

1 Measures

Let E be any set. A collection \mathcal{E} of subsets of E is called a σ -algebra if the following holds:

1. $\emptyset \in \mathcal{E}$.
2. If $A \in \mathcal{E}$, then $A^c = E \setminus A \in \mathcal{E}$.
3. If $(A_n : n \in \mathbb{N})$, $A_n \in \mathcal{E}$, then $\bigcup_n A_n \in \mathcal{E}$.

Examples.

- $\mathcal{E} = \{\emptyset, E\}$
- $\mathcal{E} = \mathcal{P}(E)$, the set of all subsets of E .

Note that $\bigcap_n A_n = (\bigcup_n A_n^c)^c$, any σ -algebra \mathcal{E} is also closed under countable intersection of its elements. Also $B \setminus A = B \cap A^c \in \mathcal{E}$ whenever $A, B \in \mathcal{E}$.

Any set E with a choice of σ -algebra \mathcal{E} is called a *measurable space*, and the elements of \mathcal{E} are called *measurable sets*.

A *measure* μ is a set-function $\mu : \mathcal{E} \rightarrow [0, \infty]$ such that $\mu(\emptyset) = 0$, and for any $(A_n : n \in \mathbb{N})$, $A_n \in \mathcal{E}$ pairwise disjoint ($A_n \cap A_m = \emptyset$ for all $n \neq m$) then

$$\mu\left(\bigcup_n A_n\right) = \sum_n \mu(A_n) \quad (\text{countable additivity of } \mu)$$

If \mathcal{E} is countable, then for any $A \in \mathcal{P}(E)$ and a measure μ

$$\mu(A) = \mu\left(\bigcup_{x \in A} \{x\}\right) = \sum_{x \in A} \mu(\{x\})$$

hence there is a one-to-one correspondence between measures and mass functions on E .

For any collection \mathcal{A} of subsets of E , we define the σ -algebra $\sigma(\mathcal{A})$ generated by \mathcal{A} as

$$\sigma(\mathcal{A}) = \{A \subseteq E : A \in \mathcal{E} \text{ } \forall \sigma\text{-algebras } \mathcal{E} \supseteq \mathcal{A}\}$$

which equals (Example sheet)

$$\sigma(\mathcal{A}) = \bigcap_{\sigma\text{-algebras } \mathcal{E} \supseteq \mathcal{A}} \mathcal{E}$$

To construct good ‘generators’ we define

1. \mathcal{A} is called a *ring over E* if $\emptyset \in \mathcal{A}$; if $A, B \in \mathcal{A}$ then $B \setminus A \in \mathcal{A}$ and $A \cup B \in \mathcal{A}$.

2. \mathcal{A} is called an *algebra over E* if $\emptyset \in \mathcal{A}$; if $A, B \in \mathcal{A}$ then $A^c \in \mathcal{A}$, $A \cup B \in \mathcal{A}$.

Notice that in a ring $A \Delta B = (B \setminus A) \cup (A \setminus B) \in \mathcal{A}$ and $A \cap B = (A \cup B) \setminus (A \Delta B) \in \mathcal{A}$. Also, $B \setminus A = B \cap A^c = (B^c \cup A)^c \in \mathcal{A}$, so an algebra is a ring.

Fact: If $\bigcup_n A_n$, $A_n \in \mathcal{E}$, \mathcal{E} some σ -algebra (or a ring if the union is finite) - then we can find $B_n \in \mathcal{E}$ disjoint such that $\bigcup_n A_n = \bigcup_n B_n$. Indeed, define $\tilde{A}_n = \bigcup_{j \leq n} A_j$, and set $B_n = \tilde{A}_n \setminus \tilde{A}_{n-1}$, then the fact follows. [“disjointification of countable unions”]

Definition. A *set function* on any collection \mathcal{A} of subsets of E (where $\emptyset \in \mathcal{A}$) is a map $\mu : \mathcal{A} \rightarrow [0, \infty]$ such that $\mu(\emptyset) = 0$. We say μ is

1. *increasing* if $\mu(A) \leq \mu(B)$ whenever $A \subseteq B$; $A, B \in \mathcal{A}$
2. *additive* if $\mu(A \cup B) = \mu(A) + \mu(B)$ whenever $A, B \in \mathcal{A}$; $A \cup B \in \mathcal{A}$ and $A \cap B = \emptyset$.
3. *countably additive* if $\mu(\bigcup_n A_n) = \sum_n \mu(A_n)$ for any $(A_n : n \in \mathbb{N})$ where $A_n \in \mathcal{A}$ disjoint and $\bigcup_n A_n \in \mathcal{A}$.
4. *countably sub-additive* if $\mu(\bigcup_n A_n) \leq \sum_n \mu(A_n)$ for all $(A_n : n \in \mathbb{N})$ such that $\bigcup_n A_n \in \mathcal{A}$

Remark: one can show that a measure μ on a σ -algebra satisfies 1-4 above.

Theorem (Caratheodory). *Let μ be a countably additive set function on a ring \mathcal{A} of subsets of E . Then there exists a measure μ^* on $\sigma(\mathcal{A})$ such that $\mu^*|_{\mathcal{A}} = \mu$.*

Proof. For $B \subseteq E$ define the *outer measure* μ^* as

$$\mu^*(B) = \inf \left\{ \sum_{n \in \mathbb{N}} \mu(A_n) : A_n \in \mathcal{A}, B \subseteq \bigcup_n A_n \right\}$$

and set $\mu^*(B) = \infty$ if the set within the infimum is empty.

Define

$$\mathcal{M} = \{A \subseteq E : \mu^*(B) = \mu^*(B \cap A) + \mu^*(B \cap A^c) \forall B \subseteq E\}$$

the “ μ^* -measurable” sets.

Step 1: μ^* is countably sub-additive on $\mathcal{P}(E)$. For any $B \subseteq E$ and $B_n \subseteq E$ such that $B \subseteq \bigcup_n B_n$ we have

$$\mu^*(B) \leq \sum_n \mu^*(B_n) \quad (\dagger)$$

WLOG we assume $\mu^*(B_n) < \infty$ for all n so for all $\varepsilon > 0$, there exists A_{nm} such that $B_n \subseteq \bigcup_m A_{nm}$ and

$$\mu^*(B_n) + \frac{\varepsilon}{2^n} \geq \sum_m \mu(A_{nm})$$

Now since μ^* and since $B \subseteq \bigcup_n B_n \subseteq \bigcup_{n,m} A_{nm}$, hence

$$\mu^*(B) \leq \mu^*\left(\bigcup_{n,m} A_{nm}\right) \leq \sum_{n,m} \mu(A_{nm}) \leq \sum_n \mu^*(B_n) + \underbrace{\sum_n \frac{\varepsilon}{2^n}}_{=\varepsilon}$$

so (\dagger) follows since ε was arbitrary.

Step 2: μ^* extends μ . Let $A \in \mathcal{A}$. Clearly $A = A \cup \emptyset \cup \dots \cup \emptyset$, so by definition of μ^* , $\mu^*(A) \leq \mu(A) + 0 + \dots + 0$. So we need to prove $\mu(A) \leq \mu^*(A)$. Again, assume $\mu^*(A) < \infty$ WLOG, and let $A_n \in \mathcal{A}$ be such that $A \subseteq \bigcup_n A_n$. Then $A = \bigcup_n \underbrace{(A \cap A_n)}_{\in \mathcal{A}}$, and since μ is countably sub-additive on \mathcal{A} , we have

$$\mu(A) = \mu\left(\bigcup_n (A \cap A_n)\right) \leq \sum_n \underbrace{\mu(A \cap A_n)}_{\subseteq A_n} \leq \sum_n \mu(A_n)$$

so since the (A_n) were arbitrary, by taking infima, we have $\mu(A) \leq \mu^*(A)$.

Step 3: $\mathcal{M} \supseteq \mathcal{A}$. Let $A \in \mathcal{A}$, then $B \subseteq (B \cap A) \cup (B \cap A^c) \cup \emptyset \dots \cup \emptyset = \bigcup_n B_n$ so by (\dagger) we have

$$\mu^*(B) \leq \mu^*(B \cap A) + \mu^*(B \cap A^c) + 0 \dots + 0$$

so we need to prove $\mu^*(B) \geq \mu^*(B \cap A) + \mu^*(B \cap A^c)$. Again, WLOG assume $\mu^*(B) < \infty$, and so for all $\varepsilon > 0$ there exist $A_n \in \mathcal{A}$ such that $B \subseteq \bigcup_n A_n$ and

$$\mu^*(B) + \varepsilon \geq \sum_n \mu(A_n) \quad (\circ)$$

now $B \cap A \subseteq \bigcup_n \underbrace{(A_n \cap A)}_{\in \mathcal{A}}$ and $B \cap A^c \subseteq \bigcup_n \underbrace{(A_n \cap A^c)}_{A_n \setminus A \in \mathcal{A}}$. Therefore by definition of inf in μ^* and additivity of μ

$$\begin{aligned} \mu^*(B \cap A) + \mu^*(B \cap A^c) &\leq \sum_n (\mu(A \cap A_n) + \mu(A^c \cap A_n)) \\ &= \sum_n \mu(A_n) \\ &\underbrace{\leq}_{\circ} \mu^*(B) + \varepsilon \end{aligned}$$

since ε was arbitrary, $\mu^*(B) = \mu^*(B \cap A) + \mu^*(B \cap A^c)$, so $A \in \mathcal{M}$.

Step 4: \mathcal{M} is an algebra. Clearly $\emptyset \in \mathcal{M}$, and by the definition of \mathcal{M} its obvious that $A^c \in \mathcal{M}$ whenever $A \in \mathcal{M}$. So let $A_1, A_2 \in \mathcal{M}$

$$\mu^*(B) = \mu^*(B \cap A_1) + \mu^*(B \cap A_1^c), \text{ since } A_1 \in \mathcal{M}$$

$$= \mu^*(B \cap A_1 \cap A_2) + \mu^*(B \cap A_1 \cap A_2^c) + \mu^*(B \cap A_1^c), \text{ since } A_2 \in \mathcal{M}$$

Clearly $A_1 \cap A_2^c = (A_1 \cap A_2^c) \cap A_1$ and $A_1^c = (A_1 \cap A_2)^c \cap A_1^c$ so

$$\begin{aligned} \mu^*(B) &= \mu^*(B \cap A_1 \cap A_2) + \mu^*(B \cap (A_1 \cap A_2)^c \cap A_1) + \mu^*(B \cap (A_1 \cap A_2)^c \cap A_1^c) \\ &= \mu^*(B \cap A_1 \cap A_2) + \mu^*(B \cap (A_1 \cap A_2)^c), \text{ since } A_1 \in \mathcal{M} \end{aligned}$$

so $A_1 \cap A_2 \in \mathcal{M}$, and \mathcal{M} is an algebra.

Step 5: Let $A = \bigcup_n A_n$, $A_n \in \mathcal{M}$, WLOG A_n disjoint (disjointification). Want $A \in \mathcal{M}$ and $\mu^*(A) = \sum_n \mu^*(A_n)$. By (\dagger) we clearly have

$$\mu^*(B) \leq \mu^*(B \cap A) + \mu^*(B \cap A^c) + 0 \dots + 0$$

and

$$\mu^*(A) \leq \sum_n \mu^*(A_n)$$

so we only need two converse inequalities. Similar to before

$$\begin{aligned}
 \mu^*(B) &= \mu^*(B \cap A_1) + \mu^*(B \cap A_1^c) \\
 &= \mu^*(B \cap A_1) + \mu^*(B \cap \underbrace{A_1^c \cap A_2}_{=A_2 \text{ as disjoint}}) + \mu^*(B \cap A_1^c \cap A_2^c) \\
 &= \sum_{n \leq N} \mu^*(B \cap A_n) + \mu^*(B \cap A_1^c \cap \dots \cap A_N^c)
 \end{aligned}$$

since $\bigcup_{n \leq N} A_n \subseteq A$ so $\bigcap_{n \leq N} A_n^c \supseteq A^c$, taking limits

$$\mu^*(B) \geq \sum_{n=1}^{\infty} \mu^*(B \cap A_n) + \mu^*(B \cap A^c)$$

and by (†)

$$\mu^*(B) \geq \mu^*(B \cap A) + \mu^*(B \cap A^c)$$

so $A \in \mathcal{M}$. Applying the previous with $B = A$, we see

$$\mu^*(A) \geq \sum_{n=1}^{\infty} \mu^*(A \cap A_n) + \mu^*(A \cap A^c) = \sum_n \mu^*(A_n)$$

□

Definition. A collection \mathcal{A} of subsets of E is called a π -system if $\emptyset \in \mathcal{A}$ and if $A, B \in \mathcal{A}$, then $A \cap B \in \mathcal{A}$.

Definition. \mathcal{A} is called a d -system if $E \in \mathcal{A}$, and if $B_1, B_2 \in \mathcal{A}$ such that $B_1 \subseteq B_2$, then $B_2 \setminus B_1 \in \mathcal{A}$, and if $A_n \in \mathcal{A}$, $A_n \uparrow \bigcup_n A_n = A$, then $A \in \mathcal{A}$.

One shows (Example sheet) that a d -system which is also a π -system is a σ -algebra.

Lemma (Dynkin). *Let \mathcal{A} be a π -system. Then any d -system that contains \mathcal{A} also contains $\sigma(\mathcal{A})$.*

Proof. Define

$$\mathcal{D} = \bigcap_{\mathcal{D}' \supseteq \mathcal{A} \text{ a } d\text{-system}} \mathcal{D}'$$

which is again a d -system (Example sheet). We show that \mathcal{D} is a π -system, hence a σ -algebra containing \mathcal{A} . Define

$$\mathcal{D}' = \{B \in \mathcal{D} : B \cap A \in \mathcal{D} \forall A \in \mathcal{A}\}$$

which contains \mathcal{A} as \mathcal{A} is a π -system. Next we show \mathcal{D}' is a d -system. Clearly $E \cap A = A \in \mathcal{A} \subseteq \mathcal{D}$, so $E \in \mathcal{D}'$. Next let $B_1, B_2 \in \mathcal{D}'$ such that $B_1 \subseteq B_2$ then $(B_2 \setminus B_1) \cap A = \underbrace{(B_2 \cap A)}_{\in \mathcal{D}} \setminus \underbrace{(B_1 \cap A)}_{\in \mathcal{D}} \in \mathcal{D}$ and so $B_2 \setminus B_1 \in \mathcal{D}'$.

Next take $B_n \uparrow B$, $B_n \in \mathcal{D}'$ then $\underbrace{B_n \cap A}_{\in \mathcal{D}} \uparrow B \cap A \in \mathcal{D}$ so $B \in \mathcal{D}'$.

Hence \mathcal{D}' is a d -system containing \mathcal{A} , so by minimality of \mathcal{D} , $\mathcal{D} \subseteq \mathcal{D}'$. Conversely, by construction $\mathcal{D}' \subseteq \mathcal{D}$, so $\mathcal{D}' = \mathcal{D}$.

Next define

$$\mathcal{D}'' = \{B \in \mathcal{D} : B \cap A \in \mathcal{D} \forall A \in \mathcal{D}\}$$

which by the preceding step ($\mathcal{D}' = \mathcal{D}$) contains \mathcal{A} . Just as before, one shows that $\mathcal{D}'' = \mathcal{D}$ and so \mathcal{D} is a π -system (as \mathcal{D}'' is by construction). \square

Theorem (Uniqueness of extension). *Let μ_1, μ_2 be measures on (E, \mathcal{E}) such that $\mu_1(E) = \mu_2(E) < \infty$, and suppose $\mu_1 = \mu_2$ on a π -system \mathcal{A} such that $\mathcal{E} \subseteq \sigma(\mathcal{A})$. Then $\mu_1 = \mu_2$ on \mathcal{E} .*

Proof. Define

$$\mathcal{D} = \{A : \mu_1(A) = \mu_2(A)\}$$

which contains \mathcal{A} by hypothesis. We show that \mathcal{D} is a d -system, and hence by Dynkin's Lemma, contains $\sigma(\mathcal{A})$, so the theorem follows.

To see this, note first that $E \in \mathcal{D}$ by hypothesis. Next, by additivity and finiteness of μ_1, μ_2 , for $B_1 \subseteq B_2$, $B_1, B_2 \in \mathcal{D}$.

$$\mu_1(B_2 \setminus B_1) = \mu_1(B_2) - \mu_1(B_1) = \mu_2(B_2) - \mu_2(B_1) = \mu_2(B_2 \setminus B_1)$$

so $B_2 \setminus B_1 \in \mathcal{D}$. Finally take $B_n \uparrow B$, $B_n \in \mathcal{D}$. This implies $B \setminus B_n \downarrow \emptyset$ and (by Example sheet) $\mu_i(B \setminus B_n) \rightarrow \mu_i(\emptyset) = 0$ for $i = 1, 2$. This implies for $\mu_i(B) < \infty$ that $\mu_i(B_n) \rightarrow \mu_i(B)$ as $n \rightarrow \infty$ for both $i = 1, 2$. But then

$$\mu_1(B) = \lim_{n \rightarrow \infty} \mu_1(B_n) = \lim_{n \rightarrow \infty} \mu_2(B_n) = \mu_2(B)$$

and so $B \in \mathcal{D}$, and thus \mathcal{D} is a d-system. \square

Remark: the above theorem applies to finite measures μ such that $\mu(E) < \infty$. The above theorem extends (as we will see) to σ -finite measures μ for which $E = \bigcup_{n \in \mathbb{N}} E_n$ such that $\mu(E_n) < \infty$.

Borel- σ -algebras

Definition. Let E be a topological space (Hausdorff, or metric space). The σ -algebra generated by $\mathcal{A} = \{B \subseteq E : B \text{ is open}\}$ is called the *Borel- σ -algebra*, denoted by $\mathcal{B}(E)$, or just \mathcal{B} when $E = \mathbb{R}$. Elements of $\mathcal{B}(E)$ are the Borel subsets of E . A measure μ on $(E, \mathcal{B}(E))$ is called a *Borel measure on E* . A *Radon* measure μ is a Borel measure such that $\mu(K) < \infty$ for all $K \subseteq E$ compact (closed in Hausdorff spaces, hence measurable).

Construction of Lebesgue measure

We will (eventually) construct a unique Borel measure μ on \mathbb{R}^d such that

$$\mu\left(\prod_{i=1}^d [a_i, b_i]\right) = \prod_{i=1}^d |b_i - a_i|, \quad a_i < b_i, \quad i = 1, \dots, d$$

We will do $d = 1$ first.

Theorem. *There exists a unique Borel measure (called the Lebesgue measure) μ on \mathbb{R} such that*

$$\mu((a, b]) = b - a, \quad \forall a < b \quad (\dagger)$$

Proof. Consider the collection \mathcal{A} of subsets of \mathbb{R} of the form

$$A = (a_1, b_1] \cup \dots \cup (a_n, b_n]$$

(intervals pairwise disjoint) which form a ring ($\emptyset = ((a, a])$, unions and differences are clear), which generates (Example sheet) generates the same σ -algebra on the open such intervals, and open intervals with rational endpoints generate \mathcal{B} , so $\sigma(\mathcal{A}) \supseteq \mathcal{B}$.

Define a set function μ on \mathcal{A} by

$$\mu(A) = \sum_{i=1}^n (b_i - a_i)$$

μ is clearly additive, and well-defined since if $A = \bigcup_j C_j$ and $A = \bigcup_k D_k$ for distinct disjoint unions, then $C_j = \bigcup_k (C_j \cap D_k)$ and $D_k = \bigcup_j (D_k \cap C_j)$, so

$$\begin{aligned} \mu(A) &= \mu\left(\bigcup_j C_j\right) = \sum_j \mu(C_j) = \sum_j \mu\left(\bigcup_k (C_j \cap D_k)\right) \\ &= \sum_{j,k} \mu(C_j \cap D_k) = \dots = \mu\left(\bigcup_k D_k\right) = \mu(A) \end{aligned}$$

by additivity of μ . Now to prove existence of μ , we apply Caratheodory's theorem and need to check that μ is countably additive on \mathcal{A} . By the Example sheet, it suffices to show that for all $A_n \in \mathcal{A}$ such that $A_n \downarrow \emptyset$ we have $\mu(A_n) \rightarrow 0$.

Assume this is not the case, so there exists some $\varepsilon > 0$ and $B_n \in \mathcal{A}$ such that $B_n \downarrow \emptyset$ but $\mu(B_n) \geq 2\varepsilon$ for all n . We can approximate B_n from within by $C_n = \bigcup_{i=1}^{N_n} \left(a_{n_i} + \frac{\varepsilon 2^{-n}}{N_n}, b_{n_i}\right] \in \mathcal{A}$ such that $\mu(B_n \setminus C_n) = \varepsilon 2^{-n} \cdot \frac{N_n}{N_n} = \varepsilon 2^{-n}$.

Now since $B_n \downarrow$, we have $B_N = \bigcap_{n \leq N} B_n$ and

$$B_N \setminus (C_1 \cap \dots \cap C_N) = B_N \cap \left(\bigcup_{n \leq N} C_n^c\right) = \bigcup_{n \leq N} B_N \setminus C_n \subseteq \bigcup_{n \leq N} B_n \setminus C_n$$

Hence since μ is increasing

$$\mu(B_N \setminus (C_1 \cap \dots \cap C_N)) \leq \mu\left(\bigcup_{n \leq N} B_n \setminus C_n\right) \leq \sum_{n \leq N} \mu(B_n \setminus C_n) \leq \varepsilon$$

Hence the “length” of what was removed $(C_1 \cap \dots \cap C_N)$ must be at least ε , i.e

$$\mu(C_1 \cap \dots \cap C_N) \geq \varepsilon > 0$$

This means that $C_1 \cap \dots \cap C_N$ is non-empty for all N , and so is

$$K_N = \overline{C_1} \cap \dots \cap \overline{C_N}$$

($\overline{C_i}$ denotes the closure of C_i) Thus K_N is a nested sequence of non-empty closed intervals, so $\emptyset \neq \bigcap_N K_N$. But $K_N \subseteq \overline{C_N} \subseteq B_N$, so $\emptyset \neq \bigcap_N K_N \subseteq \bigcap_N B_n = \emptyset$, a contradiction. So a measure μ satisfying (\dagger) must exist.

For uniqueness, suppose μ, λ measures such that (\dagger) holds, and define $\mu_n(A) = \mu(A \cap (n, n+1])$, $\lambda(A) = \lambda(A \cap (n, n+1])$ for $n \in \mathbb{Z}$, which are finite measures such that $\mu_n(E) = 1 = \lambda_n(E)$ and $\mu_n = \lambda_n$ on the π -system \mathcal{A} . So by the uniqueness theorem, we must have $\mu_n = \lambda_n$ on \mathcal{B} , and

$$\begin{aligned} \mu(A) &= \mu\left(\bigcup_n A \cap (n, n+1]\right) = \sum_n \mu(A \cap (n, n+1]) = \sum_n \mu_n(A) \\ &= \sum_n \lambda_n(A) = \dots = \lambda(A) \end{aligned}$$

so $\lambda = \mu$. □

Remarks:

1. a set $B \in \mathcal{B}$ is called a Lebesgue null set if $\mu(B) = 0$. Can write $\{x\} = \bigcap_n (x - \frac{1}{n}, x]$ and so $\mu(\{x\}) = \lim_n \frac{1}{n} = 0$. In particular $\mu((a, b)) = \mu((a, b]) = \mu([a, b])$, and any countable set Q satisfies $\mu(Q) = \mu\left(\bigcup_{q \in Q} \{q\}\right) = \sum_{q \in Q} \mu(\{q\}) = 0$. But there exist C uncountable (and measurable) in \mathcal{B} such that $\mu(C) = 0$ [Cantor set].
2. Translation invariance of μ : let $x \in \mathbb{R}$, then $B + x = \{b + x : b \in B\}$ is in \mathcal{B} whenever $B \in \mathcal{B}$ and we can define

$$\mu_x(B) = \mu(B + x)$$

and by uniqueness in the preceding theorem

$$\mu_x((a, b]) = \mu((a + x, b + x]) = (b + x) - (a + x) = b - a$$

so $\mu_x = \mu$.

3. Lebesgue-measurable sets: in the extension theorem, μ was assigned on the class \mathcal{M} , which can be shown (Example sheet) to equal

$$\mathcal{M} = \{M = A \cup N : A \in \mathcal{B}, N \subseteq B \in \mathcal{B} \text{ s.t. } \mu(B) = 0\}$$

Existence of non-measurable sets

Consider $E = (0, 1]$ with addition “+” modulo 1, and Lebesgue measure μ is still translation invariant modulo 1.

Consider the subgroup $Q = E \cap \mathbb{Q}$ of E and declare $x \sim y$ if $x - y \in Q$. This gives equivalence classes $[x] = \{y \in E : x \sim y\}$ on E . Assuming the axiom of choice, we can select a representative of $[x]$, and denote by S the set of selections running over all equivalence classes. Then we can partition E into the union of its cosets,

$$E = \bigcup_{q \in Q} (S + q)$$

a disjoint union.

Assume S is a Borel set (in $\mathcal{B}(E)$), then $S + q$ is also a Borel set for all $q \in Q$, and we can write (by countable additivity and translation invariance)

$$1 = \mu(E) = \mu\left(\bigcup_{q \in Q} (S + q)\right) = \sum_{q \in Q} \mu(S + q) = \sum_{q \in Q} \mu(S)$$

which is a contradiction. So $S \notin \mathcal{B}(E)$.

One can further show that μ cannot extend to $\mathcal{P}(E)$,

Theorem (Banach, Kuratowski). *Assuming the continuum hypothesis, there exists no measure on $([0, 1])$ such that $\mu((0, 1]) = 1$ and $\mu(\{x\}) = 0$ for all $x \in (0, 1]$.*

Proof. Not given [see Dudley, 2002]. □

Probability Spaces

If (E, \mathcal{E}, μ) (a measure space) is such that $\mu(E) = 1$, we often call it a *probability space* and write $(\Omega, \mathcal{F}, \mathbb{P})$, where Ω is the set of outcomes/the sample space; \mathcal{F} is the set of events and \mathbb{P} is the probability measure.

The axioms of probability theory (Kolmogorov, 1933) are

1. $\mathbb{P}(\Omega) = 1$
2. $0 \leq \mathbb{P}(E) \leq 1, \forall E \in \mathcal{F}$
3. If $(A_n : n \in \mathbb{N})$ are disjoint, $A_n \in \mathcal{F}$, then $\mathbb{P}(\bigcup_n A_n) = \sum_n \mathbb{P}(A_n)$ [so \mathbb{P} is a measure on a σ -algebra]

We further say that $(A_i : i \in I)$ are *independent* if for all $J \subseteq I$ finite, we have

$$\mathbb{P} \left(\bigcap_{j \in J} A_j \right) = \prod_{j \in J} \mathbb{P}(A_j)$$

We further say σ -algebras $(\mathcal{A}_i : i \in I)$ are *independent* if for any $A_j \in \mathcal{A}_j$, $j \in J$, $J \subseteq I$ finite, the A_j 's are independent.

Proposition. Let $\mathcal{A}_1, \mathcal{A}_2$ be π -systems of sets in \mathcal{F} , and suppose $\mathbb{P}(A_1 \cap A_2) = \mathbb{P}(A_1)\mathbb{P}(A_2)$ for all $A_1 \in \mathcal{A}_1$, $A_2 \in \mathcal{A}_2$. Then the σ -algebras $\sigma(\mathcal{A}_1), \sigma(\mathcal{A}_2)$ are independent.

Proof. Exercise. □

The Borel-Cantelli Lemmas

For a sequence $(A_n : n \in \mathbb{N})$, $A_n \in \mathcal{F}$, define

$$\limsup_n A_n = \bigcap_n \bigcup_{m \geq n} A_m = \{A_n \text{ infinitely often "i.o."}\}$$

$$\liminf_n A_n = \bigcup_n \bigcap_{m \geq n} A_m = \{A_n \text{ eventually}\}$$

Lemma (1st Borel-Cantelli Lemma). *If $A_n \in \mathcal{F}$ are such that $\sum_n \mathbb{P}(A_n) < \infty$ then $\mathbb{P}(A_n \text{ i.o.}) = 0$*

Proof.

$$\mathbb{P} \left(\bigcap_n \bigcup_{m \geq n} A_m \right) \leq \mathbb{P} \left(\bigcup_{m \geq n} A_m \right) \leq \sum_{m \geq n} \mathbb{P}(A_m) \rightarrow 0$$

□

Remark: the proof actually works for any measure μ .

Lemma (2nd Borel-Cantelli Lemma). *Suppose $A_n \in \mathcal{F}$ are independent and $\sum_n \mathbb{P}(A_n) = \infty$. Then $\mathbb{P}(A_n \text{ i.o.}) = 1$.*

Proof. By independence, for any $N \geq n$ and using $1 - a \leq e^{-a}$,

$$\mathbb{P} \left(\bigcap_{m=n}^N A_m^c \right) = \prod_{m=n}^N (1 - \mathbb{P}(A_m)) \leq \exp \left(- \sum_{m=n}^N \mathbb{P}(A_m) \right) \rightarrow 0 \text{ as } N \rightarrow \infty$$

Since $\bigcap_{m=n}^N A_m^c \downarrow \bigcap_{m \geq n} A_m^c$, by countable additivity we have

$$\mathbb{P} \left(\bigcap_{m \geq n} A_m^c \right) = 0$$

But then

$$\begin{aligned}\mathbb{P}(A_n \text{ i.o.}) &= \mathbb{P}\left(\bigcup_n \bigcap_{m \geq n} A_m\right) = 1 - \mathbb{P}\left(\bigcup_n \bigcap_{m \geq n} A_m^c\right) \\ &\geq 1 - \sum_n \underbrace{\mathbb{P}\left(\bigcap_{m \geq n} A_m^c\right)}_{=0} = 1\end{aligned}$$

□

2 Measurable functions

Let (E, \mathcal{E}) , (G, \mathcal{G}) be measurable spaces and let $f : E \rightarrow G$. We say that f is \mathcal{E} - \mathcal{G} -measurable if $f^{-1}(A) \in \mathcal{E}$ for all $A \in \mathcal{G}$. If $G = \mathbb{R}$ with $\mathcal{G} = \mathcal{B}(\mathbb{R})$, we just say $f : (E, \mathcal{E}) \rightarrow \mathbb{R}$ is *measurable*.

Moreover, if E is a topological space and $\mathcal{E} = \mathcal{B}(E)$, we say f is *Borel measurable*.

Preimages preserve set operations: $f^{-1}(\bigcup_i A_i) = \bigcup_i f^{-1}(A_i)$ and $f^{-1}(G \setminus A) = E \setminus f^{-1}(A)$, which implies that $\{f^{-1}(A) : A \in \mathcal{G}\}$ is a σ -algebra over E , and likewise $\{A : f^{-1}(A) \in \mathcal{E}\}$ is also a σ -algebra over G .

This implies that if \mathcal{A} is a collection of subsets of G generating \mathcal{G} and such that $f^{-1}(A) \in \mathcal{E}$ for all $A \in \mathcal{A}$, then $\{A : f^{-1}(A) \in \mathcal{E}\}$ is a σ -algebra containing \mathcal{A} , and hence \mathcal{G} . In particular, it suffices to check $f^{-1}(A) \in \mathcal{E}$, $\forall A \in \mathcal{A}$ to conclude that f is measurable.

If f takes real values, then

$$\mathcal{A} = \{(-\infty, y] : y \in \mathbb{R}\}$$

generates $\mathcal{B}(\mathbb{R})$ (Example sheet), and so f will be measurable whenever $f^{-1}((-\infty, y]) = \{x \in E : f(x) \leq y\} \in \mathcal{E}$ for all $y \in \mathbb{R}$. Moreover, if E is a topological space with $\mathcal{E} = \mathcal{B}(E)$, then if $f : E \rightarrow \mathbb{R}$ is continuous, it is Borel measurable.

The indicator function

$$1_A(x) = \begin{cases} 1 & \text{when } x \in A \\ 0 & \text{when } x \notin A \end{cases}$$

is measurable if and only if $A \in \mathcal{E}$.

One shows that compositions of measurable maps are measurable, and so are $f_1 + f_2$, $f_1 \cdot f_2$, $\inf_n f_n$, $\liminf_n f_n$, $\limsup_n f_n$ whenever the f_n are.

Moreover, given a collection of maps $\{f_i : E \rightarrow (G, \mathcal{G}), i \in I\}$ we can make them all measurable for

$$\sigma(f_i^{-1}(A) : A \in \mathcal{G}, i \in I)$$

Theorem (Monotone class theorem). *Let \mathcal{A} be a π -system generating the σ -algebra \mathcal{E} over E . Let further \mathcal{V} be a vector space of bounded maps from E to \mathbb{R} such that*

1. $1_E \in \mathcal{V}$, $1_A \in \mathcal{V}$, $\forall A \in \mathcal{A}$.
2. If f is bounded and $f_n \in \mathcal{V}$ is such that $0 \leq f_n \uparrow f$ pointwise on E , then $f \in \mathcal{V}$.

Then \mathcal{V} contains all bounded measurable $f : E \rightarrow \mathbb{R}$.

Proof. Define $\mathcal{D} = \{A \in \mathcal{E} : 1_A \in \mathcal{V}\}$. By hypothesis, \mathcal{D} contains the π -system \mathcal{A} and we now show it is also a d -system, so by Dynkin's lemma, $\mathcal{E} = \mathcal{D}$. Indeed, $E \in \mathcal{D}$ since $1_E \in \mathcal{V}$ by hypothesis. Also if $A \subseteq B$, $A, B \in \mathcal{D}$, then $1_{B \setminus A} = 1_B - 1_A \in \mathcal{V}$ as \mathcal{V} is a vector space. Finally, if $A_n \in \mathcal{D}$ and $A_n \uparrow A$, then $1_{A_n} \uparrow 1_A$ pointwise and so $1_A \in \mathcal{V}$ by hypothesis, so $A \in \mathcal{D}$. In particular $A \in \mathcal{V}$ for all $A \in \mathcal{E}$.

Let now $f : E \rightarrow \mathbb{R}$ be bounded, non-negative and measurable. Define

$$f_n = \sum_{j=0}^{n2^n} \frac{j}{2^n} 1_{A_{n_j}}$$

where $A_{n_j} = \{x \in E : \frac{j}{2^n} < f(x) \leq \frac{j+1}{2^n}\} = f^{-1}((\frac{j}{2^n}, \frac{j+1}{2^n}]) \in \mathcal{E}$ for $j = 0, \dots, n2^n - 1$, and $A_{n_{n2^n}} = \{x \in E : f(x) > n\} = f^{-1}((n, \infty)) \in \mathcal{E}$.

Clearly since f is bounded, for $n > \|f\|_\infty$, we see

$$f_n \leq f \leq f_n + 2^{-n}$$

so $|f_n - f| \leq 2^{-n} \rightarrow 0$. So by hypothesis $f \in \mathcal{V}$. For general f bounded and measurable, we can decompose $f = f^+ - f^-$ where $f^\pm \geq 0$, and repeat the argument above. \square

Image Measures

If $f : (E, \mathcal{E}) \rightarrow (G, \mathcal{G})$ is \mathcal{E} - \mathcal{G} measurable, and μ is a measure on \mathcal{E} , then the image measure $\nu = \mu \circ f^{-1}$ is obtained from

$$\nu(A) = \mu(f^{-1}(A)), \quad \forall A \in \mathcal{G}$$

which is indeed a measure on \mathcal{G} (Example sheet).

Lemma. Let $g : \mathbb{R} \rightarrow \mathbb{R}$ be a right-continuous, monotone increasing function, and set $g(\pm\infty) = \lim_{z \rightarrow \pm\infty} g(z)$. On $I = (g(-\infty), g(\infty))$ define

$$f(x) = \inf\{y \in \mathbb{R} : x \leq g(y)\}, \quad x \in I$$

Then f is monotone increasing, left-continuous and

$$f(y) \leq y \iff x \leq g(y) \quad \forall x, y$$

Proof. Define $J_x = \{y \in \mathbb{R} : x \leq g(y)\}$. Since $x > g(-\infty)$, J_x is non-empty and bounded below, so $f(x) \in \mathbb{R}$. Now if $y \in J_x$ then $y' \geq y$ implies $y' \in J_x$ as well since $g \uparrow$. Moreover if $y_n \downarrow y$, $y_n \in J_x$, then we can take limits in $x \leq g(y_n)$ to see $x \leq \lim_n g(y_n) = g(y)$ as g is right-continuous, so $y \in J_x$. We conclude that $J_x = [f(x), \infty)$, which shows the equivalence.

Moreover, if $x \leq x'$, then $J_x \supseteq J_{x'}$ since $g \uparrow$. So by properties of the infimum $f(x) \leq f(x')$. Likewise if $x_n \uparrow x$, then $J_x = \bigcap_n J_{x_n}$ so $f(x_n) \rightarrow f(x)$ as $x_n \rightarrow x$. \square

We call f the *generalised inverse of g* .

Theorem. Let g be as in the above lemma. Then there exists a unique Radon measure μ_g on \mathbb{R} such that $\mu_g((a, b]) = g(b) - g(a)$ for all $a < b$. Every Radon measure on \mathbb{R} can be obtained in this way.

Proof. For f as defined in the previous lemma, note that for all $z \in \mathbb{R}$

$$f^{-1}((-\infty, z]) = \{x : f(x) \leq z\} = \{x : x \leq g(y)\} = (g(-\infty), g(z)] \in \mathcal{B}(I)$$

Where the 2nd equality follows again from the lemma. So f is $\mathcal{B}\text{-}\mathcal{B}(I)$ measurable, and the image measure $\mu \circ f^{-1} = \mu_g$, where μ is the Lebesgue measure on I , exists.

Then for $-\infty < a < b < \infty$ we have

$$\mu_g((a, b]) = \mu(f^{-1}((a, b])) = \mu(x \in I : a < f(x) \leq b) = \mu((g(a), g(b)]) = g(b) - g(a)$$

Which uniquely determines μ_g by the same arguments as for the Lebesgue measure on \mathbb{R} . (Since g maps into \mathbb{R} , μ_g is a Radon measure).

Conversely, let ν be any Radon measure on \mathbb{R} , define

$$g(y) = \begin{cases} \nu((0, y]) & y \geq 0 \\ -\nu((y, 0]) & y < 0 \end{cases}$$

Which is clearly increasing in y (since ν is increasing). If $y_n \downarrow y$, then $(0, y_n] \downarrow (0, y]$ so $g(y_n) \rightarrow g(y)$ since ν is countably additive, so g is right-continuous. Finally (assuming $a < 0 < b$, the other cases are similar),

$$\nu((a, b]) = \nu((a, 0]) + \nu((0, b]) = -g(a) + g(b) = g(b) - g(a)$$

And by uniqueness as before, the result follows. \square

Remark: The μ_g are called Lebesgue-Stieltjes measures, with Stieltjes distribution g .

For example, the Dirac measure δ_x at $x \in \mathbb{R}$, defined by

$$\delta_x(A) = \begin{cases} 1 & \text{if } x \in A \\ 0 & \text{if } x \notin A \end{cases}$$

Which has Stieltjes distribution $g = 1_{[x, \infty)}$.

Random Variables

Let $(\Omega, \mathcal{F}, \mathbb{P})$ be a probability space, and (E, \mathcal{E}) a measurable space.

Definition. An E -valued random variable X is any \mathcal{F} - \mathcal{E} measurable map

$$X : \Omega \rightarrow E$$

When $E = \mathbb{R}, \mathbb{R}^d$ (with Borel σ -algebras) we call X a *random variable*, or random vector. The *law* or *distribution* μ_X of a random variable is given by $\mu_X = \mathbb{P} \circ X^{-1}$ (the image measure) with, for $E = \mathbb{R}$ distribution function

$$F_X(z) = \mu_X((-\infty, z]) = \mathbb{P}(X^{-1}((-\infty, z])) = \mathbb{P}(\omega \in \Omega : X(\omega) \leq z) = \mathbb{P}(X \leq z)$$

which uniquely determines μ_X .

Using properties of measures one shows that any distribution function satisfies

1. $F_X \uparrow$
2. F_X is right-continuous
3. $\lim_{z \rightarrow -\infty} F_X(z) = \mu_X(\emptyset) = 0$ and $\lim_{z \rightarrow \infty} F_X(z) = \mu_X(\mathbb{R}) = \mathbb{P}(\Omega) = 1$

Given any distribution function F_X satisfying 1,2 & 3, we can on $(\Omega, \mathcal{F}, \mathbb{P}) = ((0, 1), \mathcal{B}(0, 1), \mu)$, where μ is the Lebesgue measure obtain a random variable $X : \Omega \rightarrow \mathbb{R}$ by

$$X(\omega) = \inf\{x : \omega \leq F_X(x)\}$$

with distribution function F_X .

Definition. A countable collection $(X_i : (\Omega, \mathcal{F}, \mathbb{P} \rightarrow (E, \mathcal{E}))$ of random variables is said to be *independent* whenever the σ -algebras $\sigma(X_i^{-1}(A) : A \in \mathcal{E})$ are independent. For $(E, \mathcal{E}) = (\mathbb{R}, \mathcal{B})$ one shows (Example sheet) that this is equivalent (for $I = \{1, \dots, n\}$) to

$$\mathbb{P}(X_1 \leq x_1, \dots, X_n \leq x_n) = \prod_{i=1}^n \mathbb{P}(X_i \leq x_i), \quad \forall x_i \in \mathbb{R}$$

We now construct on $(\Omega, \mathcal{F}, \mathbb{P}) = ((0, 1), \mathcal{B}, \mu|_{(0,1)})$ with $\mu|_{(0,1)}$ the Lebesgue measure on $(0, 1)$ an infinite sequence of independent random variables with prescribed distribution functions F_n .

Any $\omega \in (0, 1)$ has a binary representation $(\omega_i) \in \{0, 1\}^{\mathbb{N}}$, where $\omega = \sum_{i=1}^{\infty} \omega_i 2^{-i}$, which is unique if we exclude sequences which terminate with infinitely many 0's (so rationals end in a sequence of 1's). Then we can define $R_n(\omega) = \omega_n$ ("Radenmacher functions"), which are of the form

$$\begin{aligned} R_1(\omega) &= 1_{(1/2, 1)} \\ R_2(\omega) &= 1_{(1/4, 1/2]} + 1_{(3/4, 1)} \\ R_3(\omega) &= 1_{(1/8, 1/4]} + 1_{(3/8, 1/2]} + 1_{(5/8, 3/4]} + 1_{(7/8, 1)} \end{aligned}$$

So the R_n are random variables such that $\mathbb{P}(R_n = 1) = \frac{1}{2} = \mathbb{P}(R_n = 0)$, so the R_n are Bernoulli for all n . Moreover for $(x_i)_{i=1}^n \in \{0, 1\}^n$

$$\mathbb{P}(R_1 = x_1, \dots, R_n = x_n) = 2^{-n} = \underbrace{\mathbb{P}(R_1 = x_1) \dots \mathbb{P}(R_n = x_n)}_{\frac{1}{2}}$$

So the R_n are all independent. Now take a bijection $m : \mathbb{N}^2 \rightarrow \mathbb{N}$ and define $Y_{nk} = R_{m(n,k)}$ which are again independent and define

$$Y_n = \sum_k 2^{-k} Y_{nk}$$

which converge for all $\omega \in \Omega$ since $|Y_{nk}| \leq 1$ are still independent. To determine the law of Y_n we consider the π -system of intervals $(\frac{i}{2^m}, \frac{i+1}{2^m}]$, $i = 0, \dots, 2^m - 1$, $m \in \mathbb{N}$, with dyadic endpoints, which generate \mathcal{B} and

$$\begin{aligned} \mathbb{P}\left(Y_n \in \left(\frac{i}{2^m}, \frac{i+1}{2^m}\right]\right) &= \mathbb{P}\left(\frac{i}{2^m} < \sum_k 2^{-k} Y_{nk} \leq \frac{i+1}{2^m}\right) = 2^{-m} \\ &= \mu|_{(0,1)}\left(\left(\frac{i}{2^m}, \frac{i+1}{2^m}\right]\right) \end{aligned}$$

so the law $\mu_{Y_n} = \mu|_{(0,1)}$ by the uniqueness theorem, and so the Y_n 's are an infinite sequence of independent uniform random variables. Now if F_n are probability distribution functions (satisfy axioms 1-3 from earlier), then taking the generalised inverse $f_n = F_n^{-1}$ from the lemma, we see that the $F_n^{-1}(Y_n)$ are independent and have distribution function F_n .

Convergence of measurable functions

Definition. We say that a property defining a set $A \in \mathcal{E}$ holds μ -almost everywhere if $\mu(A^c) = 0$ for a measure μ on \mathcal{E} . If $\mu = \mathbb{P}$, we say it holds \mathbb{P} -almost surely, or with probability 1, if $\mathbb{P}(A) = 1$.

If f_n, f are measurable maps on $(E, \mathcal{E}|_\mu)$ we say $f_n \rightarrow f$ μ -almost always if

$$\mu(x \in E : f_n(x) \not\rightarrow f(x) \text{ as } n \rightarrow \infty) = 0$$

We say $f_n \rightarrow f$ in μ -measure if for all $\varepsilon > 0$

$$\mu(x \in E : |f_n(x) - f(x)| > \varepsilon) \rightarrow 0 \text{ as } n \rightarrow \infty$$

For random variables say $X_n \rightarrow X$ \mathbb{P} -almost surely or $X_n \rightarrow X$ in \mathbb{P} -probability respectively.

If $E = \mathbb{R}$, we say $X_n \xrightarrow{d} X$ in distribution if $\mathbb{P}(X_n \leq x) \rightarrow \mathbb{P}(X \leq x)$ for all $x \in \mathbb{R}$ such that $x \mapsto \mathbb{P}(X \leq x)$ is continuous. One shows $X_n \xrightarrow{P} X$ implies $X_n \xrightarrow{d} X$.

Theorem. Let $f_n : (E, \mathcal{E}) \rightarrow \mathbb{R}$ be measurable functions.

1. If $\mu(E) < \infty$, then whenever $f_n \rightarrow 0$ a.e (almost everywhere) we have $f_n \rightarrow 0$ in measure.
2. If $f_n \rightarrow 0$ in measure, then $f_{n_k} \rightarrow 0$ a.e along some subsequence n_k .

Proof.

1. For all $\varepsilon > 0$ we have

$$\begin{aligned} \mu(|f_n| \leq \varepsilon) &\geq \mu\left(\bigcap_{m \geq n} \underbrace{\{|f_m| \leq \varepsilon\}}_{:= A_m}\right) \\ &\uparrow \mu\left(\bigcup_n \bigcap_{m \geq n} A_m\right) \\ &= \mu(|f_n| \leq \varepsilon \text{ eventually}) \\ &\geq \mu(f_n \rightarrow 0 \text{ as } n \rightarrow \infty) \\ &= \mu(E) \end{aligned}$$

so $\liminf_n \mu(|f_n| \leq \varepsilon) \geq \mu(E)$. So we see $\limsup_n \mu(|f_n| > \varepsilon) \leq \mu(E) - \mu(E) = 0$, so $\mu(|f_n| > \varepsilon) \rightarrow 0$ as $n \rightarrow \infty$ as desired.

2. By hypothesis, for all $\varepsilon > 0$ $\mu(|f_n| > \frac{1}{k}) < \varepsilon$ for n large enough. So choosing $\varepsilon = \frac{1}{k^2}$ we see that along some subsequence n_k we have $\mu(|f_{n_k}| > \frac{1}{k}) \leq \frac{1}{k^2}$ so

$$\sum_k \mu(|f_{n_k}| > \frac{1}{k}) < \infty$$

and by the 1st Borel-Cantelli Lemma, we have $\mu(|f_{n_k}| > \frac{1}{k} \text{ i.o.}) = 0$, so $f_{n_k} \rightarrow 0$ a.e.

□

Remarks: (1) is false if $\mu(E) = \infty$, as the example $1_{(n,\infty)}$ on $(\mathbb{R}, \mathcal{B}, \mu)$, μ Lebesgue measure shows. (2) is false without restricting to subsequences: take A_n independent such that $\mathbb{P}(A_n) = \frac{1}{n}$ then $1_{A_n} \rightarrow 0$ in \mathbb{P} -probability since $\mathbb{P}(1_{A_n} > \varepsilon) = \mathbb{P}(A_n) = \frac{1}{n} \rightarrow 0$ but $\sum_n \mathbb{P}(A_n) = \infty$, so by the 2nd Borel-Cantelli Lemma, $\mathbb{P}(1_{A_n} > \varepsilon \text{ i.o.}) = 1$, so $1_{A_n} \not\rightarrow 0$ a.s.

Example. Let $(X_n : n \in \mathbb{N})$ be independent and identically distributed (iid) exponential random variables with $\mathbb{P}(X_1 \leq x) = 1 - e^{-x}$, $x \geq 0$. Define $A_n = \{X_n \geq \alpha \log n\}$, $\alpha > 0$, s.t $\mathbb{P}(A_n) = n^{-\alpha}$ and $\sum_n \mathbb{P}(A_n) < \infty$ if and only if $\alpha > 1$. So by the Borel-Cantelli lemmas, we have

$$\mathbb{P}\left(\frac{X_n}{\log n} \geq 1 \text{ i.o.}\right) = 1$$

while

$$\mathbb{P}\left(\frac{X_n}{\log n} \geq 1 + \varepsilon \text{ i.o.}\right) = 0 \quad \forall \varepsilon > 0$$

So $\limsup_n \frac{X_n}{\log n} = 1$ almost surely.

Kolmogorov's 0-1 Law

For $(X_n : n \in \mathbb{N})$ random variables, define $\mathcal{T} = \sigma(X_{n+1}, X_{n+2}, \dots)$ and set $\mathcal{T} = \bigcap_{n \in \mathbb{N}} \mathcal{T}_n$, the “tail σ -algebra” which contains all events in \mathcal{F} which depend only on the limiting behaviour of the sequence.

Theorem. For $(X_n : n \in \mathbb{N})$ independent random variables, if $A \in \mathcal{T}$ then $\mathbb{P}(A) = 1$ or $\mathbb{P}(A) = 0$. Moreover if $Y : (\Omega, \mathcal{T}) \rightarrow (\mathbb{R}, \mathcal{B})$ is measurable, then Y is constant almost surely.

Proof. Define $\mathcal{F}_n = \sigma(X_1, \dots, X_n)$ which is a σ -algebra generated by the π -system of sets

$$A = (X_1 \leq x_1, \dots, X_n \leq x_n), \quad x_i \in \mathbb{R}$$

and note that the π -system of sets

$$B = (X_{n+1} \leq x_{n+1}, \dots, X_{n+k} \leq x_{n+k}), \quad k \in \mathbb{N}, \quad x_i \in \mathbb{R}$$

generates \mathcal{T}_n . By independence of X_n , $\mathbb{P}(A \cap B) = \mathbb{P}(A)\mathbb{P}(B)$, so by the theorem from earlier we see that \mathcal{T}_n and \mathcal{F}_n are independent. If we set $\mathcal{F}_\infty = \sigma(X_1, X_2, \dots)$, then $\bigcup_n \mathcal{F}_n$ is a π -system generating \mathcal{F}_∞ , and if $A \in \bigcup_n \mathcal{F}_n$, there exists \bar{n} such that $B \in \mathcal{T}_{\bar{n}}$ is independent of A , in particular A is independent of elements in $\mathcal{T} = \bigcap_{\bar{n}} \mathcal{T}_{\bar{n}}$, hence as before \mathcal{F}_∞ is independent of \mathcal{T} . But clearly $\mathcal{T} \subseteq \mathcal{F}_\infty$, so if $A \in \mathcal{T}$ it is independent to $A \in \mathcal{F}_\infty$! Now $\mathbb{P}(A) = \mathbb{P}(A \cap A) = \mathbb{P}(A)^2$, so $\mathbb{P}(A) = 0$ or 1 . Finally, if Y is \mathcal{T} measurable, then $\{Y \leq y\}$ lies in \mathcal{T} for all y , hence have probability 1 or 0. Then let

$$c = \inf\{y : F_Y(y) = 1\}$$

so $Y = c$ almost surely. □

3 Integration

For $f : (E, \mathcal{E}, \mu) \rightarrow \mathbb{R}$ measurable or “integrable” we will define the integral with respect to μ :

$$\mu(f) = \int_E f d\mu = \int_E f(x) d\mu(x)$$

and if X is a random variable, we define its (“mathematical”) expectation as

$$\mathbb{E}X = \int_{\Omega} X d\mathbb{P} = \int_{\Omega} X(\omega) d\mathbb{P}(\omega)$$

To start, call $f : (E, \mathcal{E}, \mu) \rightarrow \mathbb{R}$ *simple* if it is of the form

$$f = \sum_{k=1}^m a_k 1_{A_k}, \quad a_k \geq 0, \quad A_k \in \mathcal{E}, \quad m \in \mathbb{N}$$

We define its μ -integral to be

$$\mu(f) = \sum_{k=1}^m a_k \mu(A_k)$$

which is well-defined (Example sheet) and it satisfies the following properties:

1. $\mu(\alpha f + \beta g) = \alpha \mu(f) + \beta \mu(g)$ for all $\alpha, \beta \geq 0$ and f, g simple
2. If $g \leq f$ then $\mu(g) \leq \mu(f)$
3. If $f = 0$ almost everywhere $\mu(f)$

For general $f : (E, \mathcal{E}, \mu) \rightarrow \mathbb{R}$ non-negative, we define its μ -integral as

$$\mu(f) = \sup\{\mu(g) : g \leq f, \text{ } g \text{ simple}\}$$

which is consistent with the definition for simple functions, and takes values in $[0, \infty]$.

For $f : (E, \mathcal{E}, \mu) \rightarrow \mathbb{R}$ measurable (but not necessarily non-negative), we define $f^+ = \max(f, 0)$, $f^- = \max(-f, 0)$, so that $f = f^+ - f^-$ and $|f| = f^+ + f^-$. We say that f is μ -integrable if $\mu(|f|) < \infty$. In this case we define

$$\mu(f) = \mu(f^+) - \mu(f^-)$$

which is well-defined (i.e not $\infty - \infty$).

Theorem (Monotone Convergence Theorem). *Let $f_n, f : (E, \mathcal{E}, \mu) \rightarrow \mathbb{R}$ be measurable and non-negative such that $0 \leq f_n \uparrow f$ (i.e $f_n(x) \leq f_{n+1}(x) \leq f(x)$ and $f_n(x) \rightarrow f(x)$ for all $x \in E$). Then $\mu(f_n) \rightarrow \mu(f)$ as $n \rightarrow \infty$.*

Remark: if we take the approximating sequence $\tilde{f}_n (= \min(2^{-n} \lfloor 2^n f \rfloor, n))$ then $0 \leq \tilde{f}_n \uparrow f$ so $\mu(f) = \lim_n \mu(\tilde{f}_n)$.

Proof. Recall $\mu(f) = \sup\{\mu(g) : g \leq f, g \text{ simple}\}$. Since $0 \leq f_n \uparrow$ we have $\mu(f_n) \uparrow \sup_n \mu(f_n) = M$. But then since $f_n \leq f$ we must have $\mu(f_n) \leq \mu(f)$ so taking suprema $M \leq \mu(f)$, and if $M < \infty$ we have $\lim_n \mu(f_n) \leq \mu(f)$.

We will now show $\mu(g) \leq M$ for all simple functions g such that $g \leq f$ so that taking suprema $\mu(f) = \sup_g \mu(g) \leq M$ so $\mu(f) = \lim_n \mu(f_n)$ follows.

We define $g_n = \min(\bar{f}_n, g) = \bar{f}_n \wedge g$, where \bar{f}_n is the approximation of f_n by simple functions from the monotone class theorem, $[\bar{f}_n]_n = \bar{f}_n = \min(2^{-n} \lfloor 2^n f_n \rfloor, n)$. Now since $f_n \uparrow f$ we must have $\bar{f}_n \uparrow f$ too, and so $g_n \uparrow \min(f, g) = g$, and since $\bar{f}_n \leq f_n$ we also have $g_n \leq f_n$ for all n .

Now let g be an arbitrary simple function, of the form

$$g = \sum_{k=1}^m a_k 1_{A_k}$$

with $m \in \mathbb{N}$, $a_k \geq 0$ and $A_k \in \mathcal{E}$ disjoint (wlog). We define for $\varepsilon > 0$ arbitrary

$$A_k(n) = \{x \in A_k : g_n(x) \geq (1 - \varepsilon)a_k\}$$

Since $g = a_k$ on A_k and since $g_n \uparrow g$, we have $A_k(n) \uparrow A_k$ for all k . Also since μ is a measure, we must have $\mu(A_k(n)) \uparrow \mu(A_k)$. We have $g_n 1_{A_k} \geq g_n 1_{A_k(n)} \geq (1 - \varepsilon)a_k 1_{A_k(n)}$ on E . Moreover

$$g_n = \sum_{k=1}^m g_n 1_{A_k}$$

since the A_k 's are disjoint and support g_n (if $1_{A_n} = 0$ for all n , then $g = 0$ and $f_n = 0$). Now

$$\mu(g_n) = \sum_{k=1}^m \mu(g_n 1_{A_k}) \geq (1 - \varepsilon) \sum_{k=1}^m a_k \mu(A_k(n)) \uparrow (1 - \varepsilon) \sum_{k=1}^m a_k \mu(A_k) = (1 - \varepsilon) \mu(g)$$

So $\mu(g) \leq \frac{1}{1 - \varepsilon} \limsup_n \mu(g_n) \leq \frac{1}{1 - \varepsilon} \limsup_n \mu(f_n) \leq \frac{M}{1 - \varepsilon}$. Since ε was arbitrary we have $\mu(g) \leq M$ as required. \square

Remarks: we have shown $\mu(f) = \mu(\lim_n f_n) = \lim_n \mu(f)$, so we can interchange $\int(\cdot)d\mu$ and the limit. If $g_n \geq 0$, then $\mu(\sum_n g_n) = \sum_n \mu(g_n)$. Moreover it suffices to require $f_n \uparrow f$ almost everywhere and the $f_n \geq 0$ hypothesis is not necessary as long as f_1 is integrable (then just subtract f_1 from all terms).

Theorem. Let $f, g : (E, \mathcal{E}, \mu) \rightarrow \mathbb{R}$ be measurable and non-negative. Then

1. $\mu(\alpha f + \beta g) = \alpha \mu(f) + \beta \mu(g)$ for all $\alpha, \beta \geq 0$
2. If $g \leq f$ then $\mu(g) \leq \mu(f)$

3. $f = 0$ almost everywhere if and only if $\mu(f) = 0$.

Proof. If \tilde{f}_n, \tilde{g}_n are the approximations of f, g from the monotone class theorem, then $\alpha\tilde{f}_n \uparrow \alpha f$, $\beta\tilde{g}_n \uparrow \beta g$, $\alpha\tilde{f}_n + \beta\tilde{g}_n \uparrow \alpha f + \beta g$. And from earlier

$$\mu(\alpha\tilde{f}_n + \beta\tilde{g}_n) = \alpha\mu(\tilde{f}_n) + \beta\mu(\tilde{g}_n)$$

So taking limits the monotone convergence theorem implies

$$\mu(\alpha f + \beta g) = \alpha\mu(f) + \beta\mu(g)$$

(2) follows in a similar way. Now we show (3): if $f = 0$ almost everywhere, then $0 \leq \tilde{f}_n \leq f = 0$ a.e, so $\tilde{f}_n = 0$ a.e for all n , so $\mu(\tilde{f}_n) = 0$, so $\mu(\tilde{f}_n) \uparrow \mu(f) = 0$. Conversely if $\mu(f) = 0$ then $0 \leq \mu(\tilde{f}) \uparrow \mu(f) = 0$ so $\mu(\tilde{f}_n) = 0$ for all n , so $\tilde{f}_n = 0$ a.e. Since $0 \leq \tilde{f}_n \uparrow f$ we have that $f = 0$ a.e. \square

Remark: functions such as $1_{\mathbb{Q}}$ have $\mu(1_{\mathbb{Q}}) = 0$, and are ‘identified’ with 0.

Theorem. Let $f, g : (E, \mathcal{E}, \mu) \rightarrow \mathbb{R}$ be integrable. Then

1. $\mu(\alpha f + \beta g) = \alpha\mu(f) + \beta\mu(g)$ for all $\alpha, \beta \in \mathbb{R}$
2. $g \leq f$ implies $\mu(g) \leq \mu(f)$
3. If $f = 0$ almost everywhere then $\mu(f) = 0$

Proof. Clearly if f is integrable, so is αf , and $\mu(-f) = -\mu(f)$. And for $\alpha \geq 0$, $\mu(\alpha f) = \mu((\alpha f)^+) - \mu((\alpha f)^-) = \alpha\mu(f^+) - \alpha\mu(f^-) = \alpha\mu(f)$. So we can restrict to $\alpha = \beta = 1$.

Define $h = f + g = h^+ - h^- = f^+ - f^- + g^+ - g^-$. This is the same as $h^+ + f^- + g^- = h^- + f^+ + g^+$, and all of these functions are non-negative. Hence by the previous theorem

$$\mu(h^+) + \mu(f^-) + \mu(g^-) = \mu(h^-) + \mu(f^+) + \mu(g^+)$$

so $\mu(h) = \mu(f) + \mu(g)$ follows.

Now we show (2). Clearly $0 \leq f - g$ so $\mu(0) \leq \mu(f - g)$ by the previous theorem, and $\mu(f - g) = \mu(f) - \mu(g)$ by (1) of this theorem.

Finally we show (3): if $f = 0$ almost everywhere, $f^+ = f^- = 0$ almost everywhere, so $\mu(f) = \mu(f^+) - \mu(f^-) = 0 - 0$. \square

Lemma (Fatou). *Let $f_n, f : (E, \mathcal{E}, \mu) \rightarrow \mathbb{R}$ be measurable and non-negative. Then $\mu(\liminf_n f_n) \leq \liminf_n \mu(f_n)$.*

Remark: recall that for $x_n \in \mathbb{R}$

$$\liminf_n x_n = \sup_n \inf_{m \geq n} x_m$$

$$\limsup_n x_n = \inf_n \sup_{m \geq n} x_m$$

In particular, if $\limsup_n x_n = \liminf_n x_n$ then $\lim_n x_n = \liminf_n x_n$. Therefore if $f = \lim_n f_n$ exists in Fatou's lemma, we have $\mu(f) \leq \liminf_n \mu(f_n)$.

Proof. We have $\inf_{m \geq n} f_m \leq f_k$ for all $k \geq n$, and integrating this implies $\mu(\inf_{m \geq n} f_m) \leq \mu(f_k)$ for all $k \geq n$. So

$$\mu(\inf_{m \geq n} f_m) \leq \mu(f_k)$$

$$\mu(\inf_{m \geq n} f_m) \leq \inf_{k \geq n} \mu(f_k) \leq \sup_n \inf_{k \geq n} \mu(f_k) = \liminf_n \mu(f_n)$$

Also, $0 \leq \inf_{m \geq n} f_m \uparrow \sup_n \inf_{m \geq n} f_m$ so by the monotone convergence theorem

$$\mu(\liminf_n f_n) = \lim_n \mu(\inf_{m \geq n} f_m) \leq \liminf_n \mu(f_n)$$

□

Theorem (Dominated convergence theorem). *Let $f_n, f : (E, \mathcal{E}, \mu) \rightarrow \mathbb{R}$ be measurable such that $|f_n| \leq g$ almost everywhere on E and g is μ -integrable ($\mu(g) < \infty$). Suppose $f_n \rightarrow f$ pointwise (or almost everywhere) on E . Then f_n and f are integrable and $\mu(f_n) \rightarrow \mu(f)$ as $n \rightarrow \infty$.*

Proof. Clearly $\mu(|f_n|) \leq \mu(g) < \infty$ so the f_n are integrable and taking limits in $|f_n| \leq g$ we have $|f| \leq g$, so $\mu(|f|) < \infty$.

Next

$$0 \leq g \pm f_n \xrightarrow{\text{ptws on } E} g \pm f$$

By Fatou's lemma

$$\mu(g) + \mu(f) = \mu(g + f) = \mu(\liminf_n (g + f_n)) \leq \liminf_n (\mu(g) + \mu(f_n)) = \mu(g) + \liminf_n \mu(f_n)$$

So $\mu(f) \leq \liminf_n \mu(f_n)$. Likewise

$$\mu(g) - \mu(f) = \mu(\liminf_n (g - f_n)) \leq \mu(g) - \limsup_n \mu(f_n)$$

So $\limsup_n \mu(f_n) \leq \mu(f)$. Therefore $\limsup_n \mu(f_n) = \liminf_n \mu(f_n) = \lim_n \mu(f_n) = \mu(f)$. □

Example. On $E = [0, 1]$ with the Lebesgue measure, suppose $f_n \rightarrow f$ pointwise and $\sup_n \|f_n\|_\infty \leq g < \infty$. Then since $\mu(g) \leq g$ the dominated convergence theorem implies $\mu(f_n) \rightarrow \mu(f)$ as $n \rightarrow \infty$ (no uniform convergence of $f_n \rightarrow f$ required).

Remark: the proof of the Fundamental Theorem of Calculus (FTC) requires only $\int_x^{x+h} dt = h$. Therefore for any continuous $f : [0, 1] \rightarrow \mathbb{R}$

$$\underbrace{\int_0^x f(t) dt}_{\text{Riemann-integral}} = F(x) = \underbrace{\int_0^x f(t) d\mu(t)}_{\text{Lebesgue-integral}}, \quad x \in [0, 1]$$

So these integrals coincide for continuous maps.

One shows that all Riemann-integrable functions are μ^* -measurable (μ is Lebesgue measure) but that there exist Riemann-integrable functions that are not Borel measurable.

A bounded μ^* -measurable function is Riemann-integrable if and only if

$$\mu(\{x \in [0, 1] : f \text{ is discontinuous at } x\}) = 0$$

All standard formulae for the Riemann-integral (substitution, integration, by parts etc) extend to all bounded measurable functions by the monotone class theorem (see Example sheet).

Theorem. Let $U \subseteq \mathbb{R}$ be open, (E, \mathcal{E}, μ) a measure space, and $f : U \times E \rightarrow \mathbb{R}$ such that

- $x \mapsto f(t, x)$ for all $t \in U$ is measurable
- $t \mapsto f(t, x)$ is differentiable for all $x \in E$, with $\left| \frac{\partial f(t, x)}{\partial t} \right| \leq g(x)$ for all $t \in U$ where g is μ -integrable.

Then if

$$F(t) = \int_E f(t, x) d\mu(x)$$

we have

$$F'(t) = \int_E \frac{\partial f}{\partial t}(t, x) d\mu(x)$$

Proof. By the MVT

$$|g_h(x)| := \left| \frac{f(t+h, x) - f(t, x)}{h} - \frac{\partial f}{\partial t}(t, x) \right| = \left| \frac{\partial f(\tilde{t}, x)}{\partial t} - \frac{\partial f(t, x)}{\partial t} \right|$$

For some $\tilde{t} \in U$. SO $|g_h(x)| \leq 2g(x)$ which is μ -integrable. By differentiability, we have $g_h \rightarrow 0$ as $h \rightarrow 0$, so applying the dominated convergence theorem, $\mu(g_h) \rightarrow \mu(0) = 0$, or by linearity of μ

$$\mu(g_h) = \frac{\int_E (f(t+h, x) - f(t, x)) d\mu(x)}{h} - \int_E \frac{\partial f}{\partial t}(t, x) d\mu(x)$$

$$= \frac{F(t+h) - F(t)}{h} - F'(t) \rightarrow 0 \text{ as } h \rightarrow 0$$

□