1 Separating and convergence-determining classes

Definition 1.1 (Separating class)

Suppose Ω is a non-empty set, $\mathcal{A}$ is a σ-algebra of subsets of Ω, $(\Omega,\mathcal{A})$ is the corresponding measurable space, and $\mathcal{M}_1(\Omega,\mathcal{A})$ is the set of all probability measures defined on $\mathcal{A}$. A ***separating class*** *of subsets of $(\Omega,\mathcal{A})$ is a collection $\mathcal{S}\subset\mathcal{A}$ of subsets of Ω which satisfies the following condition: For every two probability measures $\mu,\nu\in\mathcal{M}_1(\Omega,\mathcal{A})$,*

$$\mu(S)=\nu(S),\ \text{for every } S\in\mathcal{S} \quad\Longrightarrow\quad \mu(A)=\nu(A),\ \text{for every } A\in\mathcal{A}$$

Definition 1.2 (Convergence-determining class)

Suppose Ω is a topological space, $\mathcal{B}(\Omega)$ is its Borel σ-algebra, $(\Omega,\mathcal{B}(\Omega))$ is the corresponding measurable space, and $\mathcal{M}_1(\Omega,\mathcal{B}(S))$ is the set of all probability measures defined on $\mathcal{B}(\Omega)$. A ***convergence-determining class*** *of subsets of $(\Omega,\mathcal{B}(\Omega))$ is a collection $\mathcal{C}\subset\mathcal{B}(\Omega)$ of Borel subsets of Ω which satisfies the following condition: For any $\mu,\mu_1,\mu_2,\ldots\in\mathcal{M}_1(\Omega,\mathcal{B}(\Omega))$,*

$$\lim_{n\to\infty}\mu_n(C)\;=\;\mu(C),\ \text{for every } C\in\mathcal{C}_\mu \quad\Longrightarrow\quad \mu_n\xrightarrow{w}\mu,$$

where

$$\mathcal{C}_\mu\;:=\;\{\,A\in\mathcal{C}\ \mid\ \mu(\partial A)\;=\;0\,\},$$

*and $\mathcal{C}_\mu$ is called the collection of μ-**continuity sets** in $\mathcal{C}$.*

Theorem 1.3

Suppose Ω is a non-empty set, $\mathcal{A}$ is a σ-algebra of subsets of Ω, and $(\Omega,\mathcal{A})$ is the corresponding measurable space. If

- *$\mathcal{S}\subset\mathcal{A}$ is closed under finite intersections, and*
- *$\mathcal{S}$ generates $\mathcal{A}$ (i.e. $\sigma(\mathcal{S})=\mathcal{A}$),*

then $\mathcal{S}$ is a separating class of subsets of $(\Omega,\mathcal{A})$.

Proof Let μ and ν be two probability measures defined on $(\Omega,\mathcal{A})$ such that $\mu(S)=\nu(S)$ for each $S\in\mathcal{S}$. We need to show that $\mu(A)=\nu(A)$ for each $A\in\mathcal{A}$. To this end, let

$$\mathcal{L}\;:=\;\{\,A\in\mathcal{A}=\sigma(\mathcal{S})\ \mid\ \mu(A)=\nu(A)\,\}.$$

Note that $\mathcal{S}\subset\mathcal{L}$, by the hypothesis that μ and ν agree on $\mathcal{S}$, and $\mathcal{L}\neq\varnothing$ since $\Omega\in\mathcal{L}$. By Corollary B.8, it suffices to establish that $\mathcal{L}$ is a λ-system, since then it will follow that

$$\mathcal{A}\;=\;\sigma(\mathcal{S})\;\subset\;\mathcal{L}\;:=\;\{\,A\in\mathcal{A}=\sigma(\mathcal{S})\ \mid\ \mu(A)=\nu(A)\,\}\;\subset\;\sigma(\mathcal{S})\;=\;\mathcal{A},$$

i.e., $\mathcal{A}=\sigma(\mathcal{S})=\mathcal{L}$, or equivalently, μ and ν agree on all of $\mathcal{A}=\sigma(\mathcal{S})$. Now, we have already noted that $\Omega\in\mathcal{L}$. For $A\in\mathcal{L}$, we have

$$\mu(\Omega\setminus A)\;=\;1-\mu(A)\;=\;1-\nu(A)\;=\;\nu(\Omega\setminus A),$$

hence $\Omega\setminus A\in\mathcal{L}$. Thus, $\mathcal{L}$ is closed under complementations. Lastly, let $A_1,A_2,\ldots\in\mathcal{L}$ be pairwise disjoint. Then,

$$\mu\left(\bigsqcup_{n=1}^{\infty}A_n\right)\;=\;\sum_{n=1}^{\infty}\mu(A_n)\;=\;\sum_{n=1}^{\infty}\nu(A_n)\;=\;\nu\left(\bigsqcup_{n=1}^{\infty}A_n\right),$$

thus $\bigsqcup_{n=1}^{\infty}A_n\in\mathcal{L}$, which proves that $\mathcal{L}$ is closed under countable disjoint unions. $\mathcal{L}$ is therefore indeed a λ-system and the proof of the Theorem is complete. $\square$

Corollary 1.4 *Suppose S is a topological space and $\mathcal{B}(S)$ is its Borel σ-algebra (i.e. the σ-algebra generated by the collection of open subsets of S). Then, the collection of open subsets of S is a separating class of subsets of the measurable space $(S,\mathcal{B}(S))$.*

Proof Recall that the collection of open sets are closed under finite intersections (by definition of topology), and they generate the Borel σ-algebras (by definition of Borel σ-algebras). Thus the Corollary follows immediately from Theorem 1.3. □

2 On the separating and convergence-determining classes of $\mathbb{R}^\infty$

Definition 2.1 (The metric on $\mathbb{R}^\infty$, Example 1.2, [1])
Let $\mathbb{R}^\infty$ denotes the set of all infinite sequences of real numbers, i.e.

$$\mathbb{R}^\infty := \{\, (x_1,x_2,\ldots) \mid x_i \in \mathbb{R}, \text{ for each } i\in\mathbb{N} \,\}.$$

Define $\rho : \mathbb{R}^\infty \times \mathbb{R}^\infty \longrightarrow [\,0,1\,]$ as follows:

$$\rho(x,y) := \sum_{n=1}^{\infty} \frac{\min\{\,1\,,|\,x_n-y_n\,|\,\}}{2^n}.$$

Remark 2.2 *Recall that*

$$\sum_{n=1}^{\infty}\frac{1}{2^n} = \frac{1}{2}\sum_{n=1}^{\infty}\frac{1}{2^{n-1}} = \frac{1}{2}\cdot\left(\frac{1}{1-\frac{1}{2}}\right) = 1,$$

which proves indeed that $0 \le \rho(x,y) \le 1$, for any $x,y\in\mathbb{R}^\infty$.

Theorem 2.3 (The metric space properties of $\mathbb{R}^\infty$)

(i) $(\,\mathbb{R}^\infty,\rho\,)$ *is a metric space. Let $\mathbb{R}^\infty$ denote also this metric space in the remainder of this Theorem.*

(ii) *For $x, x^{(1)}, x^{(2)}, x^{(3)}, \ldots, \in \mathbb{R}^\infty$, we have:*

$$\rho\Big(\,x^{(n)},\,x\,\Big) \longrightarrow 0 \quad\Longleftrightarrow\quad \text{for each } i\in\mathbb{N},\ \lim_{n\to\infty}\left|\,x_i^{(n)}-x_i\,\right| = 0$$

(iii) *For each $n\in\mathbb{N}$, the "natural projection to the initial segment of length n"*

$$\pi_n : \mathbb{R}^\infty \longrightarrow \mathbb{R}^n : x \longmapsto (x_1,x_2,\ldots,x_n)$$

is continuous, where $\mathbb{R}^n$ has the usual Euclidean topology.

(iv) *For each $x\in\mathbb{R}^\infty$, $n\in\mathbb{N}$, and $\varepsilon>0$, let $C_{\mathbb{R}^n}(\pi_n(x),\varepsilon)$ denote the open hypercube in $\mathbb{R}^n$ of side length 2ε centred at $\pi_n(x)\in\mathbb{R}^n$, i.e.*

$$C_{\mathbb{R}^n}(\pi_n(x),\varepsilon) := \left\{\, y\in\mathbb{R}^n \;\middle|\; \begin{array}{c} |\,y_i-x_i\,| < \varepsilon, \\ i=1,2,\ldots,n \end{array} \right\}$$

Then, its pre-image in $\mathbb{R}^\infty$ under π_n

$$\pi_n^{-1}(\,C_{\mathbb{R}^n}(\pi_n(x),\varepsilon)\,) = \left\{\, y\in\mathbb{R}^\infty \;\middle|\; \begin{array}{c} |\,y_i-x_i\,| < \varepsilon, \\ i=1,2,\ldots,n \end{array} \right\}$$

is an open subset of $\mathbb{R}^\infty$.

(v) *For each $x \in \mathbb{R}^\infty$, $n \in \mathbb{N}$, and $\varepsilon > 0$, we have:*

$$\pi_n^{-1}(\,C_{\mathbb{R}^n}(\pi_n(x),\varepsilon)\,) \;\subset\; B_{\mathbb{R}^\infty}\!\left(x\,,\,\varepsilon + \frac{1}{2^n}\right),$$

where $B_{\mathbb{R}^\infty}\left(x\,,\,\varepsilon + \frac{1}{2^n}\right)$ is the open ball in $\mathbb{R}^\infty$ centred at x of radius $\varepsilon + \frac{1}{2^n}$, i.e.

$$B_{\mathbb{R}^\infty}\!\left(x\,,\,\varepsilon + \frac{1}{2^n}\right) \;:=\; \left\{\, y \in \mathbb{R}^\infty \;\middle|\; \rho(y,x) \,<\, \varepsilon + \frac{1}{2^n} \,\right\}$$

(vi) *The collection*

$$\left\{\, \pi_n^{-1}(\,C_{\mathbb{R}^n}(\pi_n(x),\varepsilon)\,) \subset \mathbb{R}^\infty \;\middle|\; n \in \mathbb{N},\, x \in \mathbb{R}^\infty,\, \varepsilon > 0 \,\right\}$$

of all pre-images under π_n of open hypercubes in $\mathbb{R}^n$, for all $n \in \mathbb{N}$, forms a basis for the topology of $\mathbb{R}^\infty$.

(vii) *$\mathbb{R}^\infty$ is a separable metric space.*

(viii) *$\mathbb{R}^\infty$ is a complete metric space.*

Proof

(i) Clearly, ρ is non-negative and symmetric. We now show that, for any $x, y \in \mathbb{R}^\infty$, we have $\rho(x,y) = 0$ implies $x = y$. Indeed,

$$\begin{aligned}
\rho(x,y) \,=\, 0 \quad &\Longleftrightarrow \quad \sum_{i=1}^{\infty} \frac{\min\{\,1\,,|\,x_i - y_i\,|\,\}}{2^i} \;=\; 0 \\
&\Longleftrightarrow \quad \min\{\,1\,,|\,x_i - y_i\,|\,\} \;=\; 0,\;\; \text{for each } i \in \mathbb{N} \\
&\Longleftrightarrow \quad |\,x_i - y_i\,| \;=\; 0,\;\; \text{for each } i \in \mathbb{N} \\
&\Longleftrightarrow \quad x \;=\; y.
\end{aligned}$$

In order to show that ρ is a metric, it remains only to establish the Triangle Inequality. By Lemma A.2, for any $x, y, z \in \mathbb{R}^\infty$, we have

$$\begin{aligned}
\rho(x,y) \;&=\; \sum_{i=1}^{\infty} \frac{\min\{\,1\,,|\,x_i - y_i\,|\,\}}{2^i} \\
&\le\; \sum_{i=1}^{\infty} \frac{\min\{\,1\,,|\,x_i - z_i\,|\,\} \,+\, \min\{\,1\,,|\,z_i - y_i\,|\,\}}{2^i} \\
&=\; \sum_{i=1}^{\infty} \frac{\min\{\,1\,,|\,x_i - z_i\,|\,\}\,\}}{2^i} \;+\; \sum_{i=1}^{\infty} \frac{\min\{\,1\,,|\,z_i - y_i\,|\,\}}{2^i} \\
&=\; \rho(x,z) + \rho(z,y),
\end{aligned}$$

where we have used the fact that $0 \le \rho \le 1$ to split the infinite sum into two terms in second-to-last equality. This proves that ρ satisfies the Triangle Inequality, and it is thus a metric on $\mathbb{R}^\infty$.

(ii) $\underline{\lim_{n\to\infty} \rho\big(x^{(n)},x\big) = 0 \;\;\Longrightarrow\;\; \lim_{n\to\infty} \left|\,x_i^{(n)} - x_i\,\right| = 0, \text{ for each } i \in \mathbb{N}}$

$$\begin{aligned}
\lim_{n\to\infty} \rho\Big(x^{(n)},x\Big) = 0 \quad &\Longrightarrow \quad \lim_{n\to\infty} \sum_{i=1}^{\infty} \frac{\min\{\,1\,,|\,x_i^{(n)} - x_i\,|\,\}}{2^i} = 0 \\
&\Longrightarrow \quad \lim_{n\to\infty} \min\{\,1\,,|\,x_i^{(n)} - x_i\,|\,\} = 0,\;\; \text{for each } i \in \mathbb{N} \\
&\Longrightarrow \quad \lim_{n\to\infty} \left|\,x_i^{(n)} - x_i\,\right| = 0,\;\; \text{for each } i \in \mathbb{N}
\end{aligned}$$

$\underline{\lim\limits_{n\to\infty}\left|x_i^{(n)} - x_i\right| = 0, \text{ for each } i \in \mathbb{N} \implies \lim\limits_{n\to\infty}\rho\big(x^{(n)}, x\big) = 0}$

This follows from the Weierstrass M-test. Suppose $\lim\limits_{n\to\infty}\left|x_i^{(n)} - x_i\right| = 0$, for each $i \in \mathbb{N}$. Then,

$$\lim_{n\to\infty}\frac{\min\{\,1\,,|\,x_i^{(n)} - x_i\,|\,\}}{2^i} \;=\; 0 \;=:\; y_i, \quad \text{for each } i \in \mathbb{N}.$$

For each $i \in \mathbb{N}$, let $M_i \;:=\; \dfrac{1}{2^i}$. Then,

$$\frac{\min\{1\,,|\,x_i^{(n)} - x_i\,|\}}{2^i} \;\leq\; M_i \quad \text{and} \quad \sum_{i=1}^{\infty} M_i \;<\; \infty.$$

Hence, by the Weierstrass M-test (Lemma A.3), we have

$$\lim_{n\to\infty}\rho\Big(x^{(n)}, x\Big) \;=\; \lim_{n\to\infty}\sum_{i=1}^{\infty}\frac{\min\{\,1\,,|\,x_i^{(n)} - x_i\,|\,\}}{2^i} \;=\; \sum_{i=1}^{\infty} y_i \;=\; 0.$$

(iii) Immediate by (ii).

(iv) Since $C_{\mathbb{R}^n}(\pi_n(x),\varepsilon) \subset \mathbb{R}^n$ is an open subset of $\mathbb{R}^n$, its pre-image under the continuous (by (iii)) map $\pi_n : \mathbb{R}^\infty \longrightarrow \mathbb{R}^n$ is an open subset of $\mathbb{R}^\infty$.

(v) For $y \in \mathbb{R}^\infty$, we have

$$\begin{aligned} y \in \pi_n^{-1}(\,C_{\mathbb{R}^n}(\pi_n(x),\varepsilon)\,) \;&\Longrightarrow\; |\,y_i - x_i\,| < \varepsilon, \text{ for each } i = 1,2,\ldots,n \\ &\Longrightarrow\; \rho(x,y) \;:=\; \sum_{i=1}^{\infty}\frac{\min\{\,1\,,|\,x_i - y_i\,|\,\}}{2^i} \;\leq\; \sum_{i=1}^{n}\frac{\varepsilon}{2^i} \;+\; \sum_{i=n+1}^{\infty}\frac{1}{2^i} \;=\; \varepsilon + \frac{1}{2^n}. \end{aligned}$$

This proves:

$$\pi_n^{-1}(\,C_{\mathbb{R}^n}(\pi_n(x),\varepsilon)\,) \;\subset\; B_{\mathbb{R}^\infty}\left(x\,,\,\varepsilon + \frac{1}{2^n}\right).$$

(vi) It suffices to show that every open ball in $B_{\mathbb{R}^\infty}(x,r) \subset \mathbb{R}^\infty$, $r > 0$, contains the pre-image of an open hypercube centred at $\pi_n(x) \in \mathbb{R}^n$ under π_n. To this end, for $r > 0$, choose $\varepsilon > 0$ sufficiently small and $n \in \mathbb{N}$ sufficiently large such that $\varepsilon + \dfrac{1}{2^n} < r$. Then, for any $x \in \mathbb{R}^\infty$, by (v), we have:

$$x \;\in\; \pi_n^{-1}(\,C_{\mathbb{R}^n}(\pi_n(x),\varepsilon)\,) \;\subset\; B_{\mathbb{R}^\infty}\left(x\,,\,\varepsilon + \frac{1}{2^n}\right) \;\subset\; B_{\mathbb{R}^\infty}(\,x\,,r\,)\,,$$

as required.

(vii) It suffices to exhibit a countable subset of $\mathbb{R}^\infty$ that intersects every open ball in $\mathbb{R}^\infty$. To this end, let

$$D \;:=\; \bigcup_{n=1}^{\infty}\left\{\, x = (x_1, x_2, \ldots\,) \in \mathbb{R}^\infty \;\middle|\; \begin{array}{l} x_i \in \mathbb{Q}, \text{ for each } i \in \mathbb{N} \\ x_i = 0, \text{ for all } i \geq n \end{array} \right\}.$$

Clearly, D is a countable subset of $\mathbb{R}^\infty$. Now let $B_{\mathbb{R}^\infty}(x,\varepsilon)$ be an arbitrary open ball in $\mathbb{R}^\infty$. Choose $\delta > 0$ small enough and $n \in \mathbb{N}$ large enough such that $\delta + \dfrac{1}{2^n} < \varepsilon$. Then,

$$\pi_n^{-1}(\,C_{\mathbb{R}^n}(\pi_n(x),\delta)\,) \;\subset\; B_{\mathbb{R}^\infty}\left(x\,,\,\delta + \frac{1}{2^n}\right) \;\subset\; B_{\mathbb{R}^\infty}(x\,,\varepsilon\,)\,,$$

Now, for each $i = 1, 2, \ldots, n$, choose $z_i \in \mathbb{Q} \cap (x_i - \delta, x_i + \delta)$. Let $z = (z_1, z_2, \ldots, z_n, 0, 0, \ldots) \in \mathbb{R}^\infty$. Then, we have

$$z \;\in\; D \bigcap \left\{ y \in \mathbb{R}^\infty \;\middle|\; \begin{array}{c} y_i \in (x_i - \delta, x_i + \delta), \\ \text{for each } i = 1, 2, \ldots, n \end{array} \right\} \;=\; D \bigcap \pi_n^{-1}\left(C_{\mathbb{R}^n}(\pi_n(x), \delta) \right) \;\subset\; D \bigcap B_{\mathbb{R}^\infty}(x, \varepsilon)\,.$$

This proves the the countable subset $D \subset \mathbb{R}^\infty$ has non-empty intersection with every open ball in $\mathbb{R}^\infty$, i.e. D is dense in $\mathbb{R}^\infty$. Hence, $\mathbb{R}^\infty$ is separable.

(viii) We need to show that every Cauchy sequence in $\mathbb{R}^\infty$ converges to any element in $\mathbb{R}^\infty$.

$$\begin{array}{cl} & \left\{ x^{(n)} \right\}_{n\in\mathbb{N}} \subset \mathbb{R}^\infty \text{ is a Cauchy sequence in } \mathbb{R}^\infty \\ \Longleftrightarrow & \text{for each } \varepsilon > 0, \text{ there exists } N_\varepsilon \in \mathbb{N} \text{ such that } \rho\left(x^{(m)}, x^{(n)}\right) < \varepsilon, \text{ for any } m, n > N_\varepsilon \\ \Longrightarrow & \text{for each } i \in \mathbb{N}, \text{ we have:} \\ & \text{for each } \varepsilon > 0, \text{ there exists } N_\varepsilon \in \mathbb{N} \text{ such that } \left| x_i^{(m)} - x_i^{(n)} \right| < \varepsilon, \text{ for any } m, n > N_\varepsilon \\ \Longrightarrow & \text{for each } i \in \mathbb{N}, \left\{ x_i^{(n)} \right\}_{n\in\mathbb{N}} \subset \mathbb{R} \text{ is a Cauchy sequence in } \mathbb{R}; \text{ hence } x_i := \lim_{n\to\infty} x_i^{(n)} \in \mathbb{R} \text{ exists} \\ \Longrightarrow & \lim_{n\to\infty} \rho\left(x^{(n)}, x\right) = 0, \text{ where } x := (x_1, x_2, \ldots) \in \mathbb{R}^\infty \quad \text{(by (ii))} \end{array}$$

This proves that $\mathbb{R}^\infty$ indeed is a complete metric space.

□

Definition 2.4
*The **finite-dimensional class** of subsets of $\mathbb{R}^\infty$ is, by definition, the following:*

$$\mathcal{B}_f(\mathbb{R}^\infty) \;:=\; \left\{ \pi_k^{-1}(B) \subset \mathbb{R}^\infty \;\middle|\; \begin{array}{c} k \in \mathbb{N} \\ B \in \mathcal{B}(\mathbb{R}^k) \end{array} \right\},$$

where $\pi_k : \mathbb{R}^\infty \longrightarrow \mathbb{R}^k : x = (x_1, x_2, \ldots) \longmapsto (x_1, \ldots, x_k)$ is the projection of $\mathbb{R}^\infty$ onto $\mathbb{R}^k$.

Theorem 2.5

(i) $\mathcal{B}_f(\mathbb{R}^\infty) \subset \mathcal{B}(\mathbb{R}^\infty)$.

(ii) $\mathcal{B}_f(\mathbb{R}^\infty)$ *is a separating class of Borel subsets of* $\mathbb{R}^\infty$.

(iii) $\mathcal{B}_f(\mathbb{R}^\infty)$ *is a convergence-determining class of Borel subsets of* $\mathbb{R}^\infty$.

Proof

(i) Note that

$$\mathcal{B}_f(\mathbb{R}^\infty) \;:=\; \left\{ \pi_k^{-1}(B) \subset \mathbb{R}^\infty \;\middle|\; \begin{array}{c} k \in \mathbb{N} \\ B \in \mathcal{B}(\mathbb{R}^k) \end{array} \right\} \;=\; \bigcup_{k=1}^{\infty} \pi_k^{-1}\left(\mathcal{B}(\mathbb{R}^k)\right).$$

Thus, (i) is equivalent to the statement that each $\pi_k : \mathbb{R}^\infty \longrightarrow \mathbb{R}^k$ is Borel measurable. But each π_k is continuous, hence Borel measurable (Corollary B.12). This proves (i).

(ii) We apply Theorem 1.3 to $\mathcal{B}_f(\mathbb{R}^\infty)$.

$\underline{\mathcal{B}_f(\mathbb{R}^\infty) \text{ is closed under finite intersections}}$

Let $\pi_k^{-1}(A)$ and $\pi_l^{-1}(B) \in \mathcal{B}_f(\mathbb{R}^\infty)$. Note that this implies $A \in \mathcal{B}(\mathbb{R}^k)$ and $B \in \mathcal{B}(\mathbb{R}^l)$. We need to show that $\pi_k^{-1}(A) \cap \pi_l^{-1}(B) \in \mathcal{B}_f(\mathbb{R}^\infty)$. Now, if $k = l$, this is immediate, since then $A \cap B \in \mathcal{B}(\mathbb{R}^k)$, and

$$\pi_k^{-1}(A) \cap \pi_l^{-1}(B) \;=\; \pi_k^{-1}(A) \cap \pi_k^{-1}(B) \;=\; \pi_k^{-1}(A \cap B) \;\in\; \mathcal{B}_f(\mathbb{R}^\infty).$$

For the case $k \neq l$, without loss of generality, assume $k < l$. Then, note that

$$\begin{aligned}
\pi_k^{-1}(A) &= \left\{ y = (y_1, y_2, \ldots) \in \mathbb{R}^\infty \;\middle|\; (y_1, \ldots, y_k) \in A \right\} \\
&= \left\{ y = (y_1, y_2, \ldots) \in \mathbb{R}^\infty \;\middle|\; (y_1, \ldots, y_k, y_{k+1}, \ldots, y_l) \in A \times \underbrace{\mathbb{R} \times \cdots \times \mathbb{R}}_{k\text{ factors}} \right\} \\
&= \pi_l^{-1}(\, A \times \mathbb{R} \times \cdots \times \mathbb{R}\,).
\end{aligned}$$

Since $(A \times \mathbb{R} \cdots \times \mathbb{R}) \cap B \in \mathcal{B}(\mathbb{R}^l)$, we now see that

$$\pi_k^{-1}(A) \cap \pi_l^{-1}(B) \;=\; \pi_l^{-1}(A \times \mathbb{R} \cdots \times \mathbb{R}) \cap \pi_l^{-1}(B) \;=\; \pi_l^{-1}(\,(A \times \mathbb{R} \cdots \times \mathbb{R}) \cap B\,) \;\in\; \mathcal{B}_f(\mathbb{R}^\infty).$$

This proves that $\mathcal{B}_f(\mathbb{R}^\infty)$ is indeed closed under finite intersections.

$\mathcal{B}_f(\mathbb{R}^\infty)$ generates $\mathcal{B}(\mathbb{R}^\infty)$

Let $\mathcal{O}(\mathbb{R}^\infty)$ denote the collection of open sets of $\mathbb{R}^\infty$. Hence $\mathcal{B}(\mathbb{R}^\infty) := \sigma(\mathcal{O}(\mathbb{R}^\infty))$. By (i), we have $\mathcal{B}_f(\mathbb{R}^\infty) \subset \mathcal{B}(\mathbb{R}^\infty) = \sigma(\mathcal{O}(\mathbb{R}^\infty))$, which implies $\sigma(\mathcal{B}_f(\mathbb{R}^\infty)) \subset \sigma(\mathcal{O}(\mathbb{R}^\infty))$. We need to establish the reverse inclusion, which will immediately follow from:

> **Claim:** $\mathcal{O}(\mathbb{R}^\infty) \subset \sigma(\mathcal{B}_f(\mathbb{R}^\infty))$.
>
> Proof of Claim: By Theorem 2.3(v), every open ball $B_{\mathbb{R}^\infty}(x, \varepsilon)$ in $\mathbb{R}^\infty$ contains the pre-image of an open hypercube from some finite-dimensional Euclidean space, where that pre-image itself contains x. We therefore see that every open set in $\mathbb{R}^\infty$ can be expressed as a union of pre-images of open hypercubes from finite-dimensional Euclidean spaces. By Theorem 2.3(vii), $\mathbb{R}^\infty$ is separable. Hence, by Theorem C.1, we see that every open set in $\mathbb{R}^\infty$ can be expressed as a countable union of pre-images of open hypercubes from finite-dimensional Euclidean spaces. Since pre-images of open hypercubes from finite-dimensional Euclidean spaces belong to $\mathcal{B}_f(\mathbb{R}^\infty)$, we see that $\mathcal{O}(\mathbb{R}^\infty) \subset \sigma(\mathcal{B}_f(\mathbb{R}^\infty))$. This completes the proof of the Claim.

We have established that $\mathcal{B}_f(\mathbb{R}^\infty)$ is contained in $\mathcal{B}(\mathbb{R}^\infty)$, is closed under finite intersections, and $\sigma(\mathcal{B}_f(\mathbb{R}^\infty)) = \mathcal{B}_f(\mathbb{R}^\infty)$. Therefore, by Theorem 1.3, $\mathcal{B}_f(\mathbb{R}^\infty)$ is a separating class for the measurable space $(\mathbb{R}^\infty, \mathcal{B}_f(\mathbb{R}^\infty))$.

(iii) Since $\mathbb{R}^\infty$ is separable, by Theorem D.4, it suffices to show that $\mathcal{B}_f(\mathbb{R}^\infty)$ is closed under finite intersections, and for each $x \in \mathbb{R}^\infty$ and $\varepsilon > 0$, the collection

$$\partial\,\mathcal{B}_f(\mathbb{R}^\infty)(x,\varepsilon) \;:=\; \left\{ \partial A \subset S \;\middle|\; A \in \mathcal{B}_f(\mathbb{R}^\infty)(x,\varepsilon) \right\}$$

contains uncountably many disjoint sets, where

$$\mathcal{B}_f(\mathbb{R}^\infty)(x,\varepsilon) \;:=\; \left\{ A \in \mathcal{B}_f(\mathbb{R}^\infty) \;\middle|\; x \in A^\circ \subset A \subset B(x,\varepsilon) \right\}.$$

Now, we have already proved that $\mathcal{B}_f(\mathbb{R}^\infty)$ is closed under finite intersections in the proof of statement (ii). Next, let $x \in \mathbb{R}^\infty$ and $\varepsilon > 0$ be given. For any $k \in \mathbb{N}$ with $\dfrac{1}{2^k} < \dfrac{\varepsilon}{2}$ and $0 < \delta < \dfrac{\varepsilon}{2}$, define

$$A_{k,\delta} \;:=\; \left\{\; y = (y_1, y_2, \ldots) \in \mathbb{R}^\infty \;\middle\vert\; \begin{array}{l} \vert\, y_i - x_i \,\vert \,<\, \delta, \\ i = 1, 2, \ldots, k \end{array} \;\right\}.$$

Then, by Theorem 2.3(v), we have

$$x \;\in\; (A_{k,\delta})^\circ \;=\; A_{k,\delta} \;\subset\; B\!\left(x, \delta + \frac{1}{2^k}\right) \;\subset\; B(x,\varepsilon).$$

Clearly, each $A_{k,\delta} \in \mathcal{B}_f(\mathbb{R}^\infty)$. Thus, for each fixed $k \in \mathbb{N}$ with $\dfrac{1}{2^k} < \dfrac{\varepsilon}{2}$, we have

$$\left\{\; A_{k,\delta} \;\middle\vert\; 0 \,<\, \delta \,<\, \frac{\varepsilon}{2} \;\right\} \;\subset\; \mathcal{B}_f(\mathbb{R}^\infty).$$

Now, note that

$$\partial A_{k,\delta} \;=\; \left\{\; y = (y_1, y_2, \ldots) \in \mathbb{R}^\infty \;\middle\vert\; \begin{array}{ll} \vert\, y_i - x_i \,\vert \,\leq\, \delta, & \text{for each } i = 1, 2, \ldots, k \\ \vert\, y_i - x_i \,\vert \,=\, \delta, & \text{for at least one } i \in \{1, 2, \ldots, k\} \end{array} \;\right\},$$

which in particular implies

$$\partial A_{k,\delta} \,\cap\, \partial A_{k,\delta'} \;=\; \varnothing, \;\;\text{whenever } 0 < \delta \neq \delta' < \frac{\varepsilon}{2}.$$

This proves that $\partial\,\mathcal{B}_f(\mathbb{R}^\infty)(x,\varepsilon)$ indeed contains uncountably many disjoint sets, and completes and the proof of (iii).

□

3 On the separating and convergence-determining classes of $C([0,1],\mathbb{R})$

Definition 3.1 (The supremum norm on $C([0,1],\mathbb{R})$, Example 1.3, [1])
Let $C([0,1],\mathbb{R})$ denotes the set of all continuous $\mathbb{R}$-valued functions defined on the closed bounded interval $[0,1]$. Define $\|\cdot\|_\infty : C([0,1],\mathbb{R}) \longrightarrow [0,\infty)$ as follows:

$$\|\, x \,\|_\infty \;:=\; \sup_{t\in[0,1]} \left\{\; \vert\, x(t) \,\vert \;\right\}.$$

Remark 3.2
It is well known that $(\, C([0,1],\mathbb{R}), \|\cdot\|_\infty \,)$ is a separable Banach space (i.e. complete normed vector space).

- *The completeness of $(\, C([0,1],\mathbb{R}), \|\cdot\|_\infty \,)$ follows from the general fact that uniform limits of continuous functions are themselves continuous functions (see Theorem A.4).*
- *Its separability follows from the Stone-Weierstrass Theorem.*

Lemma 3.3
For $0 \leq t_1 < t_2 < \cdots < t_k \leq 1$, define

$$\pi_{t_1 t_2 \cdots t_k} \,:\, C([0,1],\mathbb{R}) \;\longrightarrow\; \mathbb{R}^k \,:\, x \;\longmapsto\; (\, x(t_1), x(t_2), \ldots, x(t_k) \,)\,.$$

Then, each $\pi_{t_1 t_2 \cdots t_k}$ is continuous, hence Borel measurable.

PROOF Suppose $\{\,x^{(n)}\,\}_{n\in\mathbb{N}} \subset C([0,1],\mathbb{R})$ is a sequence in $C([0,1],\mathbb{R})$ such that $x^{(n)}$ converges to $x \in C([0,1],\mathbb{R})$, as $n \longrightarrow \infty$. Then,

$$\begin{aligned}
\left\|\,\pi_{t_1\cdots t_k}(x^{(n)}) \,-\, \pi_{t_1\cdots t_k}(x^{(n)})\,\right\|_{\mathbb{R}^k} &= \left\|\,\left(x^{(n)}(t_1),\ldots,x^{(n)}(t_k)\right) \,-\, (x(t_1),\ldots,x(t_k))\,\right\|_{\mathbb{R}^k} \\
&= \left\|\,\left(x^{(n)}(t_1)-x(t_1)\,,\;\ldots\;,\,x^{(n)}(t_k)-x(t_k)\right)\,\right\|_{\mathbb{R}^k} \\
&= \sqrt{\sum_{i=1}^{k}\left(x^{(n)}(t_i)-x(t_i)\right)^2} \\
&\leq \sqrt{\sum_{i=1}^{k}\left\|\,x^{(n)}-x\,\right\|_\infty^2} \;=\; \sqrt{k}\cdot\left\|\,x^{(n)}-x\,\right\|_\infty \;\longrightarrow\; 0,\quad \text{as } n\longrightarrow\infty,
\end{aligned}$$

which proves the continuity of $\pi_{t_1\cdots t_k}$. The Borel measurability of $\pi_{t_1\cdots t_k}$ follows immediately from Corollary B.12. □

Definition 3.4

*The **finite-dimensional class** of subsets of $C([0,1],\mathbb{R})$ is, by definition, the following:*

$$\mathcal{B}_f(C([0,1],\mathbb{R})) \;:=\; \left\{\,\pi^{-1}_{t_1t_2\cdots t_k}(B)\,\subset\,C([0,1],\mathbb{R})\;\middle|\;\begin{array}{c}0\leq t_1<t_2<\cdots<t_k\leq 1\\ B\in\mathcal{B}(\mathbb{R}^k)\end{array}\right\},$$

where, for any $0\leq t_1<t_2<\cdots<t_k\leq 1$, the map $\pi_{t_1t_2\cdots t_k}$ is defined as follows:

$$\pi_{t_1t_2\cdots t_k}\;:\;C([0,1],\mathbb{R})\;\longrightarrow\;\mathbb{R}^k\;:\;x\;\longmapsto\;(\,x(t_1),x(t_2),\ldots,x(t_k)\,)\,.$$

Theorem 3.5

(i) $\mathcal{B}_f(C([0,1],\mathbb{R}))\subset\mathcal{B}(C([0,1],\mathbb{R}))$.

(ii) $\mathcal{B}_f(C([0,1],\mathbb{R}))$ *is a separating class of Borel subsets of* $C([0,1],\mathbb{R})$.

(iii) $\mathcal{B}_f(C([0,1],\mathbb{R}))$ *is* ***NOT*** *a convergence-determining class of Borel subsets of* $C([0,1],\mathbb{R})$.

PROOF

(i) This follows immediately from the Borel measurability of $\pi_{t_1t_2\cdots t_k}$, for each $0\leq t_1<t_2<\cdots<t_k\leq 1$. See Lemma 3.3.

(ii) We apply Theorem 1.3 to $\mathcal{B}_f(C([0,1],\mathbb{R}))$.

$\mathcal{B}_f(C([0,1],\mathbb{R}))$ is closed under finite intersections

Let $\pi^{-1}_{t_1\cdots t_k}(A)$ and $\pi^{-1}_{s_1\cdots s_l}(B)\in\mathcal{B}_f(C([0,1],\mathbb{R}))$. Note that this implies $A\in\mathcal{B}(\mathbb{R}^k)$ and $B\in\mathcal{B}(\mathbb{R}^l)$. We need to show that $\pi^{-1}_{t_1\cdots t_k}(A)\cap\pi^{-1}_{s_1\cdots s_l}(B)\in\mathcal{B}_f(C([0,1],\mathbb{R}))$. Now, if $k=l$, and $(t_1,\ldots,t_k)=(s_1,\ldots,s_k)$, then the above inclusion is immediate, since then $A\cap B\in\mathcal{B}(\mathbb{R}^k)$, and

$$\pi^{-1}_{t_1\cdots t_k}(A)\cap\pi^{-1}_{s_1\cdots s_l}(B)\;=\;\pi^{-1}_{t_1\cdots t_k}(A)\cap\pi^{-1}_{t_1\cdots t_k}(B)\;=\;\pi^{-1}_{t_1\cdots t_k}(A\cap B)\;\in\;\mathcal{B}_f(C([0,1],\mathbb{R})).$$

For the case $(t_1,\ldots,t_k)\neq(s_1,\ldots,s_l)$, write

$$\{\,t_1,t_2,\ldots,t_k\,\}\cup\{\,s_1,s_2,\ldots,s_l\,\}\;=\;\{\,r_1,r_2,\ldots,r_m\,\},$$

with $0\leq r_1<r_2<\cdots<r_m\leq 1$. Then, by the Claim below, we have

$$\pi^{-1}_{t_1\cdots t_k}(\,A\,)\;=\;\pi^{-1}_{r_1\cdots r_m}(\,A'\,)\quad\text{and}\quad\pi^{-1}_{s_1\cdots s_l}(\,B\,)\;=\;\pi^{-1}_{r_1\cdots r_m}(\,B'\,),\quad\text{for some } A',B'\in\mathcal{B}(\mathbb{R}^m).$$

Hence,

$$\pi^{-1}_{t_1\cdots t_k}(\,A\,)\cap\pi^{-1}_{s_1\cdots s_l}(\,B\,)\;=\;\pi^{-1}_{r_1\cdots r_m}(\,A'\,)\cap\pi^{-1}_{r_1\cdots r_m}(\,B'\,)\;=\;\pi^{-1}_{r_1\cdots r_m}(\,A'\cap B'\,)\;\in\;\mathcal{B}_f(C([0,1],\mathbb{R}))\,,$$

which proves that $\mathcal{B}_f(C([0,1],\mathbb{R}))$ is indeed closed under finite intersections. We now state and prove the following

Claim: Suppose

- $0 \le t_1 < t_2 < \cdots < t_k \le 1$, and $A \in \mathcal{B}(\mathbb{R}^k)$. Hence, $\pi^{-1}_{t_1 \cdots t_k}(A) \in \mathcal{B}_f(C([0,1],\mathbb{R}))$.
- $0 \le r_1 < r_2 < \cdots < r_m \le 1$ and $(t_1, \ldots, t_k)$ is a "subsequence" of $(r_1, \ldots, r_m)$ in the sense that $t_i \in \{r_1, r_2, \ldots, r_m\}$, for each $i = 1, 2, \ldots, k$.

Then, there exists $A' \in \mathcal{B}(\mathbb{R}^m)$ such that

$$\pi^{-1}_{t_1 \cdots t_k}(A) \;=\; \pi^{-1}_{r_1 \cdots r_m}(A').$$

Proof of Claim: Define

$$\psi : \mathbb{R}^m \longrightarrow \mathbb{R}^k : (z_1, \ldots, z_m) \longmapsto (\, z_j \,)_{j \in I(t)},$$

where

$$I(t) \;:=\; \left\{ \, j \in \{1, 2, \ldots, m\} \;\middle|\; r_j \in \{t_1, \ldots, t_k\} \, \right\}.$$

In other words, ψ projects $\mathbb{R}^m$ onto $\mathbb{R}^k$ by retaining only the dimensions of $\mathbb{R}^m$ whose corresponding indices belongs to $I(t)$. It is now clear that

$$\pi^{-1}_{t_1 \cdots t_k}(A) \;=\; \pi^{-1}_{r_1 \cdots r_m}\big(\, \psi^{-1}(A) \,\big).$$

Indeed, for each $x \in C([0,1],\mathbb{R})$, we have:

$$\begin{aligned} x \in \pi^{-1}_{r_1 \cdots r_m}\big(\, \psi^{-1}(A) \,\big) \quad &\Longleftrightarrow \quad x \in (\, \psi \circ \pi_{r_1 \cdots r_m} \,)^{-1}(A) \quad \Longleftrightarrow \quad \psi(\, \pi_{r_1 \cdots r_m}(x) \,) \in A \\ &\Longleftrightarrow \quad \psi(\, x(r_1), \ldots, x(r_m) \,) = (\, x(t_1), \ldots, x(t_k) \,) \in A \\ &\Longleftrightarrow \quad x \in \pi^{-1}_{t_1 \cdots t_k}(\, A \,). \end{aligned}$$

Since ψ is continuous, it is Borel measurable (by Corollary B.12). Hence, $\psi^{-1}(A) \in \mathcal{B}(\mathbb{R}^m)$, since $A \in \mathcal{B}(\mathbb{R}^k)$ by hypothesis. This completes the proof of the Claim.

<u>$\mathcal{B}_f(C([0,1],\mathbb{R}))$ generates $\mathcal{B}(C([0,1],\mathbb{R}))$</u>

We already know that $\mathcal{B}_f(C([0,1],\mathbb{R})) \subset \mathcal{B}(C([0,1],\mathbb{R}))$; hence, $\sigma(\mathcal{B}_f(C([0,1],\mathbb{R}))) \subset \mathcal{B}(C([0,1],\mathbb{R}))$, where $\sigma(\mathcal{B}_f(C([0,1],\mathbb{R})))$ is the σ-algebra generated by $\mathcal{B}_f(C([0,1],\mathbb{R}))$. It remains to establish the reverse inclusion. To this end, first observe that, for each $x \in C([0,1],\mathbb{R})$ and each $\varepsilon > 0$, we have

$$\overline{B(x,\varepsilon)} \;=\; \bigcap_{r \,\in\, \mathbb{Q} \,\cap\, [0,1]} \left\{ \, y \in C([0,1],\mathbb{R}) \;\middle|\; |\, y(r) - x(r) \,| \le \varepsilon \, \right\} \;=\; \bigcap_{r \,\in\, \mathbb{Q} \,\cap\, [0,1]} \pi_r^{-1}(\, [x(r) - \varepsilon, x(r) + \varepsilon] \,),$$

which shows that $\sigma(\mathcal{B}_f(C([0,1],\mathbb{R})))$ contains all the closed balls in $C([0,1],\mathbb{R})$. On the other hand, recall that, in any metric space, every open ball can be expressed as a countable union of closed balls; indeed, for any y in the given metric space, and any $\delta > 0$, we have:

$$B(y,\delta) \;=\; \bigcup_{n \in \mathbb{N}} \overline{B\left(y, \delta - \frac{1}{n}\right)}.$$

We thus see that $\sigma(\mathcal{B}_f(C([0,1],\mathbb{R})))$ contains all the open balls in $C([0,1],\mathbb{R})$. By the separability of $C([0,1],\mathbb{R})$ and Theorem C.1, we see that every open subset of $C([0,1],\mathbb{R})$ can be expressed as a countable union of open balls. Hence, $\sigma(\mathcal{B}_f(C([0,1],\mathbb{R})))$ in fact contains all the open subsets of $C([0,1],\mathbb{R})$, which immediately yields $\mathcal{B}(C([0,1],\mathbb{R})) \subset \sigma(\mathcal{B}_f(C([0,1],\mathbb{R})))$. This proves $\sigma(\mathcal{B}_f(C([0,1],\mathbb{R}))) = \mathcal{B}(C([0,1],\mathbb{R}))$.

(iii) We prove this by exhibiting $P, P_1, P_2, \ldots, \mathcal{M}_1(\,C([0,1],\mathbb{R})\,)$ such that P_n does NOT converge weakly to P as $n \longrightarrow \infty$, but

$$\lim_{n\to\infty} P_n(A) \;=\; P(A), \quad \text{for each } A \in \mathcal{B}_f(C([0,1],\mathbb{R})),$$

in particular, for each P-continuity set in $\mathcal{B}_f(C([0,1],\mathbb{R}))$.

Now, let $z_0 \in C([0,1],\mathbb{R})$ be the identically zero function on $[0,1]$, and for each $n \in \mathbb{N}$, define $z_n \in C([0,1],\mathbb{R})$ as follows:

$$z_n(t) \;\;:=\;\; \begin{cases} n\cdot t, & \text{for } \; t \in \left[\,0, \frac{1}{n}\,\right] \\ 2 - n\cdot t, & \text{for } \; t \in \left(\,\frac{1}{n}, \frac{2}{n}\,\right] \\ 0, & \text{for } \; t \in \left(\,\frac{2}{n}, 1\,\right] \end{cases}$$

Note that $\|\, z_n - z_0 \,\|_\infty = \sup\limits_{t\in[0,1]}\{\,|\,z_n(t) - 0\,|\,\} = 1$, for each $n \in \mathbb{N}$. In particular, z_n does NOT converge to z_0 in $C([0,1],\mathbb{R})$. Therefore, by Lemma A.6, we see that $P_n := \delta_{z_n}$ does NOT converge weakly to $P := \delta_{z_0}$. On the other hand, let $0 \le t_1 < t_2 < \cdots < t_k \le 1$ be given. Then, for each $n \in \mathbb{N}$ (sufficiently large) such that

$$\frac{2}{n} \;<\; \min\left\{\,\{\,t_i\,\}_{i=1}^k \setminus \{\,0\,\}\,\right\},$$

we have

$$\pi_{t_1\cdots\,t_k}(z_n) \;=\; (\,z_n(t_1),\ldots,z_n(t_k)\,) \;=\; (\,0,\ldots,0\,) \;=\; (\,z_0(t_1),\ldots,z_0(t_k)\,) \;=\; \pi_{t_1\cdots\,t_k}(z_0).$$

Consequently,

$$\pi_{t_1\cdots\,t_k}(z_n) \in B \;\;\Longleftrightarrow\;\; \pi_{t_1\cdots\,t_k}(z_0) \in B, \quad \text{for each } B \in \mathcal{B}(\mathbb{R}^k) \text{ and each } n \in \mathbb{N} \text{ with } \frac{2}{n} \;<\; \min\left\{\,\{\,t_i\,\}_{i=1}^k \setminus \{\,0\,\}\,\right\}.$$

Equivalently,

$$z_n \in \pi^{-1}_{t_1\cdots\,t_k}(B) \;\;\Longleftrightarrow\;\; z_0 \in \pi^{-1}_{t_1\cdots\,t_k}(B), \quad \text{for each } B \in \mathcal{B}(\mathbb{R}^k) \text{ and each } n \in \mathbb{N} \text{ with } \frac{2}{n} \;<\; \min\left\{\,\{\,t_i\,\}_{i=1}^k \setminus \{\,0\,\}\,\right\},$$

which in turn implies

$$P_n\big(\,\pi^{-1}_{t_1\cdots\,t_k}(B)\,\big) \;=\; \delta_{z_n}\big(\,\pi^{-1}_{t_1\cdots\,t_k}(B)\,\big) \;=\; \delta_{z_0}\big(\,\pi^{-1}_{t_1\cdots\,t_k}(B)\,\big) \;=\; P_0\big(\,\pi^{-1}_{t_1\cdots\,t_k}(B)\,\big)$$

for each $B \in \mathcal{B}(\mathbb{R}^k)$ and each $n \in \mathbb{N}$ with $\dfrac{2}{n} \;<\; \min\left\{\,\{\,t_i\,\}_{i=1}^k \setminus \{\,0\,\}\,\right\}$. In particular, we can now infer that

$$\lim_{n\to\infty} P_n\big(\,\pi^{-1}_{t_1\cdots\,t_k}(B)\,\big) \;=\; P_0\big(\,\pi^{-1}_{t_1\cdots\,t_k}(B)\,\big)\,, \quad \text{for each } B \in \mathcal{B}(\mathbb{R}^k).$$

Since $0 \le t_1 < t_2 < \cdots < t_k \le 1$ and $B \in \mathcal{B}(\mathbb{R}^k)$ are arbitrary, we may now conclude that

$$\lim_{n\to\infty} P_n(\,A\,) \;=\; P_0(\,A\,)\,, \quad \text{for each } A \in \mathcal{B}_f(C([0,1],\mathbb{R})).$$

This completes the proof that $\mathcal{B}_f(C([0,1],\mathbb{R}))$ is NOT a convergence-determining class of Borel subsets of $C([0,1],\mathbb{R})$.

□

A Technical Lemmas

Lemma A.1 *Define*

$$\phi\,:\,[\,0,\infty\,)\longrightarrow[\,0,1\,]\,:\,t\longmapsto\min\{\,1\,,t\,\}.$$

Then, ϕ satisfies:

$$\phi(s+t)\;\leq\;\phi(s)\;+\;\phi(t),\;\;\text{for each } s,t\in[0,\infty).$$

Proof For any $s,t\in[0,\infty)$, either $s+t\geq 1$ or $s+t<1$. If $s+t\geq 1$, then

$$\phi(s+t)\;=\;\min\{1,s+t\}\;=\;1\;<\;2\;=\;1+1\;\leq\;\min\{1,s\}+\min\{1,t\}\;=\;\phi(s)+\phi(t),$$

hence, the required inequality holds. On the other hand, if $s+t<1$, then we must also have $s<1$ and $t<1$ (since $s,t\geq 0$). Hence,

$$\phi(s+t)\;=\;\min\{1,s+t\}\;=\;s+t\;=\;\min\{1,s\}+\min\{1,t\}\;=\;\phi(s)+\phi(t),$$

thus, the required inequality also holds. □

Lemma A.2 *For any $x,y,z\in\mathbb{R}$, we have:*

$$\min\{1,|\,x-y\,|\}\;\leq\;\min\{1,|\,x-z\,|\}\;+\;\min\{1,|\,z-y\,|\}.$$

Proof Observe that $|\,x-y\,|\;\leq\;|\,x-z\,|+|\,z-y\,|$ implies

$$\min\{\,1\,,|\,x-y\,|\,\}\;\leq\;|\,x-z\,|+|\,z-y\,|.$$

The above inequality, together with $\min\{\,1\,,|\,x-y\,|\,\}\;\leq\;1$, thus in turn imply:

$$\min\{\,1\,,|\,x-y\,|\,\}\;\leq\;\min\{\,1\,,|\,x-z\,|+|\,z-y\,|\,\}.$$

By Lemma A.1, we therefore have:

$$\min\{\,1\,,|\,x-y\,|\,\}\;\leq\;\min\{\,1\,,|\,x-z\,|+|\,z-y\,|\,\}.\;\leq\;\min\{\,1\,,|\,x-z\,|\,\}\;+\;\min\{\,1\,,|\,z-y\,|\,\},$$

which proves the present Lemma. □

Lemma A.3 (The Weierstrass M-test, Theorem A.28, [2])
Suppose that $\lim\limits_{n\to\infty}x_i^{(n)}\;=\;x_i$, for each $i\in\mathbb{N}$, and that $\left|\,x_i^{(n)}\,\right|\;\leq\;M_i$, where $\sum\limits_{i=1}^{\infty}M_i<\infty$. Then,

(i) $\sum\limits_{i=1}^{\infty}x_i$ *exists, and* $\sum\limits_{i=1}^{\infty}x_i^{(n)}$ *exists for each $n\in\mathbb{N}$.*

(ii) *Furthermore,*

$$\lim_{n\to\infty}\sum_{i=1}^{\infty}x_i^{(n)}\;=\;\sum_{i=1}^{\infty}x_i.$$

Proof

(i) $\sum\limits_{i=1}^{\infty}M_i<\infty$ and $\left|\,x_i^{(n)}\,\right|\leq M_i\quad\Longrightarrow$ the series $\sum\limits_{i=1}^{\infty}x_i$ and $\sum\limits_{i=1}^{\infty}x_i^{(n)}$, $n\in\mathbb{N}$, converge absolutely.

(ii) Let $\varepsilon > 0$ be given. Choose $K \in \mathbb{N}$ sufficiently large such that $\sum_{j=K+1}^{\infty} M_i < \frac{\varepsilon}{3}$. Next, choose $N \in \mathbb{N}$ sufficiently large such that

$$\left| x_i^{(n)} - x_i \right| < \frac{\varepsilon}{3K}, \text{ for any } n > N \text{ and } i = 1, 2, \ldots, K.$$

Then, we have, for each $n > N$,

$$\begin{aligned}
\left| \sum_{i=1}^{\infty} x_i^{(n)} - \sum_{i=1}^{\infty} x_i \right| &= \left| \sum_{i=1}^{K} \left(x_i^{(n)} - x_i \right) + \sum_{i=K+1}^{\infty} x_i^{(n)} - \sum_{i=K+1}^{\infty} x_i \right| \\
&\leq \sum_{i=1}^{K} \left| x_i^{(n)} - x_i \right| + \sum_{i=K+1}^{\infty} \left| x_i^{(n)} \right| + \sum_{i=K+1}^{\infty} |\, x_i \,| \\
&\leq K \cdot \frac{\varepsilon}{3K} + \sum_{i=K+1}^{\infty} M_i + \sum_{i=K+1}^{\infty} M_i \leq \frac{\varepsilon}{3} + 2 \cdot \frac{\varepsilon}{3} = \varepsilon.
\end{aligned}$$

Since ε is arbitrary, this proves:

$$\lim_{n \to \infty} \sum_{i=1}^{\infty} x_i^{(n)} = \sum_{i=1}^{\infty} x_i.$$

□

Theorem A.4 (Uniform Limit Theorem)
Suppose:

- *X is a topological space, and (Y, d) is a metric space.*
- *$f : X \longrightarrow Y$ is a function from X into Y.*

If there exists a sequence $\{ f_n : X \longrightarrow Y \}_{n \in \mathbb{N}}$ of continuous functions from X into Y which converges uniformly to f, then f is itself a continuous functions from X into Y.

Remark A.5
Recall: Let S be a non-empty set, and (Y, d) a metric space. A sequence $\{ g_n : S \longrightarrow Y \}_{n \in \mathbb{N}}$ of functions converges uniformly to a function $g : S \longrightarrow Y$ if, for each $\varepsilon > 0$, there exists $N \in \mathbb{N}$ such that

$$d(\, g_n(x), \, g(x) \,) < \varepsilon, \quad \text{for every } n \geq N \text{ and every } x \in S.$$

Proof Let $x_0 \in X$ be an arbitrary point of X. We need to establish that f is continuous at $x_0 \in X$. Thus, let $\varepsilon > 0$ be given. We need to find an open subset U of X such that

$$x_0 \in U, \quad \text{and} \quad d(\, f(x_0), \, f(x) \,) < \varepsilon, \text{ for each } x \in U.$$

Since f_n converges to f uniformly, there exists $n \in \mathbb{N}$ such that

$$d(\, f_n(x), \, f(x) \,) < \frac{\varepsilon}{3}, \quad \text{for each } x \in X.$$

Since f_n is continuous, there exists an open subset $U \subset X$ such that

$$x_0 \in U, \quad \text{and} \quad d(\, f_n(x_0), \, f_n(x) \,) < \frac{\varepsilon}{3}, \text{ for each } x \in U.$$

Thus, for every $x \in U$, we have:

$$d(\, f(x_0), \, f(x) \,) \leq d(\, f(x_0), \, f_n(x_0) \,) + d(\, f_n(x_0), \, f_n(x) \,) + d(\, f_n(x), \, f(x) \,) < \frac{\varepsilon}{3} + \frac{\varepsilon}{3} + \frac{\varepsilon}{3} = \varepsilon.$$

This proves the continuity of $f : X \longrightarrow Y$. □

Lemma A.6 (Characterization of weak convergence of point-mass Borel measures on metric spaces)
Suppose (S,ρ) is a metric space. For each $x \in S$, let $\delta_x \in \mathcal{M}_1(S,\mathcal{B}(S))$ be the point-mass measure concentrated at $x \in S$; in other words, for each $A \in \mathcal{B}(S)$, we have

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

Then, for $x_0, x_1, x_2, \ldots \in S$, we have

$$\delta_{x_n} \overset{w}{\longrightarrow} \delta_{x_0}, \text{ as } n \longrightarrow \infty \quad \Longleftrightarrow \quad \lim_{n\to\infty} \rho(x_n, x_0) \,=\, 0.$$

Proof

$\underline{(\Longleftarrow)}$ Suppose $x_n \longrightarrow x_0$. Then, for each bounded continuous $f : S \longrightarrow \mathbb{R}$, we have

$$\delta_{x_n}(f) \,=\, f(x_n) \;\longrightarrow\; f(x_0) \,=\, \delta_{x_0}(f),$$

which proves that $\delta_{x_n} \overset{w}{\longrightarrow} \delta_{x_0}$, as $n \longrightarrow \infty$.

$\underline{(\Longrightarrow)}$ Conversely, suppose x_n does NOT converge to x_0. Then, there exists $\varepsilon > 0$ such that

$$\rho(x_n, x_0) \,>\, \varepsilon, \quad \text{for infinitely many } n.$$

Now, define $f : S \longrightarrow \mathbb{R}$ by

$$f(x) \;:=\; \max\left\{ 0\,,\, 1 - \frac{\rho(x,x_0)}{\varepsilon} \right\}.$$

Then, f is bounded and continuous, and

$$\delta_{x_0}(f) \,=\, f(x_0) \,=\, \max\left\{ 0\,,\, 1 - \frac{\rho(x_0,x_0)}{\varepsilon} \right\} \,=\, \max\left\{ 0\,,\, 1 - \frac{0}{\varepsilon} \right\} \,=\, 1,$$

while, for infinitely many $n \in \mathbb{N}$, we have $\rho(x_n, x_0) > \varepsilon$, and hence

$$\delta_{x_n}(f) \,=\, f(x_n) \,=\, \max\left\{ 0\,,\, 1 - \frac{\rho(x_n,x_0)}{\varepsilon} \right\} \,=\, 0.$$

Hence, $\delta_{x_n}(f)$ does NOT converge to $\delta_{x_0}(f)$. This proves δ_{x_n} does NOT converge weakly to δ_{x_0}. □

B σ-algebras and λ-systems

Definition B.1
Suppose Ω is a non-empty set. A σ-algebra of subsets of Ω is a collection $\mathcal{A}$ of subsets of Ω which satisfies the following conditions:

- *$\Omega \in \mathcal{A}$.*
- *$\Omega \setminus A \in \mathcal{A}$, for every $A \in \mathcal{A}$.*
- *$\displaystyle\bigcup_{i=1}^{\infty} A_i \in \mathcal{A}$, whenever $A_1, A_2, \ldots \in \mathcal{A}$*

Definition B.2
Suppose Ω is a non-empty set. A λ-system of subsets of Ω is a collection $\mathcal{L}$ of subsets of Ω which satisfies the following conditions:

- $\Omega \in \mathcal{L}$.
- $\Omega \setminus A \in \mathcal{L}$, *for every* $A \in \mathcal{L}$.
- $\bigsqcup_{i=1}^{\infty} A_i \in \mathcal{L}$, *whenever* $A_1, A_2, \ldots \in \mathcal{L}$ *and* $A_i \cap A_j = \varnothing$, *for any* $i, j \in \mathbb{N}$ *with* $i \neq j$.

Remark B.3 *Clearly, every σ-algebra is also a λ-system.*

Theorem B.4
Suppose Ω is a non-empty set and $\mathcal{L}$ is a λ-system of subsets of Ω.

(i) *$\mathcal{L}$ is closed under proper set-theoretic differences, i.e. $A, B \in \mathcal{L}$ and $A \subset B$ together imply $B \setminus A \in \mathcal{L}$.*

(ii) *If $\mathcal{L}$ is closed under finite intersections, then $\mathcal{L}$ is a σ-algebra of subsets of Ω.*

PROOF For each $X \subset \Omega$, write $\Omega \setminus X$ as X^c.

(i) Suppose $A, B \in \mathcal{L}$ with $A \subset B$. Then, $B^c \cap A = \varnothing$. Hence, $B \setminus A = B \cap A^c = (B^c \cup A)^c = (B^c \sqcup A)^c \in \mathcal{L}$, since $\mathcal{L}$ is closed under complementations and finite disjoint unions.

(ii) Since $\mathcal{L}$ is a λ-system, we immediately have $\Omega \in \mathcal{L}$, and hence $\Omega \setminus A \in \mathcal{L}$, for every $A \in \mathcal{L}$. It remains to show that $\mathcal{L}$ closed under countable unions, i.e. for $A_1, A_2, \ldots \in \mathcal{L}$, we need to show $\bigcup_{i=1}^{\infty} A_i \in \mathcal{L}$. To this end, define:

$$\begin{aligned}
B_1 &:= A_1 \\
B_2 &:= A_2 \cap A_1^c \\
B_3 &:= A_3 \cap A_1^c \cap A_2^c \\
&\vdots \\
B_n &:= A_n \cap A_1^c \cap A_2^c \cap \cdots \cap A_n^c
\end{aligned}$$

Being a λ-system, $\mathcal{L}$ is closed under complementations. By hypothesis, $\mathcal{L}$ is furthermore closed under finite intersections. We thus see that $B_n \in \mathcal{L}$, for each $n \in \mathbb{N}$. Note also that the B_n's are pairwise disjoint, and

$$\bigcup_{i=1}^{n} A_i = \bigsqcup_{i=1}^{n} B_i, \quad \text{for each } n \in \mathbb{N}.$$

Hence,

$$\bigcup_{i=1}^{\infty} A_i = \bigsqcup_{i=1}^{\infty} B_i \in \mathcal{L},$$

since $\mathcal{L}$ is closed under countable pairwise disjoint unions ($\mathcal{L}$ being a λ-system). This proves that $\mathcal{L}$ is a σ-algebra of subsets of Ω.

□

Theorem B.5 *Let Ω be a non-empty set.*

(i) *The intersection of a non-empty collection of σ-algebras of subsets of Ω is itself a σ-algebra of subsets of Ω.*

(ii) *The intersection of a non-empty collection of λ-systems of subsets of Ω is itself a λ-system of subsets of Ω.*

PROOF

(i) Suppose Γ is an (arbitrary) non-empty set, and, for each $\gamma \in \Gamma$, $\mathcal{A}_\gamma$ is a σ-algebra of subsets of Ω. We need to prove that $\mathcal{A} := \bigcap_{\gamma\in\Gamma} \mathcal{A}_\gamma$ is itself a σ-algebra of subsets of Ω.

$\underline{\Omega \,\in\, \mathcal{A} := \bigcap\limits_{\gamma\in\Gamma} \mathcal{A}_\gamma}$

Since, for each $\gamma \in \Gamma$, $\mathcal{A}_\gamma$ is a σ-algebra of subsets of Ω, we have $\Omega \in \mathcal{A}_\gamma$. Thus, $\Omega \in \bigcap\limits_{\gamma\in\Gamma} \mathcal{A}_\gamma$.

$\underline{A \in \mathcal{A} \implies \Omega \backslash A \in \mathcal{A}}$

$$A \,\in\, \mathcal{A} := \bigcap_{\gamma\in\Gamma} \mathcal{A}_\gamma \quad\iff\quad A \,\in\, \mathcal{A}_\gamma,\ \forall\,\gamma\in\Gamma \quad\implies\quad \Omega\backslash A \,\in\, \mathcal{A}_\gamma,\ \forall\,\gamma\in\Gamma \quad\implies\quad \Omega\backslash A \,\in\, \bigcap_{\gamma\in\Gamma} \mathcal{A}_\gamma \,=:\, \mathcal{A}$$

$\underline{A_1, A_2, \ldots \in \mathcal{A} \implies \bigcup\limits_{i=1}^{\infty} A_i \in \mathcal{A}}$

$$\begin{aligned} A_1, A_2, \ldots \,\in\, \mathcal{A} := \bigcap_{\gamma\in\Gamma} \mathcal{A}_\gamma \quad&\implies\quad A_1, A_2, \ldots \,\in\, \mathcal{A}_\gamma,\ \forall\,\gamma\in\Gamma \quad\implies\quad \bigcup_{i=1}^{\infty} A_i \,\in\, \mathcal{A}_\gamma,\ \forall\,\gamma\in\Gamma \\ &\implies\quad \bigcup_{i=1}^{\infty} A_i \,\in\, \bigcap_{\gamma\in\Gamma} \mathcal{A}_\gamma \,=:\, \mathcal{A} \end{aligned}$$

(ii) Suppose Γ is an (arbitrary) non-empty set, and, for each $\gamma \in \Gamma$, $\mathcal{L}_\gamma$ is a λ-system of subsets of Ω. We need to prove that $\mathcal{L} := \bigcap_{\gamma\in\Gamma} \mathcal{L}_\gamma$ is itself a λ-system of subsets of Ω.

$\underline{\Omega \,\in\, \mathcal{L} := \bigcap\limits_{\gamma\in\Gamma} \mathcal{L}_\gamma}$

Since, for each $\gamma \in \Gamma$, $\mathcal{L}_\gamma$ is a λ-system of subsets of Ω, we have $\Omega \in \mathcal{L}_\gamma$. Thus, $\Omega \in \bigcap\limits_{\gamma\in\Gamma} \mathcal{L}_\gamma$.

$\underline{A \in \mathcal{L} \implies \Omega \backslash L \in \mathcal{L}}$

$$A \,\in\, \mathcal{L} := \bigcap_{\gamma\in\Gamma} \mathcal{L}_\gamma \quad\iff\quad A \,\in\, \mathcal{L}_\gamma,\ \forall\,\gamma\in\Gamma \quad\implies\quad \Omega\backslash A \,\in\, \mathcal{L}_\gamma,\ \forall\,\gamma\in\Gamma \quad\implies\quad \Omega\backslash A \,\in\, \bigcap_{\gamma\in\Gamma} \mathcal{L}_\gamma \,=:\, \mathcal{L}$$

$\underline{A_1, A_2, \ldots \in \mathcal{L} \text{ and } A_i \cap A_j \text{ whenever } i \neq j \implies \bigsqcup\limits_{i=1}^{\infty} A_i \in \mathcal{L}}$

$$\begin{aligned} & A_1, A_2, \ldots \,\in\, \mathcal{L} := \bigcap_{\gamma\in\Gamma} \mathcal{L}_\gamma\,, \ \text{ and } \ A_i \cap A_j \text{ whenever } i \neq j \\ \implies\quad & A_1, A_2, \ldots \,\in\, \mathcal{L}_\gamma,\ \forall\,\gamma\in\Gamma\,, \ \text{ and } \ A_i \cap A_j \text{ whenever } i \neq j \\ \implies\quad & \bigsqcup_{i=1}^{\infty} A_i \,\in\, \mathcal{L}_\gamma,\ \forall\,\gamma\in\Gamma \\ \implies\quad & \bigsqcup_{i=1}^{\infty} A_i \,\in\, \bigcap_{\gamma\in\Gamma} \mathcal{L}_\gamma \,=:\, \mathcal{L} \end{aligned}$$

$\square$

Theorem B.6 *Suppose Ω is a non-empty set, $\mathcal{S}$ is non-empty collection of subsets of Ω. Denote the power set of Ω by $\mathcal{P}(\Omega)$. Define*

$$\sigma(\mathcal{S}) \;:=\; \bigcap_{\mathcal{A}\,\in\,\Sigma(\mathcal{S})} \mathcal{A}\,, \quad \text{where} \quad \Sigma(\mathcal{S}) \;:=\; \left\{ \mathcal{A} \subset \mathcal{P}(\Omega) \;\middle|\; \begin{array}{c} \mathcal{A} \text{ is a } \sigma\text{-algebra of subsets of } \Omega, \\ \text{and } \mathcal{S} \,\subset\, \mathcal{A} \end{array} \right\}, \quad \text{and}$$

$$\lambda(\mathcal{S}) \;:=\; \bigcap_{\mathcal{L}\,\in\,\Lambda(\mathcal{S})} \mathcal{L}\,, \quad \text{where} \quad \Lambda(\mathcal{S}) \;:=\; \left\{ \mathcal{L} \subset \mathcal{P}(\Omega) \;\middle|\; \begin{array}{c} \mathcal{L} \text{ is a } \lambda\text{-system of subsets of } \Omega, \\ \text{and } \mathcal{S} \,\subset\, \mathcal{L} \end{array} \right\}.$$

Then, $\sigma(\mathcal{S})$ is the unique smallest σ-algebra of subsets of Ω that contains $\mathcal{S} \subset \mathcal{P}(\Omega)$, and $\lambda(\mathcal{S})$ is the unique smallest λ-system of subsets of Ω that contains $\mathcal{S} \subset \mathcal{P}(\Omega)$. More precisely, we have

- *$\mathcal{S} \subset \sigma(\mathcal{S})$, $\mathcal{S} \subset \lambda(\mathcal{S})$, and*
- *$\sigma(\mathcal{S})$ is a σ-algebra of subsets of Ω, and $\lambda(\mathcal{S})$ is a λ-system of subsets of Ω, and*
- *if $\mathcal{A} \subset \mathcal{P}(\Omega)$ is a σ-algebra and $\mathcal{S} \subset \mathcal{A}$, then $\sigma(\mathcal{S}) \subset \mathcal{A}$.*
- *if $\mathcal{L} \subset \mathcal{P}(\Omega)$ is a λ-system and $\mathcal{S} \subset \mathcal{L}$, then $\lambda(\mathcal{S}) \subset \mathcal{L}$.*

Proof First, note that $\Sigma(\mathcal{S}) \neq \varnothing$ since $\mathcal{P}(\Omega) \in \Sigma(\mathcal{S})$. Similarly, $\Lambda(\mathcal{S}) \neq \varnothing$ since $\mathcal{P}(\Omega) \in \Lambda(\mathcal{S})$. It is immediate that $\mathcal{S} \subset \sigma(\mathcal{S})$, and $\sigma(\mathcal{S})$ is contained in every σ-algebra which contains $\mathcal{S}$. Similarly, $\mathcal{S} \subset \lambda(\mathcal{S})$, and $\lambda(\mathcal{S})$ is contained in every λ-system which contains $\mathcal{S}$. Since $\sigma(\mathcal{S})$ is, by definition, an intersection of σ-algebras, it itself is a σ-algebra of subsets of Ω by Theorem B.5. Similarly, since $\lambda(\mathcal{S})$ is, by definition, an intersection of λ-systems, it itself is a λ-system of subsets of Ω by Theorem B.5. $\square$

Theorem B.7 *Suppose Ω is a non-empty set and $\mathcal{S}$ is a non-empty collection of subsets of Ω. Then,*

$$\mathcal{S} \text{ is closed under finite intersections} \quad \Longrightarrow \quad \lambda(\mathcal{S}) \text{ is a } \sigma\text{-algebra of subsets of } \Omega,$$

where $\lambda(\mathcal{S})$ is λ-system of subsets of Ω generated by $\mathcal{S}$.

Proof By Theorem B.4(ii), it suffices to show that $\lambda(\mathcal{S})$ is closed under finite intersections. We establish the proof in the following series of claims:

Claim 1: For each $A \in \lambda(\mathcal{S})$,

$$\mathcal{L}(A) \;:=\; \{\; B \subset \Omega \;\mid A \cap B \in \lambda(\mathcal{S}) \;\}$$

is a λ-system of subsets of Ω.

Proof of Claim 1: Clearly, $\Omega \in \mathcal{L}(A)$, since $A \cap \Omega = A \in \lambda(\mathcal{S})$. Next, we prove that $\mathcal{L}(A)$ is closed under complementations. Let $B \in \mathcal{L}(A)$. Then, $A \cap B \in \lambda(\mathcal{S})$. Note that $A = (A \cap B) \bigsqcup (A \cap B^c)$, hence $A \cap B^c = A \backslash (A \cap B) \in \lambda(\mathcal{S})$, since $A, A \cap B \in \lambda(\mathcal{S})$ and $\lambda(\mathcal{S})$ is closed under proper set-theoretic differences by Theorem B.4(i). This proves that $\mathcal{L}(A)$ is indeed closed under complementations. We now prove that $\mathcal{L}(A)$ is closed under countable disjoint unions. Let $B_1, B_2, \ldots \in \mathcal{L}(A)$ be pairwise disjoint. Then, $A \cap B_1, A \cap B_2, \ldots \subset \lambda(\mathcal{S})$ are pairwise disjoint. Hence,

$$A \bigcap \left(\bigsqcup_{i=1}^{\infty} B_i \right) \;=\; \bigsqcup_{i=1}^{\infty} (\, A \,\cap\, B_i \,) \;\in\; \lambda(\mathcal{S})\,,$$

since $\lambda(\mathcal{S})$ is closed under countable disjoint unions. This proves that $\mathcal{L}(A)$ is a λ-system and thus completes the proof of the Claim 1.

Claim 2: $\mathcal{S} \subset \mathcal{L}(A)$, for each $A \in \mathcal{S}$. Consequently, $\lambda(\mathcal{S}) \subset \mathcal{L}(A)$, for each $A \in \mathcal{S}$.

Proof of Claim 2: Suppose $A \in \mathcal{S}$. Then, $A \cap B \in \mathcal{S}$ for each $B \in \mathcal{S}$, by the hypothesis that $\mathcal{S}$ is closed under finite intersections. Thus, $A \cap B \in \lambda(\mathcal{S})$, since $\mathcal{S} \subset \lambda(\mathcal{S})$. Hence, $B \in \mathcal{L}(A)$, for any $A, B \in \mathcal{S}$. This proves that $\mathcal{S} \subset \mathcal{L}(A)$, for each $A \in \mathcal{S}$. By Claim 1, $\mathcal{L}(A)$ is a λ-system. Hence, $\mathcal{L}(A) \supset \lambda(\mathcal{S})$, the smallest λ-system containing $\mathcal{S}$. This proves Claim 2.

Claim 3: $A \cap B \in \lambda(\mathcal{S})$, for each $A \in \mathcal{S}$ and $B \in \lambda(\mathcal{S})$.

Proof of Claim 3: Let $A \in \mathcal{S}$ and $B \in \lambda(\mathcal{S})$. By Claim 2, we have $\lambda(\mathcal{S}) \subset \mathcal{L}(A)$. Thus we have $B \in \mathcal{L}(A)$, which is equivalent to $A \cap B \in \lambda(S)$. This proves Claim 3.

Claim 4: $\mathcal{S} \subset \mathcal{L}(B)$, for each $B \in \lambda(\mathcal{S})$. Consequently, $\lambda(\mathcal{S}) \subset \mathcal{L}(B)$, for each $B \in \lambda(\mathcal{S})$.

Proof of Claim 4: Suppose $B \in \lambda(\mathcal{S})$. Then, $A \cap B \in \lambda(\mathcal{S})$ for each $A \in \mathcal{S}$, by Claim 3. This proves that $\mathcal{S} \subset \mathcal{L}(B)$. By Claim 1, $\mathcal{L}(B)$ is a λ-system. Hence, $\mathcal{L}(B) \supset \lambda(\mathcal{S})$, the smallest λ-system containing $\mathcal{S}$. This proves Claim 4.

Claim 5: $A \cap B \in \lambda(\mathcal{S})$, for each $A, B \in \lambda(\mathcal{S})$.

Proof of Claim 5: Let $A, B \in \lambda(\mathcal{S})$. By Claim 4, we have $\lambda(\mathcal{S}) \subset \mathcal{L}(B)$. Thus we have $A \in \mathcal{L}(B)$, which is equivalent to $A \cap B \in \lambda(S)$. This proves Claim 5.

Claim 5 states precisely that $\lambda(\mathcal{S})$ is closed under finite intersections, and completes the proof. $\square$

Corollary B.8 *Suppose Ω is a non-empty set and $\mathcal{S}$ is a non-empty collection of subsets of Ω. If $\mathcal{S}$ is closed under finite intersections, then*

(i) $\sigma(S) \subset \lambda(\mathcal{S})$, *and*

(ii) $\sigma(S) \subset \mathcal{L}$, *for any λ-system $\mathcal{L}$ of subsets of Ω such that $\mathcal{S} \subset \mathcal{L}$,*

where $\sigma(\mathcal{S})$ and $\lambda(\mathcal{S})$ are, respectively, the σ-algebra and λ-system of subsets of Ω generated by $\mathcal{S}$.

Proof

(i) By Theorem B.6, $\lambda(\mathcal{S})$ is the smallest λ-system containing $\mathcal{S}$. Since $\mathcal{S}$ is, by hypothesis, closed under finite intersections, $\lambda(\mathcal{S})$ is furthermore a σ-algebra, by Theorem B.7. Thus, by Theorem B.6 again, we have $\sigma(S) \subset \lambda(\mathcal{S})$.

(ii) This is now immediate since
$$\sigma(S) \ \subset\ \lambda(\mathcal{S}) \ \subset\ \mathcal{L},$$
where the first inclusion follows by (i), and the second inclusion follows by Theorem B.6.

$\square$

Lemma B.9 (The pre-image of a σ-algebra is itself a σ-algebra.)
Suppose Ω is a non-empty set, $(X, \mathcal{X})$ is a measurable space, and $f : \Omega \longrightarrow X$ is a map from Ω into X. Then,
$$f^{-1}(\mathcal{X}) \ := \ \{\ f^{-1}(V) \subset \Omega \ |\ V \in \mathcal{X}\ \}$$
is a σ-algebra of subsets of Ω.

Proof

$\Omega \in f^{-1}(\mathcal{X})$ $f(\Omega) \subset X \implies \Omega = f^{-1}(X) \in f^{-1}(\mathcal{X})$.

$f^{-1}(\mathcal{X})$ is closed under complementations Let $V \in \mathcal{X}$. Then, $X \setminus V \in \mathcal{X}$, and

$$\Omega \setminus f^{-1}(V) \;=\; \{\, \omega \in \Omega \mid f(\omega) \notin V \,\} \;=\; \{\, \omega \in \Omega \mid f(\omega) \in X \setminus V \,\} \;=\; f^{-1}(X \setminus V) \;\in\; f^{-1}(\mathcal{X}),$$

which shows that $f^{-1}(\mathcal{X})$ is indeed closed under complementations.

$f^{-1}(\mathcal{X})$ is closed countable unions Let $V_1, V_2, \ldots \in \mathcal{X}$. Then, $\displaystyle\bigcup_{i=1}^{\infty} V_i \in \mathcal{X}$, and

$$\bigcup_{i=1}^{\infty} f^{-1}(V_i) \;=\; \left\{ \omega \in \Omega \;\middle|\; \begin{array}{c} f(\omega) \in V_i \\ \text{for some } i \in \mathbb{N} \end{array} \right\} \;=\; f^{-1}\left(\bigcup_{i=1}^{\infty} V_i \right) \;\in\; f^{-1}(\mathcal{X}),$$

which proves that $f^{-1}(\mathcal{X})$ is indeed closed under countable unions.

This concludes the proof that that $f^{-1}(\mathcal{X})$ is a σ-algebra of subsets of Ω. □

Lemma B.10
Suppose $(\Omega, \mathcal{A})$ is a measurable space, X is a non-empty set, and $f : \Omega \longrightarrow X$ is a map from Ω into X. Then,

$$\mathcal{F} \;:=\; \{\, V \subset X \mid f^{-1}(V) \in \mathcal{A} \,\}$$

is a σ-algebra of subsets of X.

Proof

$X \in \mathcal{F}$ $f^{-1}(X) = \Omega \in \mathcal{A} \implies X \in \mathcal{F}$.

$\mathcal{F}$ is closed under complementations $V \in \mathcal{F} \implies f^{-1}(V) \in \mathcal{A} \implies f^{-1}(X \setminus V) = \Omega \setminus f^{-1}(V) \in \mathcal{A} \implies X \setminus V \in \mathcal{F}$, which proves that $\mathcal{F}$ is indeed closed under complementations.

$\mathcal{F}$ is closed under countable unions

$$\begin{aligned} V_1, V_2, \ldots \;\in\; \mathcal{F} \;&\implies\; f^{-1}(V_1), f^{-1}(V_2), \ldots \;\in\; \mathcal{A} \\ &\implies\; f^{-1}\left(\bigcup_{i=1}^{\infty} V_i \right) \;=\; \bigcup_{i=1}^{\infty} f^{-1}(V_i) \;\in\; \mathcal{A} \\ &\implies\; \bigcup_{i=1}^{\infty} V_i \;\in\; \mathcal{F}, \end{aligned}$$

which proves that $\mathcal{F}$ is indeed closed under countable unions. □

Theorem B.11
Suppose $(\Omega, \mathcal{A})$ and $(X, \mathcal{X})$ are measurable spaces, and $f : \Omega \longrightarrow X$ is a map from Ω into X. Then, f is $(\mathcal{A}, \mathcal{X})$-measurable if there exists $\mathcal{S} \subset \mathcal{X}$ satisfying the following conditions:

- *$\mathcal{S}$ generates $\mathcal{X}$, i.e. $\sigma(\mathcal{S}) = \mathcal{X}$, and*
- *$f^{-1}(\mathcal{S}) \subset \mathcal{A}$.*

PROOF By Lemma B.10,

$$\mathcal{F} \;:=\; \left\{\, V \subset X \;\middle|\; f^{-1}(V) \in \mathcal{A} \,\right\}$$

is a σ-algebra of subsets of X. By hypothesis, $\mathcal{S} \subset \mathcal{F}$; hence, $\mathcal{X} = \sigma(\mathcal{S}) \subset \mathcal{F}$. Thus, $f^{-1}(\mathcal{X}) \subset \mathcal{A}$; equivalently, f is $(\mathcal{A}, \mathcal{X})$-measurable. □

Corollary B.12 (Continuous maps are Borel measurable.)
Suppose X_1, X_2 are topological spaces, and $\mathcal{B}_1$, $\mathcal{B}_2$ are their respective Borel σ-algebras. Then, every continuous map $f : X_1 \longrightarrow X_2$ is $(\mathcal{B}_1, \mathcal{B}_2)$-measurable.

C Topology

Theorem C.1 (Appendix M3, [1])
Suppose S is a metric space. Then, the following conditions are equivalent:

(i) *S is separable.*

(ii) *The topology of S has a countable basis.*

(iii) *Every open cover of each subset of S has a countable subcover.*

D The Portmanteau Theorem and its corollaries (criteria for weak convergence of measures)

Theorem D.1 (The Portmanteau Theorem, Theorem 2.1, [1])
Suppose:

- *(S, ρ) is a metric space, $\mathcal{B}(S)$ its the Borel σ-algebra, $(S, \mathcal{B}(S))$ is the corresponding measurable space.*
- *$P, P_1, P_2, \ldots \in \mathcal{M}_1(S, \mathcal{B}(S))$ are probability measures on $(S, \mathcal{B}(S))$.*

Then, the following are equivalent:

(i) *P_n converges weakly to P, i.e. for each bounded continuous $\mathbb{R}$-valued function $f : S \longrightarrow \mathbb{R}$, we have*

$$\lim_{n\to\infty} \int_S f(s)\,\mathrm{d}P_n(s) \;=\; \int_S f(s)\,\mathrm{d}P(s).$$

(ii) *For each closed set $F \subset S$, we have*

$$\limsup_{n\to\infty} P_n(F) \;\leq\; P(F).$$

(iii) *For each open set $G \subset S$, we have*

$$\liminf_{n\to\infty} P_n(G) \;\geq\; P(G).$$

(iv) *For each $A \in \mathcal{B}(S)$, we have*

$$P(A^\circ) \;\leq\; \liminf_{n\to\infty} P_n(A^\circ) \;\leq\; \liminf_{n\to\infty} P_n(A) \;\leq\; \limsup_{n\to\infty} P_n(A) \;\leq\; \limsup_{n\to\infty} P_n\big(\overline{A}\big) \;\leq\; P\big(\overline{A}\big).$$

(v) *For each P-continuity set $A \in \mathcal{B}(S)$, i.e. $P(\partial A) = 0$, we have*

$$\lim_{n\to\infty} P_n(A) \;=\; P(A).$$

Theorem D.2 (Theorem 2.2, [1])
Suppose (S,ρ) is a metric space, and $P, P_1, P_2, \ldots \mathcal{M}_1(S,\mathcal{B}(S))$ are probability measures on the measurable space $(S,\mathcal{B}(S))$. Then, $P_n \xrightarrow{w} P$ if there exists a sub-collection $\mathcal{A} \subset \mathcal{B}(S)$ satisfying the following conditions:

(i) *$\mathcal{A}$ is closed under finite intersections,*

(ii) *$\lim_{n\to\infty} P_n(A) = P(A)$, for each $A \in \mathcal{A}$, and*

(iii) *each open subset of S is a countable union of sets in $\mathcal{A}$.*

Proof
By the Portmanteau Theorem (Theorem D.1), it suffices to establish the following:

$$P(G) \;\leq\; \liminf_{n\to\infty} P_n(G), \quad \text{for each open subset } G \subset S.$$

By hypothesis, $G = \bigcup_{i=1}^\infty A_i$, where $A_i \in \mathcal{A}$ for each $i \in \mathbb{N}$. For each $\varepsilon > 0$, choose $r \in \mathbb{N}$ sufficiently large such that

$$P(G) - \varepsilon \;<\; P\left(\bigcup_{i=1}^r A_i\right) \;\leq\; P(G).$$

Now, observe that:

$$\begin{aligned}
P_n\left(\bigcup_{i=1}^r A_i\right) &= \sum_{i=1}^r P_n(A_i) - \sum_{i=1}^r \sum_{j=i+1}^r P_n(A_i \cap A_j) + \sum_{i=1}^r \sum_{j=i+1}^r \sum_{k=j+1}^r P_n(A_i \cap A_j \cap A_k) - \cdots \\
&\longrightarrow \sum_{i=1}^r P(A_i) - \sum_{i=1}^r \sum_{j=i+1}^r P(A_i \cap A_j) + \sum_{i=1}^r \sum_{j=i+1}^r \sum_{k=j+1}^r P(A_i \cap A_j \cap A_k) - \cdots \\
&= P\left(\bigcup_{i=1}^r A_i\right),
\end{aligned}$$

where we have used the hypotheses (i) and (ii) and the fact the ellipses above represent sums of finitely many terms. Thus we have:

$$P(G) - \varepsilon \;\leq\; P\left(\bigcup_{i=1}^r A_i\right) \;=\; \lim_{n\to\infty} P_n\left(\bigcup_{i=1}^r A_i\right) \;\leq\; \liminf_{n\to\infty} P_n(G).$$

Since $\varepsilon > 0$ is arbitrary, it follows that:

$$P(G) \;\leq\; \liminf_{n\to\infty} P_n(G),$$

which completes the proof the present Theorem. □

Theorem D.3 (Theorem 2.3, [1])
Suppose (S,ρ) is a separable metric space, and $P, P_1, P_2, \ldots \mathcal{M}_1(S,\mathcal{B}(S))$ are probability measures on the measurable space $(S,\mathcal{B}(S))$. Then, $P_n \xrightarrow{w} P$ if there exists a sub-collection $\mathcal{A} \subset \mathcal{B}(S)$ satisfying the following conditions:

(i) *$\mathcal{A}$ is closed under finite intersections,*

(ii) *$\lim_{n\to\infty} P_n(A) = P(A)$, for each $A \in \mathcal{A}$, and*

(iii) *for each $x \in S$ and $\varepsilon > 0$, the set*

$$\mathcal{A}(x,\varepsilon) \;:=\; \left\{\, A \in \mathcal{A} \;\middle|\; x \in A^\circ \subset A \subset B(x,\varepsilon) \,\right\} \;\neq\; \varnothing.$$

PROOF
By the preceding Theorem, it suffices to establish that each open subset $G \subset S$ can be expressed as a countable union of sets in $\mathcal{A}$. But this follows from the separability of S and hypothesis (iii). Indeed, let $G \subset S$ be an open subset of S. For each $x \in G$, choose $\epsilon_x > 0$ such that $B(x, \varepsilon_x) \subset G$. Next, by hypothesis (iii), we may choose $A_x \in \mathcal{A}$ such that

$$x \in A_x^\circ \subset A_x \subset B(x, \varepsilon_x) \subset G.$$

Thus,

$$G = \bigcup_{x \in G} A_x^\circ.$$

Since S is separable, by Theorem C.1, there exists $x_1, x_2, \ldots \in G$ such that $G = \bigcup_{i=1}^{\infty} A_{x_i}^\circ$. But then

$$G = \bigcup_{i=1}^{\infty} A_{x_i}^\circ \subset \bigcup_{i=1}^{\infty} A_{x_i} \subset \bigcup_{i=1}^{\infty} B(x_i, \varepsilon_{x_i}) \subset G,$$

which implies

$$G = \bigcup_{i=1}^{\infty} A_{x_i}.$$

This completes the proof of the present Theorem. $\square$

Theorem D.4 (Theorem 2.4, [1])
Suppose (S, ρ) is a separable metric space. Then, a sub-collection $\mathcal{A} \subset \mathcal{B}(S)$ is a convergence-determining class of Borel subsets of $(S, \mathcal{B}(S))$ if $\mathcal{A}$ satisfies the following conditions:

(i) *$\mathcal{A}$ is closed under finite intersections, and*

(ii) *for each $x \in S$ and $\varepsilon > 0$, the set*

$$\partial\mathcal{A}(x,\varepsilon) := \left\{ \partial A \subset S \;\middle|\; A \in \mathcal{A}(x,\varepsilon) \right\}$$

either contains $\varnothing$ or contains uncountably many disjoint sets, where

$$\mathcal{A}(x,\varepsilon) := \left\{ A \in \mathcal{A} \;\middle|\; x \in A^\circ \subset A \subset B(x,\varepsilon) \right\}.$$

PROOF We need to prove that the following implication holds:

$$\left.\begin{array}{c} P,\, P_1,\, P_2,\, \ldots \in \mathcal{M}_1(S, \mathcal{B}(S)), \text{ and} \\ \lim\limits_{n\to\infty} P_n(A) = P(A), \text{ for each } A \in \mathcal{A}_P \end{array}\right\} \Longrightarrow P_n \xrightarrow{w} P,$$

where $\mathcal{A}_P := \{ A \in \mathcal{A} \mid P(\partial A) = 0 \}$ is the collection of P-continuity sets in $\mathcal{A}$.

By the preceding Theorem, it suffices to establish that $\mathcal{A}_P$ is closed under finite intersections and that

$$\mathcal{A}_P(x,\varepsilon) := \left\{ A \in \mathcal{A}_P \;\middle|\; x \in A^\circ \subset A \subset B(x,\varepsilon) \right\} = \mathcal{A}_P \cap \mathcal{A}(x,\varepsilon) \neq \varnothing, \text{ for each } x \in S \text{ and } \varepsilon > 0.$$

$\mathcal{A}_P$ is closed under finite intersections

For any $A, B \subset S$, note that

$$\begin{aligned}
\partial(A \cap B) &:= \left\{ x \in S \;\middle|\; \begin{array}{l} \text{for each } \varepsilon > 0: \\ B(x,\varepsilon) \cap (A \cap B) \neq \varnothing, \text{ and} \\ B(x,\varepsilon) \cap (A \cap B)^c \neq \varnothing \end{array} \right\} \\
&= \left\{ x \in S \;\middle|\; \begin{array}{l} \text{for each } \varepsilon > 0: \\ B(x,\varepsilon) \cap (A \cap B) \neq \varnothing, \text{ and} \\ B(x,\varepsilon) \cap (A^c \cup B^c) \neq \varnothing \end{array} \right\} \\
&= \left\{ x \in S \;\middle|\; \begin{array}{l} \text{for each } \varepsilon > 0: \\ B(x,\varepsilon) \cap (A \cap B) \neq \varnothing, \text{ and} \\ (B(x,\varepsilon) \cap A^c) \cup (B(x,\varepsilon) \cap B^c) \neq \varnothing \end{array} \right\} \\
&\subset \left\{ x \in S \;\middle|\; \begin{array}{l} \text{for each } \varepsilon > 0: \\ B(x,\varepsilon) \cap A \neq \varnothing, \text{ and} \\ B(x,\varepsilon) \cap A^c \neq \varnothing \end{array} \right\} \bigcup \left\{ x \in S \;\middle|\; \begin{array}{l} \text{for each } \varepsilon > 0: \\ B(x,\varepsilon) \cap B \neq \varnothing, \text{ and} \\ B(x,\varepsilon) \cap B^c \neq \varnothing \end{array} \right\} \\
&= (\partial A) \cup (\partial B),
\end{aligned}$$

which immediately implies that $A \cap B \in \mathcal{A}_P$ whenever $A, B \in \mathcal{A}_P$. Thus, $\mathcal{A}_P$ is closed under finite intersections.

$\mathcal{A}_P(x,\varepsilon) \neq \varnothing$, for each $x \in S$ and $\varepsilon > 0$

$$\begin{aligned}
\text{(ii)} \quad &\Longrightarrow \quad \partial\mathcal{A}(x,\varepsilon) \text{ contains a set of } P\text{-measure zero} \\
&\Longrightarrow \quad \text{there exists } B \in \partial\mathcal{A}(x,\varepsilon) \text{ such that } P(B) = 0 \\
&\Longrightarrow \quad \text{there exists } A \in \mathcal{A}(x,\varepsilon) \text{ such that } P(\partial A) = 0 \\
&\Longrightarrow \quad \text{there exists } A \in \mathcal{A}(x,\varepsilon) \cap \mathcal{A}_P \;=\; \mathcal{A}_P(x,\varepsilon) \\
&\Longrightarrow \quad \mathcal{A}_P(x,\varepsilon) \;\neq\; \varnothing,
\end{aligned}$$

where the first implication follows from the general fact that, for an arbitrary finite measure space $(\Omega, \mathcal{F}, \mu)$, $\mu(\varnothing) = 0$, and in every uncountable collection of disjoint $\mathcal{F}$-measurable sets, at most countably many of these sets can have positive μ-measures.

The proof of the present Theorem is now complete. □

References

[1] Billingsley, P. *Convergence of Probability Measures*, second ed. John Wiley & Sons, 1999.

[2] Billingsley, P. *Probability and Measure*, anniversary ed. John Wiley & Sons, 2012.