Lecture 3: Dynkin's π-λ Theorem and Borel σ-fields

Thm (Dynkins' π-λ)

$\mathcal{P}$ is a π-system $\Longrightarrow \lambda\langle\mathcal{P}\rangle = \sigma\langle\mathcal{P}\rangle$.

Remark:
The most important use of Dynkin's thm is in the proof that probability measures are characterized by their values on a π-system of generators.

For example, in undergrad probability we tell students that the CDF characterizes probability distributions ... so if P & Q are probabilities on $((0,1], \mathcal{B}^{(0,1]})$ then $P = Q$ if

$$P((0,x]) = Q((0,x]) \quad \forall x \in (0,1].$$

This follows since (by a HWK)

$$\mathcal{B}^{(0,1]} = \sigma\langle\mathcal{P}\rangle$$

where $\mathcal{P} = \{(0,x] : 0 < x \le 1\}$ is a π-system.

Remark: Dynkin's π-λ thm also allows us to extend the "good sets" technique

i.e. $\mathcal{P} \subset \mathcal{G} \Longrightarrow \lambda\langle\mathcal{P}\rangle \subset \mathcal{G} \Longrightarrow \sigma\langle\mathcal{P}\rangle \subseteq \mathcal{G}$

a π-system a λ-system

since these are equal.

Remark: The proof of Dynkin's π-λ thm is an excellent example of using the "good sets" technique.

Proof of Dynkin's π-λ Thm:

show $\lambda\langle\mathcal{P}\rangle \subset \sigma\langle\mathcal{P}\rangle$: Follows immediatly by good sets.

$\therefore$ just show $\sigma\langle\mathcal{P}\rangle \subset \lambda\langle\mathcal{P}\rangle$

$\therefore$ just show $\lambda\langle\mathcal{P}\rangle$ is a σ-field (by good sets)

$\therefore$ just show $\lambda\langle\mathcal{P}\rangle$ is closed under "$\cap$" (by $\sigma = \lambda + \pi$)

$\therefore$ just show $A, B \in \lambda\langle\mathcal{P}\rangle \Longrightarrow A \cap B \in \lambda\langle\mathcal{P}\rangle$

For $A \in \lambda\langle\mathcal{P}\rangle$ let

$$\boxed{\mathcal{G}_A := \{B : A \cap B \in \lambda\langle\mathcal{P}\rangle\}.} \quad (*)$$

$\therefore$ just show $A \in \lambda\langle\mathcal{P}\rangle \Longrightarrow \lambda\langle\mathcal{P}\rangle \subset \mathcal{G}_A$

$\therefore$ just show $\boxed{\begin{array}{l}\mathcal{P} \subset \mathcal{G}_A \\ \mathcal{G}_A \text{ is a } \lambda\text{-sys}\end{array}}$ for all $A \in \lambda\langle\mathcal{P}\rangle$ $(**)$

which is sufficient by "good sets".

We will show $(**)$ first under the case $A \in \mathcal{P}$.

However first Notice

$$\boxed{B \in \mathcal{G}_A \iff A \cap B \in \lambda\langle\mathcal{P}\rangle \iff A \in \mathcal{G}_B} \quad (***)$$

Show $(**)$ when $A \in \mathcal{P}$:

- $\mathcal{P} \subset \mathcal{G}_A$ since

  $B \in \mathcal{P} \Longrightarrow A \cap B \in \mathcal{P}$, by π-sys.

  $\Longrightarrow B \in \mathcal{G}_A$, by $(*)$

- $\mathcal{G}_A$ is not $\emptyset$ since $A \in \mathcal{G}_A$.
- $\mathcal{G}_A$ is closed under complementation since $B \in \mathcal{G}_A \Rightarrow A \cap B \in \lambda\langle\mathcal{P}\rangle$

  $\Longrightarrow \underbrace{A - A \cap B}_{= A \cap (A \cap B)^c = A \cap B^c} \in \lambda\langle\mathcal{P}\rangle$, nested set subtraction

  $\Longrightarrow B^c \in \lambda\langle\mathcal{P}\rangle$

  $\Longrightarrow B^c \in \mathcal{G}_A$

- $\mathcal{G}_A$ is closed under countable disjoint union since

$$\underbrace{B_1, B_2, \ldots}_{\text{disjoint}} \in \mathcal{G}_A \Rightarrow A \cap \underbrace{\bigcup_{k=1}^{\infty} B_k}_{} \in \mathcal{G}_A$$

$$= \bigcup_{k=1}^{\infty} (B_k \cap A) \text{ where}$$

$B_k \cap A$ are disjoint members of $\mathcal{G}_A$

Show (**) for general $A \in \lambda\langle \mathcal{P} \rangle$

- $\mathcal{P} \subset \mathcal{G}_A$ since

$$B \in \mathcal{P} \Rightarrow A \in \mathcal{G}_B, \text{ since (**) holds over } \mathcal{P}$$

$$\Leftrightarrow B \in \mathcal{G}_A$$

- The proof that $\mathcal{G}_A$ is a λ-sys is exactly similar as previous case.

QED

The following thm is similar to Dynkin's π-λ but for fields & monotonic classes.

Thm (Halmos's monotone class thm)

$$\mathcal{F} \text{ is a field} \Rightarrow \mathcal{M}\langle \mathcal{F} \rangle = \sigma\langle \mathcal{F} \rangle$$

Proof: exercise

Remark: This thm is used when extending a prob P on a field $\mathcal{F}$ to $\sigma\langle \mathcal{F} \rangle$ by adding monotonic limits to $\mathcal{F}$ & defining the extension to P with limits.

Borel σ-fields

Def:

If Ω is a metric space with distance $d: \Omega \times \Omega \to [0, \infty]$ then

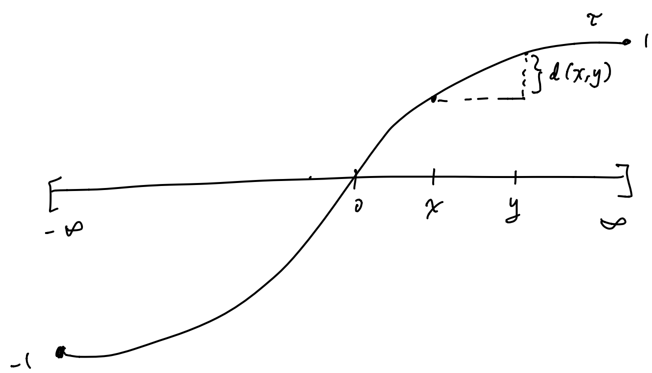
$$\mathcal{B}^{\Omega} := \underbrace{\text{Borel } \sigma\text{-field}}_{\text{w.r.t } d} := \sigma\langle \underbrace{\text{open subsets of } \Omega}_{\text{w.r.t } d} \rangle.$$

This defines $\mathcal{B}^{\mathbb{R}}, \mathcal{B}^{\mathbb{R}^d}, \mathcal{B}^{\bar{\mathbb{R}}}, \mathcal{B}^{\bar{\mathbb{R}}^d}$ etc ...

where $\bar{\mathbb{R}} := \mathbb{R} \cup \{-\infty, \infty\}$ uses metric

$$d(x,y) = |\tau(x) - \tau(y)|$$

$$\tau(x) := \begin{cases} \frac{x}{1+|x|} & \text{for } |x| < \infty \\ -1 & \text{for } x = -\infty \\ 1 & \text{for } x = \infty \end{cases}$$



Remark: Even though $\mathcal{B}^{\Omega} = \sigma\langle \text{open sets} \rangle$ there exists other generators exist & are useful for different purposes.

e.g. The FAP $([0,1], \mathcal{B}_0^{[0,1]}, P)$ from first lecture will be extended to $([0,1], \mathcal{B}^{[0,1]}, P)$ using $\mathcal{B}^{[0,1]} = \sigma\langle \mathcal{B}_0^{[0,1]} \rangle$ ... which will give Lebesgue measure on $[0,1]$.

e.g. we discussed $\mathcal{B}^{[0,1]} = \sigma\langle (0,x] : 0 \le x \le 1 \rangle$ is useful for proving two prob measures on $[0,1]$ are equal

Remark: It is good practice to prove a few equivalent generators for Borel σ-fields. This is typically done with "good sets" i.e.

$$\sigma\langle \mathcal{E}_1 \rangle \subset \sigma\langle \mathcal{E}_2 \rangle \text{ follows by } \mathcal{E}_1 \subset \sigma\langle \mathcal{E}_2 \rangle$$

Most are easy ... but a few can be slightly subtle:

$$\mathcal{B}^{\bar{\mathbb{R}}} = \sigma\langle [-\infty, a] : a \in \mathbb{R} \rangle$$
$$= \sigma\langle [-\infty, a) : a \in \mathbb{R} \rangle$$
$$\neq \sigma\langle (-\infty, a) : a \in \mathbb{R} \rangle$$

Remark: The Lebesgue σ-field of $\mathbb{R}$ extends $\mathcal{B}^{\mathbb{R}}$ by adding sets with "outer measure 0."

Thm: Suppose Ω is a metric space.

(i) $\Omega_0 \subset \Omega \Longrightarrow \underbrace{\mathcal{B}^{\Omega_0}}_{\text{w.r.t the induced metric on } \Omega_0} = \mathcal{B}^{\Omega} \cap \Omega_0$

(ii) $\Omega_0 \subset \Omega$ & $\Omega_0 \in \mathcal{B}^{\Omega}$
$$\Longrightarrow \mathcal{B}^{\Omega_0} = \{B : B \in \mathcal{B}^{\Omega} \text{ \& } B \subset \Omega_0\}$$

Proof: see notes.

Thm: If Ω is a separable metric space then $\mathcal{B}^{\Omega} = \sigma\langle \text{open balls in } \Omega \rangle$.

Proof: exercise