Solutions

Chapter 2 Foundations of Probability

2.1 Since g is $\mathcal{G}/\mathcal{H}$-measurable, therefore $\forall C \in \mathcal{H}$, $\exists B = g^{-1}(C) \in \mathcal{G}$. Similarly, since f is $\mathcal{F}/\mathcal{G}$-measurable, $\forall B \in \mathcal{G}$, $\exists A = f^{-1}(B) \in \mathcal{F}$. Thus $\forall C \in \mathcal{H}$, $\exists A = f^{-1}(g^{-1}(C)) = (g \circ f)^{-1}(C) \in \mathcal{F}$ and the proof is complete.

2.2 We claim that $X = (X_1, X_2, ..., X_n)$ is $\mathcal{F}/\mathcal{B}(\mathbb{R}^n)$ measurable. Define $a = (a_1, a_2, ..., a_n)$ $b = (b_1, b_2, ..., b_n)$ with $a, b \in \mathbb{R}^n$ where $a < b$. Since $X_1, X_2, ..., X_n$ is $\mathcal{F}/\mathcal{B}(\mathbb{R})$ measurable, therefore $\exists A_1 = X_1^{-1}((a_1, b_1)), A_2 = X_2^{-1}((a_2, b_2)), ..., A_n = X_n^{-1}((a_n, b_n)) \in \mathcal{F}$. Let $A = A_1 \cap A_2 \cap ... \cap A_n = \bigcap_{i=1}^{n} A_i$. It follows that $X^{-1}((a, b)) = \bigcap_{i=1}^{n}((a, b)) = A \in \mathcal{F}$. Therefore X is $\mathcal{F}/\mathcal{B}(\mathbb{R}^n)$ measurable and X is random vector.

2.3

(i) We need to show that Σ_X is closed under countable union. Let $U_i = X^{-1}(A_i), A_i \in \Sigma, i \in \mathbb{N}$. It follows that $\bigcup_{i=1}^{\infty} U_i = \bigcup_{i=1}^{\infty} X^{-1}(A_i) = X^{-1}(\bigcup_{i=1}^{\infty} A_i)$. Since $\bigcup_{i=1}^{\infty} A_i \in \Sigma(\Sigma$ is sigma algebra), $\bigcup_{i=1}^{\infty} U_i \in \Sigma_X$.

(ii) We need to show that Σ_X is closed under set subtraction $-$. $\forall U_1, U_2 \in \Sigma_X, U_1 - U_2 = X^{-1}(A_1) - X^{-1}(A_2) = X^{-1}(A_1 - A_2)$. Since $A_1 - A_2 \in \Sigma(Sigma$ is sigma algebra),$U_1 - U_2 \in \Sigma_X$.

(iii) We need to show that Σ_X is closed to $\mathcal{U}$ itself. Since $\mathcal{U} = X^{-1}(\mathcal{V})$ and $\mathcal{V} \in \Sigma$, it follows that $\mathcal{U} \in \Sigma_X$.

2.4

(a)
  (i) We need to show that $\mathcal{F}|_A$ is closed under countable union. Let $X_1 = A \cap B_1, X_2 = A \cap B_2, ...$ and $X' = \bigcup_{i=1}^{\infty} X_i$ and $B' = \bigcup_{i=1}^{\infty}$ where $B_1, B_2, ... \in \mathcal{F}$. Since $\mathcal{F}$ is sigma algebra, $B' \in \mathcal{F}$. Furthermore, since $X' = \bigcup_{i=1}^{\infty} X_i = \bigcup_{i=1}^{\infty} A \bigcap B_i = A \bigcap \left(\bigcup_{i=1}^{\infty}\right) = A \bigcap B'$, we can see that $X' \in \mathcal{F}|_A$.

  (ii) We need to show that $\mathcal{F}|_A$ is closed under set subtraction $-$. $\forall X_1, X_2 \in \mathcal{F}|_A$, $X_1 - X_2 = (A \bigcap B_1) - (A \bigcap B_2) = A \bigcap (B_1 - B_2)$. Since $B_1 - B_2 \in \mathcal{F}(F$ is sigma algebra), it follows that $X_1 - X_2 \in \mathcal{F}|_A$.

  (iii) We need to show that Σ_X is closed to A itself. Since $\varnothing \in \mathcal{F}$, we have $\varnothing = A \bigcap \varnothing \in \mathcal{F}|_A$ and $A = \varnothing^C \in \mathcal{F}|_A$.

(b) Let $P = \{A \bigcap B : B \in \mathcal{F}\}, Q = \{B : B \subset A, B \in \mathcal{F}\}$.

  (i) We claim that $P \subset Q$. Let $X = A \bigcap B, B \in \mathcal{F}$. Since $A \in \mathcal{F}$, $X = A \bigcap B \in \mathcal{F}$. Furthermore, $X \in Q = \{B : B \subset A, B \in \mathcal{F}\}$.

  (ii) We claim that $Q \subset P$. $\forall X \in Q$, we have $X \subset A$ and $X \in \mathcal{F}$, which means that $X = X \bigcap A$ and $X \in \mathcal{F}$. It follows that $X \in P$.

  (iii) Take both (i)(ii) into consideration, we can see that $P = Q$.

2.5

(a) Clearly $\sigma(\mathcal{G})$ should be the intersection of all σ-algebras that contain $\mathcal{G}$. Formally speaking, let $\mathcal{K} = \{\mathcal{F} | \mathcal{F} \text{ is a } \sigma\text{-algebra and contains } \mathcal{G}\}$. Then $\bigcap_{\mathcal{F}\in\mathcal{K}} \mathcal{F}$ contains exactly those sets that are in every σ-algebra that contains $\mathcal{G}$. Given its existence, we only need to prove that $\bigcap_{\mathcal{F}\in\mathcal{K}} \mathcal{F}$ is the smallest σ-algebra that contains $\mathcal{G}$.

First we show $\bigcap_{\mathcal{F}\in\mathcal{K}} \mathcal{F}$ is a σ-algebra. Since $\mathcal{F}$ is a σ-algebra and therefore $\Omega \in \mathcal{F}$ for all $\mathcal{F} \in \mathcal{K}$, it follows that $\Omega \in \bigcap_{\mathcal{F}\in\mathcal{K}} \mathcal{F}$. Next, for any $A \in \bigcap_{\mathcal{F}\in\mathcal{K}} \mathcal{F}$, $A^c \in \mathcal{F}$ for all $\mathcal{F} \in \mathcal{K}$. Since they are all σ-algebras, $A^c \in \mathcal{F}$ for all $\mathcal{F} \in \mathcal{K}$. Hence $A^c \in \bigcap_{\mathcal{F}\in\mathcal{K}} \mathcal{F}$. Finally, for any $\{A_i\}_i \subset \bigcap_{\mathcal{F}\in\mathcal{K}} \mathcal{F}$, $\{A_i\}_i \subset \mathcal{F}$ for all $\mathcal{F} \in \mathcal{K}$. Since they are all σ-algebras, $\bigcup_i A_i \in \mathcal{F}$ for all $\mathcal{F} \in \mathcal{K}$. Hence $\bigcup_i A_i \in \bigcap_{\mathcal{F}\in\mathcal{K}} \mathcal{F}$.

It is quite obvious that $\bigcap_{\mathcal{F}\in\mathcal{K}} \mathcal{F}$ is the smallest one as $\bigcap_{\mathcal{F}\in\mathcal{K}} \mathcal{F} \subseteq \mathcal{F}'$ for all $\mathcal{F}' \in \mathcal{K}$.

(b) We first introduce a useful lemma: the map X is $\mathcal{F}/\mathcal{G}$-measurable if and only $\sigma(X) \subseteq \mathcal{F}$, where $\sigma(X) = \{X^{-1}(A) : A \in \mathcal{G}\}$ is the σ-algebra generated by X. With this lemma, the main idea to prove X is $\mathcal{F}/\sigma(\mathcal{G})$-measurable is to show that $\sigma(X) = \{X^{-1}(A) : A \in \sigma(\mathcal{G})\} \subseteq \mathcal{F}$.

Let $X^{-1}(\mathcal{G}) = \{X^{-1}(A) : A \in \mathcal{G}\}$. Clearly we have $X^{-1}(\mathcal{G}) \subseteq \mathcal{F}$. $\sigma(X^{-1}(\mathcal{G}))$ is the smallest σ-algebra that contains $X^{-1}(\mathcal{G})$. And we know $\mathcal{F}$ is a σ-algebra that contains $X^{-1}(\mathcal{G})$. According to the result of the previous question, $\sigma(X^{-1}(\mathcal{G})) \subseteq \mathcal{F}$. Furthermore, $\sigma(X^{-1}(\mathcal{G})) = X^{-1}(\sigma(\mathcal{G})) = \{X^{-1}(A) : A \in \sigma(\mathcal{G})\} = \sigma(X)$. Hence $\sigma(X) \subseteq \mathcal{F}$.

Readers can further refer to the penultimate paragraph in Page 16, where the author provides a general idea to check whether a map is measurable.

(c) The idea is to show $\forall B \in \mathfrak{B}(\mathbb{R})$, $\mathbb{I}\{A\}^{-1}(B) \in \mathcal{F}$.

If $\{0,1\} \in B$, $\mathbb{I}\{A\}^{-1}(B) = \Omega \in \mathcal{F}$. If $\{0\} \in B$, $\mathbb{I}\{A\}^{-1}(B) = A^c \in \mathcal{F}$. If $\{1\} \in B$, $\mathbb{I}\{A\}^{-1}(B) = A \in \mathcal{F}$. If $\{0,1\} \cap B = \emptyset$, $\mathbb{I}\{A\}^{-1}(B) = \emptyset \in \mathcal{F}$.

2.6 As the hint suggests, Y is not $\sigma(X)$-measurable under such conditions since $Y^{-1}((0,1)) = (0,1) \notin \sigma(X)$, where $\sigma(X) = \{X^{-1}(A) : A \in \mathcal{G}\} = \{\emptyset, \mathbb{R}\}$.

2.7 First we have $\mathbb{P}(\Omega \mid B) = \frac{\mathbb{P}(\Omega\cap B)}{\mathbb{P}(B)} = \frac{\mathbb{P}(B)}{\mathbb{P}(B)} = 1$. Then, for all $A \in \mathcal{F}$, $\mathbb{P}(A \mid B) = \frac{\mathbb{P}(A\cap B)}{\mathbb{P}(B)} \geq 0$. Next, for all $A \in \mathcal{F}$, $\mathbb{P}(A^c \mid B) = \frac{\mathbb{P}(A^c\cap B)}{\mathbb{P}(B)} = \frac{\mathbb{P}((\Omega-A)\cap B)}{\mathbb{P}(B)} = \frac{\mathbb{P}(B)-\mathbb{P}(A\cap B)}{\mathbb{P}(B)} = 1 - \mathbb{P}(A \mid B)$. Finally, for all countable collections of disjoint sets $\{A_i\}_i$ with $A_i \in \mathcal{F}$ for all i, we have $\mathbb{P}\left(\bigcup_i A_i \mid B\right) = \frac{\mathbb{P}((\bigcup_i A_i)\cap B)}{\mathbb{P}(B)} = \frac{\mathbb{P}(\bigcup_i (A_i\cap B))}{\mathbb{P}(B)} = \sum_i \frac{\mathbb{P}(A_i\cap B)}{\mathbb{P}(B)} = \sum_i \mathbb{P}(A_i \mid B)$.

2.8 With the definition of conditional probability, we have $\mathbb{P}(A \mid B) = \frac{\mathbb{P}(A\cap B)}{\mathbb{P}(B)} = \frac{\mathbb{P}(B|A)\mathbb{P}(A)}{\mathbb{P}(B)}$.

2.9

(a)There are 36 possible events

1.$X_1 < 2$,X_2 =even

$$X_1 = 1, X_2 = 2$$

$$X_1 = 1, X_2 = 4$$

$$X_1 = 1, X_2 = 6$$

So P($X_1 < 2$,X_2 =even)= $\frac{3}{36} = \frac{1}{12}$

and $P(X_1 < 2) = \frac{(}{1})(6)$,P($X_2$ =even)= $\frac{1}{2}$

So,P($X_1 < 2$,X_2 =even)= $P(X_1 < 2)*$P(X_2 =even).According to the definition of independent event, two events are independent

(b)Prove$P(A \bigcap B) = P(A)P(B)$

2.10

(a)Empty sets and complete sets are independent of any event

$$P(A \bigcap \Omega) = P(A) = 1 * P(A) = P(\Omega) * P(A)$$

$$P(A \bigcap \phi) = P(\phi) = 0 = P(\phi) * P(A)$$

(b)Prove when$P(A) = 0or1$ A is independent of any event for any$B \in \Omega$
$P(A) \in \{0, 1\}$
When$P(A) = 1$,$P(A^c \bigcap B) \le P(A^c) = 1 - P(A) = 0$,
we have $P(A \bigcap B) = P(A \bigcap B) + P(A^c \bigcap B) = P(B) = P(A)P(B)$
When$P(A) = 0$,we have $P(A \bigcap B) \le P(A) = 0 = P(A)P(B)$
(c)$P(A^c \bigcap A) = P(A)P(A^c)$
we have $0 = P(A)(1 - P(A)) \Rightarrow P(A) \in \{0, 1\}$
(d)$P(A \bigcap A) = P(A)P(A)$, $P(A) = 0, 1$
(e)$\Omega = (1, 1), (1, 0), (0, 1), (0, 0)$
Just verify that each case is independent $P(A = 1, B = 1) = \frac{1}{4} = \frac{1}{2} * \frac{1}{2} = P(A)P(B)$
$P(A = 1, B = 0) = \frac{1}{4} = \frac{1}{2} * \frac{1}{2} = P(A)P(B)$
$P(A = 0, B = 1) = \frac{1}{4} = \frac{1}{2} * \frac{1}{2} = P(A)P(B)$
$P(A = 0, B = 0) = \frac{1}{4} = \frac{1}{2} * \frac{1}{2} = P(A)P(B)$
(f)$P(X_1 \le 2) = 2/3$
$P(X_1 = X_2) = 3/9 = 1/3$
$P(X_1 \le 2, X_1 = X_2) = P(X_1 = X_2 = 1) + P(X_1 = X_2 = 2) = 1/9 + 1/9 = 2/9$
So, $P(X_1 \le 2, X_1 = X_2) = P(X_1 = X_2)P(X_1 \le 2)$
(g)Necessity $\frac{|A \bigcap B|}{n} = P(A \bigcap B) = P(A)P(B) = \frac{|A|}{n}\frac{|B|}{n}$
$\Rightarrow |A \bigcap B| * n = |A||B|$
Sufficiency $|A \bigcap B| * n = |A||B| \Rightarrow \frac{|A|}{n}\frac{|B|}{n} = \frac{|A \bigcap B|}{n}$
$\Rightarrow P(A \bigcap B) = P(A)P(B)$
(h)$|A \bigcap B| * n = |A||B|, \Rightarrow n \le |A| \le n \Rightarrow A \ne \phi or \Omega$
(j)Let's take a counter example: roll a die and set the A event to$\{1, 2, 3\}$,B event is set to$\{1, 2, 4\}$,C event is set to$\{1, 4, 5, 6\}$
$P(X_1 X_2 X_3) = \frac{1}{6}$
$P(X_1)P(X_2)P(X_3) = (1/2) * (1/2) * (2/3) = 1/6$
while$P(X_1 \bigcap X_2) = 1/3 \ne \frac{1}{2} * \frac{1}{2}$

2.11

(a)X:$\Omega \to x$
Because X, Y are independent equivalent to$\sigma(X)$,$\sigma(Y)$ are independent
For any A$\in \sigma(Y)$,

$$P(\phi \bigcap A) = P(\phi) = 0 = P(\phi)P(A)$$

$$P(\Omega \bigcap A) = P(A) = P(\Omega)P(A)$$

(b)We know that $P(X = x) = 1$

$$P(X = x|Y) = \frac{P((X = x) \bigcap Y)}{P(Y)} = 1 = P(X = x)$$

$$P(X \ne x|Y) = 1 - P(X = x|Y) = 0 = P(X \ne x)$$

(c)Notice the relation $P(A) = P(X(A) = 1)$
$P(B) = P(X(B) = 1)$
$P(A \bigcap B) = P(X(A \bigcap B) = 1)$
The first two formulas follow the definition. Let's prove the third equation
$P(X(A \bigcap B) = P(X(A) + X(B) - X(A \bigcup B) = 1)$
Let's discuss$X(A), X(B), X(A \bigcup B)$

X(A)	X(B)	X(A$\bigcup$ B)	$X(A) + X(B) - X(A \bigcup B)$
1	1	1	1
1	0	1	0
0	1	1	0
0	0	0	0

We can see that $P(X(A \bigcap B) = P(X(A) + X(B) - X(A \bigcup B) = 1)$, this is only one case of the first row of the table

that is$P(X(A\bigcap B)=1)=P(X(A)=1,X(B)=1)=P(A\bigcap B)$
that is$P(X(A\bigcap B)=1)=P(A\bigcap B)$
So $P(A\bigcap B)=P(A)P(B)$ is equivalent to $P(X(A\bigcap B)=1)=P(X(A)=1)P(X(B)=1)$
(d)A_i pairwise i $\Leftrightarrow I\{A_i\}$ pairwise i
mutual i $\Leftrightarrow P(\bigcap_i A_i)=\prod_i P(A_i)$
$\Leftrightarrow P(\bigcap_{i\in K^I} A_i \bigcap \bigcap_{i\in K^I} A_i^c)$
$=\prod_{i\in K^I} P(A_i)\prod_{i\in K^I} P(A_i^c)$
$\Leftrightarrow \{\phi,\Omega,A_i,A_i^c\}$ mutual independent
$\Leftrightarrow \sigma(I\{w\in A_i\})$mutual i
$\Leftrightarrow I\{w\in A_i\}$ mutual i

2.12 X integrable $|X|$ integrable
(a)For any $A\in B(R)\Rightarrow$A is open,
so,$f^{-1}(A)$is open so $f^{-1}(A)\in B(R)$
(b)X is known to be a random variable $f(x)=|x|$ continuous
r.v. X is $\mathbf{F}/\mathbf{B}(R)$-measurable
$\Rightarrow |X|$ is $\mathbf{B}(R)/\mathbf{B}(R)$-measurable
$\Rightarrow |X|$ is $\mathbf{F}/\mathbf{B}(R)$-measurable
$\Rightarrow |X|$ is r.v.
From (a)(b) X integrable $\Leftrightarrow |X|$ integrable.