The Portmanteau Theorem

Study Notes July 19, 2015 Kenneth Chu

1 The Portmanteau Theorem

Theorem 1.1 (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* P*-continuity set* $A \in \mathcal{B}(S)$*, i.e.* $P(\partial A) = 0$*, we have*

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

Proof

<u>(i) $\Longrightarrow$ (ii)</u>

For each $\varepsilon > 0$, by Lemma A.2(ii), choose a bounded continuous functions $f_\varepsilon : S \longrightarrow [0,1]$ such that

$$I_F \;\leq\; f_\varepsilon \;\leq\; I_{F^\varepsilon}.$$

This implies, for each $\varepsilon > 0$, we have

$$P_n(F) \;=\; \int_S I_F(x)\,\mathrm{d}P_n(x) \;\leq\; \int_S f_\varepsilon(x)\,\mathrm{d}P_n(x).$$

By (i), we thus have

$$\limsup_{n\to\infty} P_n(F) \;\leq\; \lim_{n\to\infty} \int_S f_\varepsilon(x)\,\mathrm{d}P_n(x) \;=\; \int_S f_\varepsilon(x)\,\mathrm{d}P(x) \;\leq\; \int_S I_{F^\varepsilon}(x)\,\mathrm{d}P(x) \;=\; P(F^\varepsilon)\,.$$

By Lemma A.2(i), we have $F^\varepsilon \downarrow F$ as $\varepsilon \downarrow 0$. Hence, $P(F^\varepsilon) \downarrow P(F)$ as $\varepsilon \downarrow 0$. We may now conclude:

$$\limsup_{n\to\infty} P_n(F) \;\leq\; \lim_{\varepsilon\to 0^+} P(F^\varepsilon) \;=\; P(F)\,.$$

<u>(ii) $\Longrightarrow$ (iii)</u>

Assume (ii) holds. Let $G \subset S$ be a open subset. Then, $F := S \setminus G$ is closed. By (ii), we have:

$$\begin{aligned} 1 - \liminf_{n\to\infty} P_n(G) &= \limsup_{n\to\infty} \{ 1 - P_n(G) \} = \limsup_{n\to\infty} P_n(S \setminus G) = \limsup_{n\to\infty} P_n(F) \\ &\leq P(F) = P(S \setminus G) = 1 - P(G), \end{aligned}$$

which yields

$$\liminf_{n\to\infty} P_n(G) \geq P(G). \tag{1.1}$$

(ii) $\Longrightarrow$ (iii)

Assume (iii) holds. Let $F \subset S$ be an closed subset. Then, $G := S \setminus F$ is open. By (iii), we have:

$$\begin{aligned} 1 - \limsup_{n\to\infty} P_n(F) &= \liminf_{n\to\infty} \{ 1 - P_n(F) \} = \liminf_{n\to\infty} P_n(S \setminus F) = \liminf_{n\to\infty} P_n(G) \\ &\geq P(G) = P(S \setminus F) = 1 - P(F), \end{aligned}$$

which yields

$$\limsup_{n\to\infty} P_n(F) \leq P(F). \tag{1.2}$$

(ii) and (iii) $\Longrightarrow$ (iv)

Let $A \in \mathcal{B}(S)$. Then, by (ii) and (iii), we have:

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

Hence, if $\partial A := \overline{A} \setminus A^\circ$ is a P-continuity set, i.e. $P(\partial A) = 0$, hence $P(A^\circ) = P(A) = P\big(\overline{A}\big)$, then (iv) follows.

(iv) $\Longrightarrow$ (ii)

(iii) $\Longrightarrow$ (i)

Let $g : S \longrightarrow [0,\infty)$ be continuous $\mathbb{R}$-valued function on S. Then, for each $t \in (0,\infty)$, the set $g^{-1}(\,(t,\infty)\,) = \{\, s \in S \mid g(s) > t \,\}$ is an open subset of S. Hence, by (iii), Lemma A.3, and Fatou's Lemma, we have

$$\begin{aligned} \int_S g(s)\,\mathrm{d}P(s) &= \int_0^\infty P(g > t)\,\mathrm{d}t \leq \int_0^\infty \liminf_{n\to\infty} P_n(g > t)\,\mathrm{d}t \\ &\leq \liminf_{n\to\infty} \int_0^\infty P_n(g > t)\,\mathrm{d}t \leq \liminf_{n\to\infty} \int_S g(s)\,\mathrm{d}P_n(s). \end{aligned}$$

Now, let $f : S \longrightarrow \mathbb{R}$ be continuous and bounded with $|\,f\,| \leq c < \infty$. Then, $c \pm f : S \longrightarrow [0,\infty)$ are continuous and non-negative $\mathbb{R}$-valued functions on S. Applying the preceding inequality to each yields:

$$\begin{aligned} \int_S c + f(s)\,\mathrm{d}P(s) &\leq \liminf_{n\to\infty} \int_S c + f(s)\,\mathrm{d}P_n(s) \\ \int_S c - f(s)\,\mathrm{d}P(s) &\leq \liminf_{n\to\infty} \int_S c - f(s)\,\mathrm{d}P_n(s). \end{aligned}$$

These respectively imply:

$$\begin{aligned} \int_S f(s)\,\mathrm{d}P(s) &\leq \liminf_{n\to\infty} \int_S f(s)\,\mathrm{d}P_n(s) \\ \limsup_{n\to\infty} \int_S f(s)\,\mathrm{d}P_n(s) &\leq \int_S f(s)\,\mathrm{d}P(s), \end{aligned}$$

which proves (i). $\square$

A Technical Lemmas

Lemma A.1 *Suppose (S,ρ) is a metric space, and $A \subset S$ is an arbitrary non-empty subset. Define*

$$\rho(\,\cdot\,,A)\ :\ S\ \longrightarrow\ \mathbb{R}\ :\ x\ \longmapsto\ \inf_{y\in A}\{\,\rho(x,y)\,\}$$

Then,

(i) *$\rho(\,\cdot\,,A)$ is a continuous $\mathbb{R}$-valued function on S.*

(ii) *For each $x\in S$, $\rho(x,A)=0$ if and only if $x\in\overline{A}$.*

Proof

(i) Suppose $x_n \longrightarrow x$. We need to prove $\rho(x_n,A)\longrightarrow\rho(x,A)$, which follows immediately from the following two Claims:

Claim 1: $\rho(x,A)\ \leq\ \liminf\limits_{n\to\infty}\rho(x_n,A)$.

Claim 2: $\limsup\limits_{n\to\infty}\rho(x_n,A)\ \leq\ \rho(x,A)$.

Proof of Claim 1: For each $y\in S$, we have:

$$\rho(x,y)\ \leq\ \rho(x,x_n)\ +\ \rho(x_n,y).$$

Hence,

$$\rho(x,A)\ =\ \inf_{y\in A}\rho(x,y)\ \leq\ \rho(x,x_n)\ +\ \inf_{y\in A}\rho(x_n,y)\ =\ \rho(x,x_n)\ +\ \rho(x_n,A).$$

Since $\rho(x,x_n)\longrightarrow 0$, the preceding inequality implies

$$\rho(x,A)\ \leq\ \liminf_{n\to\infty}\rho(x_n,A).$$

This proves Claim 1.

Proof of Claim 2: For each $y\in S$, we have:

$$\rho(x_n,y)\ \leq\ \rho(x_n,x)\ +\ \rho(x,y).$$

Hence,

$$\rho(x_n,A)\ =\ \inf_{y\in A}\rho(x_n,y)\ \leq\ \rho(x_n,x)\ +\ \inf_{y\in A}\rho(x,y)\ =\ \rho(x_n,x)\ +\ \rho(x,A).$$

Since $\rho(x,x_n)\longrightarrow 0$, the preceding inequality implies

$$\limsup_{n\to\infty}\rho(x_n,A)\ \leq\ \rho(x,A).$$

This proves Claim 2.

(ii)

$$\begin{aligned}\rho(x,A)=0 \quad &\Longleftrightarrow\quad \inf_{y\in A}\rho(x,y)=0\\ &\Longleftrightarrow\quad \text{For each } \varepsilon>0\text{, there exists } y\in A \text{ such that } \rho(x,y)<\varepsilon\\ &\Longleftrightarrow\quad y\in\overline{A}\end{aligned}$$

□

Lemma A.2 *Suppose (S,ρ) is a metric space, and $A \subset S$ is an arbitrary non-empty subset. For each $\varepsilon > 0$, define*

$$A^\varepsilon \;:=\; \{\, s \in S \;\mid\; \rho(s,A) < \varepsilon \,\}\,.$$

Then the following are true:

(i) *A^ε is an open subset of S. In particular, A^ε is a $\mathcal{B}(S)$-measurable subset of S.*

(ii) *$A^\varepsilon \downarrow \overline{A}$, as $\varepsilon \downarrow 0$.*

(iii) *There exists a bounded continuous $\mathbb{R}$-valued function $f : S \longrightarrow \mathbb{R}$ such that*

$$I_{\bar{A}}(x) \;\leq\; f(x) \;\leq\; I_{A^\varepsilon}(x)\,, \quad \text{for each } x \in S.$$

PROOF

(i)

(ii)

(iii) Define $f : S \longrightarrow \mathbb{R}$ as follows:

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

Then, by Lemma A.1(i), f is continuous $\mathbb{R}$-valued function on S. Clear, $0 \leq f(x) \leq 1$, for each $x \in S$. By Lemma A.1(ii), we have

$$x \;\in\; \overline{A} \quad\Longleftrightarrow\quad \rho(x,F) \;=\; 0 \quad\Longleftrightarrow\quad f(x) \;=\; 1.$$

This proves $I_{\bar{A}}(x) \leq 1 = f(x)$, for each $x \in \overline{A}$, and hence for each $x \in S$ (since $I_{\bar{A}}(x) = 0$ for $x \in S\backslash\overline{A}$, and the inequality holds trivially). On the other hand,

$$x \;\in\; S\backslash A^\varepsilon \quad\Longleftrightarrow\quad \varepsilon \;\leq\; \rho(x,A) \quad\Longleftrightarrow\quad 1 - \frac{\rho(x,A)}{\varepsilon} \;\leq\; 0 \quad\Longrightarrow\quad f(x) \;=\; 0.$$

This proves $f(x) = 0 \leq I_{A^\varepsilon}(x)$, for each $x \in S\backslash A^\varepsilon$, and hence for each $x \in S$ (since $I_{A^\varepsilon}(x) = 1$ for each $x \in A^\varepsilon$ and the inequality holds trivially). This completes the proof of (ii).

□

Lemma A.3
Let $(\,\Omega, \mathcal{A}, P\,)$ be any probability space. Then, for each $p > 0$ and for each non-negative random variable (i.e. measurable function) $f : \Omega \longrightarrow [0,\infty)$, we have:

$$E[\,f^p\,] \;=\; p\int_0^\infty P(\,f > t\,)\cdot t^{p-1}\,\mathrm{d}t \;=\; p\int_0^\infty P(\,f \geq t\,)\cdot t^{p-1}\,\mathrm{d}t\,.$$

PROOF

We first prove the first equality:

$$\begin{aligned}
E[\,f^p\,] \;&:=\; \int_\Omega f(\omega)^p\,\mathrm{d}P(\omega) \;=\; \int_\Omega \left[\,\int_0^{f(\omega)^p} 1\,\mathrm{d}s\,\right]\mathrm{d}P(\omega) \;=\; \int_\Omega \left[\,\int_0^\infty 1_{\{\,0\,\leq\, s\,<\, f(\omega)^p\,\}}\,\mathrm{d}s\,\right]\mathrm{d}P(\omega) \\
&=\; \int_\Omega \left[\,\int_0^\infty 1_{\left\{\,0\,\leq\, s^{1/p}\,<\, f(\omega)\,\right\}}\,\mathrm{d}s\,\right]\mathrm{d}P(\omega) \;=\; \int_\Omega \left[\,\int_0^\infty 1_{\{\,0\,\leq\, t\,<\, f(\omega)\,\}}\cdot p\cdot t^{p-1}\,\mathrm{d}t\,\right]\mathrm{d}P(\omega) \\
&=\; \int_0^\infty \left[\,\int_\Omega 1_{\{\,0\,\leq\, t\,<\, f(\omega)\,\}}\cdot p\cdot t^{p-1}\,\mathrm{d}P(\omega)\,\right]\mathrm{d}t \;=\; p\cdot\int_0^\infty \left[\,\int_\Omega 1_{\{\,0\,\leq\, t\,<\, f(\omega)\,\}}\,\mathrm{d}P(\omega)\,\right]\cdot t^{p-1}\,\mathrm{d}t \\
&=\; p\cdot\int_0^\infty P(\,f > t\,)\cdot t^{p-1}\,\mathrm{d}t.
\end{aligned}$$

The proof of the second inequality is analogous. □

References

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