^2$ such that $\mathbb{P}(A_{(x,y)}) = F(x, y)$.