Problem 2

Let $\{U_i\}_{i\in I}$ be an open cover of $[a,b]$. Since the open intervals are a base for τ_{st} on $\mathbb{R}$, we may assume that all the U_i are open intervals. There are then $U_1, U_2 \subseteq \mathbb{R}$ open such that $a \in U_1$ and $b \in U_2$.

Let $c_1 = \sup(U_1 \cap [a,b])$ and $d_1 = \inf(U_2 \cap [a,b])$. If $c_1 < d_1$, we may apply a similar procedure to the case of $[c_1, d_1] \subseteq [a,b]$, choosing U_3, U_4 such that $c_2 \in U_3 \cap [c_1, d_1]$ and $d_2 \in U_4 \cap [c_1, d_1]$, and so on and so forth. We claim that this process must stop eventually.

If this process were not to stop, we then have a collection of nested closed intervals

$$[a,b] \supseteq [c_1, d_1] \supseteq [c_2, d_2] \supseteq \cdots,$$

so by the nested intervals property, there would be some $x \in [a,b]$ such that $x \in [a,b] \cap \bigcap_{i=1}^{\infty}[c_i, d_i]$. This x is necessarily not covered by any such $U_i \in \{U_i\}_{i\in I}$, contradicting the assumption that $\{U_i\}_{i\in I}$ is an open cover of $[a,b]$.

Problem 17

Write

$$\sum_{i=1}^{m} |x_i + y_i|^p = \sum_{i=1}^{m} |x_i||x_i + y_i|^{p-1} + |y_i||x_i + y_i|^{p-1}.$$

Then, by applying Hölder's Inequality, we have

$$\begin{aligned}
\sum_{i=1}^{m} |x_i||x_i + y_i|^{p-1} &\leqslant \left(\sum_{i=1}^{m} |x_i|^p\right)^{1/p} \left(\sum_{i=1}^{m} |x_i + y_i|^{(p-1)q}\right)^{q}\\
\sum_{i=1}^{m} |y_i||x_i + y_i|^{p-1} &\leqslant \left(\sum_{i=1}^{m} |y_i|^p\right)^{1/p} \left(\sum_{i=1}^{m} |x_i + y_i|^{(p-1)q}\right)^{q}.
\end{aligned}$$

Since $(p-1)q = p$, we then have

$$\sum_{i=1}^{m} |x_i + y_i|^p \leqslant \left(\sum_{i=1}^{m} |x_i + y_i|^p\right)^{q} \left(\left(\sum_{i=1}^{m} |x_i|^p\right)^{1/p} + \left(\sum_{i=1}^{m} |y_i|^p\right)^{1/p}\right),$$

and dividing, we get

$$\left(\sum_{i=1}^{m} |x_i + y_i|^p\right)^{1/p} \leqslant \left(\sum_{i=1}^{m} |x_i|^p\right)^{1/p} + \left(\sum_{i=1}^{m} |y_i|^p\right)^{1/p}.$$

Problem 19

(i) We see that

$$\sup_{i\in\mathbb{N}} |x_i| = 0$$

if and only if $|x_i| \leqslant 0$ for all i, meaning that $(x_i)_i$ is the zero sequence. Similarly,

$$\|\alpha x\| = \sup_{i\in\mathbb{N}} |\alpha x_i|$$

$$
\begin{aligned}
&= |\alpha| \sup_{i \in I} |x_i| \\
&= |\alpha| \|x\|.
\end{aligned}
$$

Finally,

$$
\begin{aligned}
\|x + y\| &= \sup_{i \in \mathbb{N}} |x_i + y_i| \\
&\leqslant \sup_{i \in \mathbb{N}} (|x_i| + |y_i|) \\
&\leqslant \sup_{i \in \mathbb{N}} |x_i| + \sup_{j \in \mathbb{N}} |y_j| \\
&= \|x\| + \|y\|,
\end{aligned}
$$

meaning that $\|\cdot\|$ is a bona fide norm.

(ii) Let $B = \{x \in X \mid \|x\| \leqslant 1\}$. Let $(x_n)_n \subseteq B$ converge to $x \in \ell_\infty$ in the ℓ_∞ norm.

Note that for all n, $\sup_{i \in \mathbb{N}} |x_n(i)| \leqslant 1$, meaning that since

$$
\sup_{i \in \mathbb{N}} |x(i) - x_n(i)| \to 0,
$$

we have that

$$
|x(i) - x_n(i)| \to 0
$$

for each i, so

$$
x_n(i) \to x(i)
$$

for all i. Thus, $|x(i)| \leqslant 1$ for all i, meaning $\sup_{i \in \mathbb{N}} |x(i)| \leqslant 1$, so $\|x\| \in B$.

(iii) Let $\varepsilon = 1/2$, and consider the collection $(e_n)_n$ of sequences in ℓ_∞ consisting of 1 at position n and zero elsewhere. Then, $(e_n)_n \subseteq B$, but since $\sup_{i \in \mathbb{N}} |e_n(i) - e_m(i)| = 1$ for all $n \neq m$, we cannot have balls of radius $1/2$ cover the family $(e_n)_n$ with finitely many such balls, meaning that B is not totally bounded.

Problem 20

(i) We see that $d(x, y) = 0$ if and only if $x_n = y_n$ for each n, since each d_n is a metric; therefore, $d(x, y) = 0$ if and only if $x = y$.

Furthermore, we have that for all $x = (x_n)_n$, $y = (y_n)_n$, and $z = (z_n)_n$, $\frac{1}{2^n} d(x_n, z_n) \leqslant \frac{1}{2^n} d(x_n, y_n) + \frac{1}{2^n} d(y_n, z_n)$. Therefore, we get

$$
\begin{aligned}
d(x, z) &= \sum_{n=1}^{\infty} \frac{1}{2^n} d(x_n, z_n) \\
&\leqslant \sum_{n=1}^{\infty} \frac{1}{2^n} d(x_n, y_n) + \frac{1}{2^n} d(y_n, z_n) \\
&\leqslant d(x, y) + d(y, z).
\end{aligned}
$$

Since $d(x_n, y_n), d(y_n, z_n) \leqslant 1$, these sums must converge, so $d(x, y)$ is indeed a metric.

(ii) We will show that a sequence $(y_n)_n \subseteq X$ converges to $y \in X$ with the given distance metric if and only if it does so pointwise. This will show that the metric d induces the topology of pointwise convergence, which is exactly the topology τ_{prod}.[I]

To start, let $(y_n)_n \to y$ in the given distance metric. Then, for all $\varepsilon > 0$, there is some $N \in \mathbb{N}$ such that for all $n \geqslant N$, we have

$$\begin{aligned} d(y_n, y) &= \sum_{j=1}^{\infty} \frac{1}{2^j} d_j(y_n(j), y(j)) \\ &< \varepsilon, \end{aligned}$$

so we see that for each j, $d(y_n(j), y(j)) < \varepsilon$, meaning that $y_n(j) \to y(j)$ for each j.

Let $(y_n)_n \to y$ pointwise. If $\varepsilon > 0$, convergence of series gives some J such that $\sum_{j=J+1}^{\infty} \frac{1}{2^j} < \varepsilon/2$, meaning that

$$\sum_{j=J+1}^{\infty} \frac{1}{2^j} d_j(y_n(j), y(j)) < \varepsilon/2$$

For $j = 1, \dots, J$, we find $N_1, \dots, N_J$ such that for all $n \geqslant N_j$, $d_j(y_n(j), y(j)) < \varepsilon/2$. Therefore, for $n \geqslant \max(N_1, \dots, N_J)$, we have

$$\begin{aligned} d(y_n, y) &= \sum_{j=1}^{\infty} \frac{1}{2^j} d_j(y_n(j), y(j)) \\ &= \sum_{j=1}^{J} \frac{1}{2^j} d_j(y_n(j), y(j)) + \sum_{j=J+1}^{\infty} \frac{1}{2^j} d_j(y_n(j), y(j)) \\ &< \sum_{j=1}^{J} \frac{\varepsilon}{2^{j+1}} + \frac{\varepsilon}{2} \\ &< \frac{\varepsilon}{2} + \frac{\varepsilon}{2} \\ &= \varepsilon. \end{aligned}$$

Therefore, $(y_n)_n \to y$ in our given distance metric.

Since convergence of sequences in our given distance metric is given by pointwise convergence, the induced topologies must be equal, so $\tau_d = \tau_{\text{prod}}$.

(iii) We prove that X is complete if and only if X_n is complete for all n.

To see this, note that $(y_n)_n \subseteq X$ is Cauchy if and only if $(y_n(j))_n \subseteq X_j$ is Cauchy for each j, as for all $\varepsilon > 0$ and $m, n \geqslant N$ with $d(y_n, y_m) < \varepsilon$, then

$$\sum_{j=1}^{\infty} \frac{1}{2^j} d_j(y_n(j), y_m(j)) < \varepsilon,$$

meaning this holds for all j, and in the reverse direction, we use the same $\frac{\varepsilon}{2}$ method from part (ii).

The sequence $(y_n)_n$ thus converges in X if and only if every $y_n(j)$ converges in X_j (as τ_d is the topology of pointwise convergence), meaning that X is complete if and only if each X_j is complete.

[I] Technically we need to show this for all *nets* in X rather than sequences, but since all nets are sequences as X has been established to be a metric space, this is sufficient.

Problem 21

Let X be complete, and let $(C_n)_n \subseteq P(X)$ be nonempty, decreasing, closed sets with $\operatorname{diam}(C_n) \to 0$.

Let $(x_n)_n$ be defined by $x_n \in C_n$ for each n. Then, for any $\varepsilon > 0$, we may find C_N such that $\operatorname{diam}(C_N) < \varepsilon$, meaning that for all $n, m \geqslant N$, we have that $x_n, x_m \in C_N$, so $d(x_n, x_m) < \varepsilon$, meaning that $(x_n)_n$ is Cauchy. Since X is complete, $(x_n)_n \to x$ for some $x \in X$. This point must be in all such C_n, meaning that

$$\bigcap_{n=1}^{\infty} C_n = \{x\}.$$

Now, let X be a metric space such that for any $(C_n)_n \subseteq P(X)$ nonempty, decreasing, and closed with $\operatorname{diam}(C_n) \to 0$, there is some $x \in X$ with $\bigcap_{n=1}^{\infty} C_n = \{x\}$. Let $(x_n)_n$ be a Cauchy sequence in X.

Define a family of closed sets by

$$C_n = \overline{\{x_n, x_{n+1}, \dots\}}.$$

We note the following:

- each of the C_n is closed;
- $C_n \supseteq C_{n+1}$ by construction, since $\{x_n, x_{n+1}, \dots\} \supseteq \{x_{n+1}, x_{n+2}, \dots\}$, and closures respect set inclusion;
- $\operatorname{diam}(C_n) \to 0$, as $(x_n)_n$ is Cauchy, so if $\varepsilon > 0$, there is some N such that for all $n, m \geqslant N$, $d(x_n, x_m) < \varepsilon$, meaning that the diameter of the closure of the set $\{x_N, x_{N+1}, \dots\}$ is no more than ε.

Therefore, there is some $x \in X$ such that

$$\bigcap_{n=1}^{\infty} C_n = \{x\},$$

meaning that $(x_n)_n \to x$, and X is complete.