

Script 9

Continuous Functions

9.1 Journal

2/16: **Lemma 9.1.** *Let $X \subset \mathbb{R}$ and $f : X \rightarrow \mathbb{R}$. If $A, B \subset \mathbb{R}$, then*

$$\begin{aligned}f^{-1}(A \cup B) &= f^{-1}(A) \cup f^{-1}(B) \\f^{-1}(A \cap B) &= f^{-1}(A) \cap f^{-1}(B) \\f^{-1}(A \setminus B) &= f^{-1}(A) \setminus f^{-1}(B) \\f^{-1}(\mathbb{R}) &= X\end{aligned}$$

Proof. To prove that $f^{-1}(A \cup B) = f^{-1}(A) \cup f^{-1}(B)$, Definition 1.2 tells us that it will suffice to show that every $x \in f^{-1}(A \cup B)$ is an element of $f^{-1}(A) \cup f^{-1}(B)$ and vice versa. Suppose first that x is an arbitrary element of $f^{-1}(A \cup B)$. Then by Definition 1.18, $f(x) \in A \cup B$. Thus, by Definition 1.5, $f(x) \in A$ or $f(x) \in B$. We now divide into two cases. If $f(x) \in A$, then by Definition 1.18, $x \in f^{-1}(A)$. It follows by Definition 1.5 that $x \in f^{-1}(A) \cup f^{-1}(B)$, as desired. The argument is symmetric in the other case. Now suppose that $x \in f^{-1}(A) \cup f^{-1}(B)$. Then by Definition 1.5, $x \in f^{-1}(A)$ or $x \in f^{-1}(B)$. We now divide into two cases. If $x \in f^{-1}(A)$, then by Definition 1.18, $f(x) \in A$. It follows by Definition 1.5 that $f(x) \in A \cup B$. Therefore, by Definition 1.18, $x \in f^{-1}(A \cup B)$. The argument is symmetric in the other case, as desired.

To prove that $f^{-1}(A \cap B) = f^{-1}(A) \cap f^{-1}(B)$, Definition 1.2 tells us that it will suffice to show that every $x \in f^{-1}(A \cap B)$ is an element of $f^{-1}(A) \cap f^{-1}(B)$ and vice versa. Suppose first that x is an arbitrary element of $f^{-1}(A \cap B)$. Then by Definition 1.18, $f(x) \in A \cap B$. Thus, by Definition 1.6, $f(x) \in A$ and $f(x) \in B$. It follows by consecutive applications of Definition 1.18 that $x \in f^{-1}(A)$ and $x \in f^{-1}(B)$. Therefore, by Definition 1.6, $x \in f^{-1}(A) \cap f^{-1}(B)$, as desired. Now suppose that $x \in f^{-1}(A) \cap f^{-1}(B)$. Then by Definition 1.6, $x \in f^{-1}(A)$ and $x \in f^{-1}(B)$. It follows by consecutive applications of Definition 1.18 that $f(x) \in A$ and $f(x) \in B$. Thus, by Definition 1.6, $f(x) \in A \cap B$. Therefore, by Definition 1.18, $x \in f^{-1}(A \cap B)$, as desired.

To prove that $f^{-1}(A \setminus B) = f^{-1}(A) \setminus f^{-1}(B)$, Definition 1.2 tells us that it will suffice to show that every $x \in f^{-1}(A \setminus B)$ is an element of $f^{-1}(A) \setminus f^{-1}(B)$ and vice versa. Suppose first that x is an arbitrary element of $f^{-1}(A \setminus B)$. Then by Definition 1.18, $f(x) \in A \setminus B$. Thus, by Definition 1.11, $f(x) \in A$ and $f(x) \notin B$. It follows by consecutive applications of Definition 1.18 that $x \in f^{-1}(A)$ and $x \notin f^{-1}(B)$. Therefore, by Definition 1.11, $x \in f^{-1}(A) \setminus f^{-1}(B)$, as desired. Now suppose that $x \in f^{-1}(A) \setminus f^{-1}(B)$. Then by Definition 1.11, $x \in f^{-1}(A)$ and $x \notin f^{-1}(B)$. It follows by consecutive applications of Definition 1.18 that $f(x) \in A$ and $f(x) \notin B$. Thus, by Definition 1.11, $f(x) \in A \setminus B$. Therefore, by Definition 1.18, $x \in f^{-1}(A \setminus B)$, as desired.

To prove that $f^{-1}(\mathbb{R}) = X$, Definition 1.2 tells us that it will suffice to show that every $x \in f^{-1}(\mathbb{R})$ is an element of X and vice versa. Suppose first that x is an arbitrary element of $f^{-1}(\mathbb{R})$. Then by Definition 1.18, $x \in X$, as desired. Now suppose that $x \in X$. Then by Definition 1.16, $f(x) \in \mathbb{R}$. It follows by Definition 1.18 that $x \in f^{-1}(\mathbb{R})$, as desired. \square

Exercise 9.2. Let $f : X \rightarrow \mathbb{R}$. Let $A \subset X$ and $B \subset \mathbb{R}$. Show that

$$\begin{aligned} f(f^{-1}(B)) &\subset B \\ A &\subset f^{-1}(f(A)) \end{aligned}$$

Give examples to show that the inclusions can be proper.

Proof. To prove that $f(f^{-1}(B)) \subset B$, Definition 1.3 tells us that it will suffice to show that every $y \in f(f^{-1}(B))$ is an element of B . Let y be an arbitrary element of $f(f^{-1}(B))$. Then by Definition 1.18, $y = f(x)$ for some $x \in f^{-1}(B)$. By Definition 1.18 again, $f(x) \in B$. Therefore, since $y = f(x)$, it follows that $y \in B$, as desired.

To prove that $A \subset f^{-1}(f(A))$, Definition 1.3 tells us that it will suffice to show that every $x \in A$ is an element of $f^{-1}(f(A))$. Let x be an arbitrary element of A . Then by Definition 1.18, $f(x) \in f(A)$. Therefore, by Definition 1.18, we have $x \in f^{-1}(f(A))$, as desired.

Let $X = \{1, 2\}$ and let $f : X \rightarrow \mathbb{R}$ be defined by $f(1) = 3$ and $f(2) = 3$. If we let $B = \{3, 4\}$, then $f(f^{-1}(B)) = \{3\} \subsetneq \{3, 4\}$. Additionally, if we let $A = \{1\}$, then $A \subsetneq f^{-1}(f(A)) = \{1, 2\}$. \square

Exercise 9.3. Let $f : X \rightarrow \mathbb{R}$. Let $A \subset X$ and $B \subset \mathbb{R}$. Then $f(A) \subset B \iff A \subset f^{-1}(B)$.

Proof. Suppose first that $f(A) \subset B$. To prove that $A \subset f^{-1}(B)$, Definition 1.3 tells us that it will suffice to show that every $x \in A$ is an element of $f^{-1}(B)$. Let x be an arbitrary element of A . Then by Definition 1.18, $f(x) \in f(A)$. It follows by the hypothesis and Definition 1.3 that $f(x) \in B$. Therefore, by Definition 1.18 again, $x \in f^{-1}(B)$.

Now suppose that $A \subset f^{-1}(B)$. To prove that $f(A) \subset B$, Definition 1.3 tells us that it will suffice to show that every $y \in f(A)$ is an element of B . Let y be an arbitrary element of $f(A)$. Then by Definition 1.18, $y = f(x)$ for some $x \in A$. It follows by the hypothesis and Definition 1.3 that $x \in f^{-1}(B)$. Therefore, by Definition 1.18 again, $y = f(x) \in B$. \square

Definition 9.4. Let $X \subset \mathbb{R}$. A function $f : X \rightarrow \mathbb{R}$ is **continuous** if for every open set $U \subset \mathbb{R}$, the preimage $f^{-1}(U)$ is open in X .

Proposition 9.5. Let $X \subset \mathbb{R}$. A function $f : X \rightarrow \mathbb{R}$ is continuous if and only if for every closed set $F \subset \mathbb{R}$, the preimage $f^{-1}(F)$ is closed in X .

Proof. Suppose first that f is continuous. We seek to prove that for every closed set $F \subset \mathbb{R}$, the preimage $f^{-1}(F)$ is closed in X . Let F be an arbitrary closed subset of \mathbb{R} . Then by Definition 4.8, $F = \mathbb{R} \setminus U$ for some open set $U \subset \mathbb{R}$. It follows by Definition 9.4 since f is continuous that $f^{-1}(U)$ is open in X . Additionally, by consecutive applications of Lemma 9.1, $f^{-1}(F) = f^{-1}(\mathbb{R} \setminus U) = f^{-1}(\mathbb{R}) \setminus f^{-1}(U) = X \setminus f^{-1}(U)$. Therefore, since $f^{-1}(U)$ is open in X , Exercise 8.13 implies that $X \setminus f^{-1}(U) = f^{-1}(F)$ is closed in X .

The proof is symmetric in the other direction. \square

Definition 9.6. Let $X \subset Y \subset \mathbb{R}$ and let $f : Y \rightarrow \mathbb{R}$. Then the **restriction** (of f to X), written $f|_X$ is the function $f|_X : X \rightarrow \mathbb{R}$ defined by

$$f|_X(x) = f(x)$$

for all $x \in X$.

Proposition 9.7. Let $X \subset Y \subset \mathbb{R}$. If $f : Y \rightarrow \mathbb{R}$ is continuous, then the restriction of f to X is continuous.

Proof. To prove that $f|_X$ is continuous, Definition 9.4 tells us that it will suffice to show that for every open set $U \subset \mathbb{R}$, the preimage $f|_X^{-1}(U)$ is open in X . Let U be an open subset of \mathbb{R} . Then

$$\begin{aligned} f|_X^{-1}(U) &= \{x \in X \mid f|_X(x) \in U\} && \text{Definition 1.18} \\ &= \{x \in X \mid f(x) \in U\} && \text{Definition 9.6} \\ &= \{x \in Y \mid f(x) \in U\} \cap X && \text{Script 1} \\ &= f^{-1}(U) \cap X && \text{Definition 1.18} \\ &= (Y \cap G) \cap X && \text{Definitions 9.4 and 8.11} \end{aligned}$$

$$= X \cap G$$

Script 1

Since $f|_X^{-1}(U) = X \cap G$ where G is an open set, Definition 8.11 asserts that $f|_X^{-1}(U)$ is open in X . \square

Exercise 9.8. Show that for any $X \subsetneq \mathbb{R}$ that is not open and any continuous function $f : X \rightarrow \mathbb{R}$, there is an open set U for which $f^{-1}(U)$ is open in X but is not open in \mathbb{R} .

Proof. We will prove that \mathbb{R} is an open set for which $f^{-1}(\mathbb{R})$ is open in X but not in \mathbb{R} . First, by Theorem 5.1, \mathbb{R} is open. Next, by Lemma 9.1, $f^{-1}(\mathbb{R}) = X$. It follows since $f^{-1}(\mathbb{R}) = X = X \cap \mathbb{R}$ (where \mathbb{R} is an open set) by Definition 8.11 that $f^{-1}(\mathbb{R})$ is open in X . Last, since X is not open (in \mathbb{R}) by definition, $f^{-1}(\mathbb{R}) = X$ is not open in \mathbb{R} . \square

Definition 9.9. The function $f : X \rightarrow \mathbb{R}$ is **continuous** (at $x \in X$) if for every region R containing $f(x)$, there exists an open set S containing x such that $S \cap X \subset f^{-1}(R)$.

Theorem 9.10. The function $f : X \rightarrow \mathbb{R}$ is continuous if and only if it is continuous at every $x \in X$.

Proof. Suppose first that f is continuous, and suppose for the sake of contradiction that f is not continuous at every $x \in X$. Then by Definition 9.9, there exists some $x \in X$ such that f is not continuous at x . Thus, there exists a region R with $f(x) \in R$ such that for all open sets S containing x , $S \cap X \not\subset f^{-1}(R)$. Since f is continuous by hypothesis and R is open by Corollary 4.11, $f^{-1}(R)$ is open in X . It follows by Definition 8.11 that $f^{-1}(R) = X \cap S$ for some open set S . But this implies that $f^{-1}(R) \not\subset f^{-1}(R)$, a contradiction.

Now suppose that f is continuous at every $x \in X$. To prove that f is continuous, Definition 9.4 tells us that it will suffice to show that for every open set $U \subset \mathbb{R}$, the preimage $f^{-1}(U)$ is open in X . We divide into two cases ($f^{-1}(U) = \emptyset$ and $f^{-1}(U) \neq \emptyset$). If $f^{-1}(U) = \emptyset$, then since $\emptyset \cap X = \emptyset$ by Script 1 where \emptyset is open by Theorem 5.1, Definition 8.11 tells us that $\emptyset = f^{-1}(U)$ is open in X , as desired. On the other hand, if $f^{-1}(U) \neq \emptyset$, Definition 8.11 tells us that it will suffice to show that $f^{-1}(U) = S \cap X$ where S is an open set. We first seek to show that for every $x \in f^{-1}(U)$, there exists an open set S_x containing x such that $S_x \cap X \subset f^{-1}(U)$. Let x be an arbitrary element of $f^{-1}(U)$. It follows by Definition 1.18 that $f(x) \in U$. Thus, since U is open, we have by Theorem 4.10 that there exists a region R such that $f(x) \in R$ and $R \subset U$. Consequently, since R is open by Corollary 4.11, we have by Definition 9.9 that there exists an open set S_x containing x such that $S_x \cap X \subset f^{-1}(R)$. Additionally, Script 1 tells us based off of the fact that $R \subset U$ that $f^{-1}(R) \subset f^{-1}(U)$. Thus, by subset transitivity, $S_x \cap X \subset f^{-1}(U)$. At this point, let $S = \bigcup_{x \in f^{-1}(U)} S_x$. It follows immediately from Corollary 4.18 that S is open. Additionally, since the intersection of each set in the union with X is a subset of $f^{-1}(U)$, it follows by Script 1 that $S \cap X \subset f^{-1}(U)$. Furthermore, for all $x \in f^{-1}(U)$, Definition 1.18 asserts that $x \in X$. In addition, we have defined an S_x such that $x \in S_x$. These last two results combined demonstrate by Definition 1.6 that $x \in S \cap X$. Thus, by Definition 1.3, $f^{-1}(U) \subset S \cap X$. Consequently, by Theorem 1.7, $f^{-1}(U) = S \cap X$. Since $f^{-1}(U)$ is the intersection of X with an open set, Definition 8.11 asserts that it is open in X , as desired. \square