

Normal Families and the Riemann Mapping theorem

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This note is used to list every theorems in chapter 9 of the book **Complex made simple**.

1 Quasi-metrics

Definition 1. A function $d: X \times X \rightarrow [0, \infty]$ satisfying the condition

- $d(x, x) = 0 (x \in X)$
- $d(x, y) = d(y, x) (x, y \in X)$
- $d(x, z) \leq d(x, y) + d(y, z) (x, y, z)$

then it is called a quasi-metric on space X . We can see that d is almost the same as a metric except that $d(x, y)$ can be zero for distinct x, y .

One can construct a metric \bar{d} from quasi-metric d , noting that d is an equivalence relation on X .

Now we introduction the notion of *concave function*: The function $\psi: I \rightarrow \mathbb{R}$ is said to be *concave* if

$$\psi(tx + (1-t)y) \leq t\psi(x) + (1-t)\psi(y),$$

for all $x, y \in X$ and $0 \leq t \leq 1$. It can be inferred from the definition that ψ is concave iff $-\psi$ is convex. Now we have the following lemma

Lemma 1. Suppose that $\psi: I \rightarrow \mathbb{R}$ is concave and $a_1, a_2, b_1, b_2 \in I$ such that $a_1 < b_1, a_2 < b_2, a_2 \geq a_1, b_2 \geq b_1$. Then

$$\frac{\psi(b_2) - \psi(a_2)}{b_2 - a_2} \leq \frac{\psi(b_1) - \psi(a_1)}{b_1 - a_1}$$

Geometrically speaking, the slope of the segment joining two points on the graph of ψ decreases as the points moves to the right.

Applying this lemma for $a_1 = 0, b_1 = x = a_2, b_2 = x + y$, we get the following result:

Lemma 2. Suppose that $\psi: [0, \infty] \rightarrow \mathbb{R}$ is concave and $\psi(0) = 0$. Then

$$\psi(x + y) \leq \psi(x) + \psi(y),$$

for all $x, y \geq 0$.

Lemma 3. Suppose that $\psi: [0, \infty] \rightarrow \mathbb{R}$ is concave and

$$\psi(0) = 0.$$

Suppose further that ψ is nondecreasing, $\psi(t) > 0$ for $t > 0$ and this function is continuous at 0.

If d is a quasi-metric on X then $\tilde{d} = \psi \circ d$ is also a quasi-metric on X such that

- $\tilde{d}(x, y) = 0$ iff $d(x, y) = 0$.
- $\tilde{d}(x_n, y_n) \rightarrow 0$ iff $d(x_n, y_n) \rightarrow 0$.

Now choosing ψ to be a bounded function, we can further assume that \tilde{d} is bounded. Two traditional choices are:

$$\psi_1(t) = \frac{t}{t+1}$$

and

$$\psi_2(t) = \begin{cases} t & (0 \leq t \leq 1) \\ 1 & (t > 1) \end{cases}$$

One might choose ψ_1 since it is a smooth function, or choose ψ_2 as it is easy to compute. The main reason for choosing a new equivalent bounded quasi-metric is because it is easy to add up. For example, in the next lemma, showing that given a countable family of quasi-metrics (d_j) , there exists a single quasi-metric d such that $d(x_n, y_n) \rightarrow 0$ if and only if $d_j(x_n, y_n) \rightarrow 0$ for every j , begins by converting the original family of quasi-metrics to a family of bounded quasi-metrics.

Lemma 4. Suppose that d_j is a quasi-metric on X for $j = 1, 2, \dots$. Define

$$d(x, y) = \sum_{j=1}^{\infty} 2^{-j} \frac{d_j(x, y)}{1 + d_j(x, y)} \quad (x, y \in X)$$

Then d is a quasi-metric on X with the property that $d(x_n, y_n) \rightarrow 0$ as $n \rightarrow \infty$ if and only if $d_j(x_n, y_n) \rightarrow 0$ for every j . Furthermore, d is a metric on X if and only if for every $x, y \in X$ with $x \neq y$ there exists a positive integer j such that $d_j(x, y) > 0$.