Collection of Problems

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Problem 1. (Analysis) If for a function $f:\mathbb{R}\to\mathbb{R}$ image of each compact set is compact then f is continous. T/F.

Solution. No, we can take the function

$$f=\begin{cases} sin(\frac{1}{x}) \text{ if } x\neq 0,\\ 0 \text{ else.}\end{cases}$$

This function is discontinous at 0. □

Problem 2. Existence of the limit $\lim_{n\to\infty}\frac{1}{1}+\frac{1}{2}+\cdots+\frac{1}{n}-\log n$.

Solution. Let $x_n=\frac{1}{1}+\frac{1}{2}+\cdots+\frac{1}{n}-log n$. Then $x_{n+1}-x_n=\frac{1}{n+1}-log(\frac{n+1}{n})$. But $log(1+x)\geq\frac{x}{x+1}$. Thus the sequence is decreasing and we can show(!) that it is bounded below. □

Problem 3. What is the smallest positive real numer c such that $||x||_1\leq c||x||_\infty$ for all $x\in\mathbb{R}^n$.

Solution. Clearly $||x||_1\leq n||x||_\infty$. Now, we claim that $c=n$. Let if possible $||x||_1\leq(n-\epsilon)||x||_\infty$ for some $\epsilon>0$, for all $x\in\mathbb{R}^n$. But for $x=(1,1,\ldots,1)$ we will have $||x||_1=n, ||x||_\infty=1$ and hence $||x||>||x||_\infty$. □

Problem 4. If a group is finitely generated then there exist atmost finitely many subgroup of any index.

Solution. Let us consider G be the group and H be its subgroup such that $[G:H]=n$. The group acts on the cosets $\{H,g_2H,\ldots,g_nH\}=\{1,2,3,\ldots,n\}$ and it induces a homomorphism

$$\varphi_H:G\longrightarrow S_n \text{ such that } g\mapsto_{\varphi_H}\sigma_g.$$

Now the stabilizer of the element H in G/H can be identified as $\{g\in G\mid\sigma_g=1\}$ i.e., $\{g\in G\mid gg_iH=g_iH, 1\leq i\leq n\}$ i.e., H. We claim that different subgroups H and H' will induce different maps. For $h\in H, h\notin H'$ we have $\varphi_H(h)=1$ but $\varphi_{H'}(h)\neq 1$. Again there are atmost finitely many maps from G to S_n and hence as a result there can exist only finite many subgroups of index n. □

Problem 5. For primes $p>q>2$, group of order pq^2 contains a subgroup of ordre pq.

Solution. The number of sylow p subgroup n_p divides q^2 as well as $p\mid n_p-1$. Now n_p is odd if it is equal to q or q^2. Since p is also an odd prime we can not have $p\mid n_p-1$ in this case. Thus we must have $n_p=1$ i.e., the sylow$-p$ subgroup, H in G is normal and has order p. Now by Cauchy's theorem there exists $b\in G$ of order q. Let $K=<b>$. Then HK is the desired subgroup of G. □

Problem 6. SL_n is a product of matrices of the form $E_{ij}(a) = I + a\delta_{ij}, 1 \le i \neq j \le n$.

Solution. Clearly $E_{ij}(a) \in SL_n$ and

$$\delta_{ij}\delta_{kl} = \begin{cases} \delta_{il} & \text{if } j = k, \\ 0 & \text{else.} \end{cases}$$

implies

$$\begin{aligned} E_{ij}(a)E_{ij}(-a) &= (I + a\delta_{ij})(I - a\delta_{ij}) \\ &= I - a^2\delta_{ij}\delta_{ij} \\ &= I. \end{aligned}$$

For $A \in SL_n$, since not all entries in the first column can be zero we must have $a_{i1} \neq 0$ and $E_{1i}(1)A = (I + \delta_{1i})A = A+$ □

Problem 7. X be a compact metric space with atleast two points and $a \in X$. Then

1. either $X \setminus \{a\}$ is compact or X is connected,
2. but not both.

Solution.

1. Let us assume that $A = X \setminus \{a\}$ is not compact then we know A is not closed.
2. Let us assume that X is connected and if possible $X \setminus \{a\}$ is compact. Then $X \setminus \{a\}$ is closed. Also $\{a\}$ is a closed subset of X. This contradicts that $X = (X \setminus \{a\}) \cup \{a\}$ is connected.

   Conversely if $A = X \setminus \{a\}$ is compact then it will be closed in X and we will have $X = A \cup B$, for $B = \{a\}$. Thus X is not connected.

□

Problem 8. $GL_n^+(\mathbb{R})$ and $GL_n^-(\mathbb{R})$ are homeomorphic.

Solution. We can define $\psi : GL_n^+(\mathbb{R}) \to GL_n^-(\mathbb{R})$ such that $\psi(M) = AM$, where A is a diagonal matrix such that $a_{11} = -1$ and $a_{ii} = 1$ for $1 < i \le n$. □

Problem 9. Show that the General Linear group with positive determinant, $GL_n^+(\mathbb{R})$ is connected.

Solution. We know that $GL_n^+(\mathbb{R}) = \det^{-1}((0,\infty))$ and hence it is open. If we can show that this there is some kind of homeomorphism we are through. □

Problem 10. (Matrix, Topology) Show that $SL_2(\mathbb{R})$ is connected.

Solution. Here we will use the fact that the General Linear group with positive determinant, $GL_n^+(\mathbb{R})$ is path connected. With the help of this fact we can define a continous map

$$\phi : GL_n^+(\mathbb{R}) \to SL_n(\mathbb{R})$$

such that

$$\phi(A) = \frac{A}{(\det(A))^{\frac{1}{n}}}.$$

Clearly this is a surjection and hence $SL_n(\mathbb{R})$ is connected. $\square$

Problem 11. $f : \mathbb{R} \to \mathbb{R}$ is continous. Then show that f is open iff it is strictly monotone.

Solution. Let us assume that f is open and if possible there exist $a < b < c$ such that $f(a) < f(b) > f(c)$. Now if we restrict f to the interval $[a, c]$, then its supremum, M will exist and M will strictly be greater than $f(a), f(c)$ i.e., $f([a, c]) = [m, M]$. Therefore $f((a, c))$ will be a half closed interval i.e., either $f((a, c)) = [m, M]$ or $f((a, c)) = (m.M])$, contradicting our assumption that the map f is open.

Conversely WLOG let us assume that f is strictly increasing. It is sufficient to show that f maps open intetrval to open sets. Now, f being continous and strictly increasing implies $f((a, b)) = (f(a), f(b))$. $\square$