# Script 6

# Construction of the Real Numbers

## 6.1 Journal

1/12: **Definition 6.1.** A subset $A$ of $\mathbb{Q}$ is said to be a **cut** (or **Dedekind cut**) if it satisfies the following:

(a) $A \neq \emptyset$ and $A \neq \mathbb{Q}$.

(b) If $r \in A$ and $s \in \mathbb{Q}$ satisfy $s < r$, then $s \in A$.

(c) $A$ does not have a last point; i.e., if $r \in A$, then there is some $s \in A$ with $s > r$.

We denote the collection of all cuts by $\mathbb{R}$.

**Lemma 6.2.** *Let $A$ be a Dedekind cut and $x \in \mathbb{Q}$. Then $x \notin A$ if and only if $x$ is an upper bound for $A$.*

*Proof.* Suppose first that $x \notin A$. To prove that $x$ is an upper bound for $A$, Definition 5.6 tells us that it will suffice to show that for all $r \in A$, $r \leq x$. Let $r$ be an arbitrary element of $A$. Then by the contrapositive of Definition 6.1b and the hypothesis that $x \notin A$, we know that $r \notin A$, $x \notin \mathbb{Q}$, or $x \not< r$. But since $r \in A$ and $x \in \mathbb{Q}$, it must be that $x \not< r$. Therefore, $r \leq x$, as desired.

Now suppose that $x$ is an upper bound for $A$. By Definition 5.6, this implies that for all $r \in A$, $r \leq x$. Therefore, since there is no $r \in A$ with $r > x$, by the contrapositive of Definition 6.1c, $x \notin A$, as desired. $\square$

**Exercise 6.3.**

(a) Prove that for any $q \in \mathbb{Q}$, $\{x \in \mathbb{Q} \mid x < q\}$ is a Dedekind cut. We then define $\mathbf{0} = \{x \in \mathbb{Q} \mid x < 0\}$.

(b) Prove that $\{x \in \mathbb{Q} \mid x \leq 0\}$ is not a Dedekind cut.

(c) Prove that $\{x \in \mathbb{Q} \mid x < 0\} \cup \{x \in \mathbb{Q} \mid x^2 < 2\}$ is a Dedekind cut.

*Proof of a.* Let $q$ be an arbitrary element of $\mathbb{Q}$. To prove that $A = \{x \in \mathbb{Q} \mid x < q\}$ is a Dedekind cut, Definition 6.1 tells us that it will suffice to show that $A \neq \emptyset$; $A \neq \mathbb{Q}$; if $r \in A$ and $s \in \mathbb{Q}$ satisfy $s < r$, then $s \in A$; and if $r \in A$, then there is some $s \in A$ with $s > r$. We will take this one claim at a time.

To show that $A \neq \emptyset$, Definition 1.8 tells us that it will suffice to find an element of $A$. By Exercise 3.9d, $q$ is not the first point of $\mathbb{Q}$. Thus, by Definition 3.3, there exists an object $x \in \mathbb{Q}$ such that $x < q$. By the definition of $A$, this implies that $x \in A$, as desired.

To show that $A \neq \mathbb{Q}$, Definition 1.2 tells us that it will suffice to find an element of $\mathbb{Q}$ that is not an element of $A$. By hypothesis, $q \in \mathbb{Q}$. By Exercise 3.9d, $q \not< q$. Therefore, $q \in \mathbb{Q}$ but $q \notin A$, as desired.

To show that if $r \in A$ and $s \in \mathbb{Q}$ satisfy $s < r$, then $s \in A$, we let $r \in A$ and $s \in \mathbb{Q}$ be arbitrary elements of their respective sets that satisfy $s < r$ and seek to verify that $s \in A$. Since $r \in A$, $r < q$. This combined with the fact that $s < r$ implies by transitivity that $s < q$. Therefore, since $s \in \mathbb{Q}$ and $s < q$, $s \in A$, as desired.

To show that if $r \in A$, then there is some $s \in A$ with $s > r$, we let $r \in A$ and seek to find such an $s$. By the definition of $A$, $r < q$. Thus, by Additional Exercise 3.1, there exists a point $s \in \mathbb{Q}$ such that $r < s < q$. Since $s \in \mathbb{Q}$ and $s < q$, $s \in A$. It follows that $s$ is the desired element of $A$ satisfying $s > r$. $\square$

*Proof of b.* To prove that $A = \{x \in \mathbb{Q} \mid x \leq 0\}$ is not a Dedekind cut, Definition 6.1 tells us that it will suffice to show that $A$ does have a last point. To show this, we will demonstrate that 0 is the last point of $A$. To demonstrate this, Definition 3.1 tells us that it will suffice to confirm that $0 \in A$ and for all $x \in A$, $x \leq 0$. Since $0 \leq 0$ and $0 \in \mathbb{Q}$, $0 \in A$. Additionally, by the definition of $A$, it is true that for all $x \in A$, $x \leq 0$. □

*Proof of c.* Let $B = \{x \in \mathbb{Q} \mid x < 0\}$ and let $C = \{x \in \mathbb{Q} \mid x^2 < 2\}$. To prove that $A = B \cup C$ is a Dedekind cut, Definition 6.1 tells us that it will suffice to show that $A \neq \emptyset$; $A \neq \mathbb{Q}$; if $r \in A$ and $s \in \mathbb{Q}$ satisfy $s < r$, then $s \in A$; and if $r \in A$, then there is some $s \in A$ with $s > r$. We will take this one claim at a time.

To show that $A \neq \emptyset$, Definition 1.8 tells us that it will suffice to find an element of $A$. Since $-1 \in \mathbb{Q}$ and $-1 < 0$, $-1 \in B$. Therefore, by Definition 1.5, $-1 \in A$, as desired.

To show that $A \neq \mathbb{Q}$, Definition 1.2 tells us that it will suffice to find an element of $\mathbb{Q}$ that is not an element of $A$. Since $2 \in \mathbb{Q}$ and $2 \geq 0$, $2 \notin B$. Additionally, since $2^2 \geq 2$, $2 \notin C$. Therefore, by Definition 1.5, $2 \notin A$, as desired.

To show that if $r \in A$ and $s \in \mathbb{Q}$ satisfy $s < r$, then $s \in A$, we let $r \in A$ and $s \in \mathbb{Q}$ be arbitrary elements of their respective sets that satisfy $s < r$ and seek to verify that $s \in A$. Since $r \in A$, Definition 1.5 tells us that $r \in B$ or $r \in C$. We now divide into two cases. Suppose first that $r \in B$. Then $s < r < 0$, which implies that $s \in B$, meaning that $s \in A$. Now suppose that $r \in C$. We divide into two cases again ($r \leq 0$ and $r > 0$). If $r \leq 0$, then $s < r \leq 0$ implies that $s < 0$. Thus, by the definition of $B$, $s \in B$, implying that $s \in A$. On the other hand, if $r > 0$, then $0 < s^2 < r^2 < 2$. Thus, by the definition of $C$, $s \in C$, implying that $s \in A$.

To show that $A$ does not have a last point, suppose for the sake of contradiction that $A$ has a last point $p$. We now divide into two cases ($p \leq 0$ and $p > 0$). Suppose first that $p \leq 0$. Since $p$ is the last point of $A$, Definition 3.3 tells us that $x \leq p$ for all $x \in A$. But $1 \in A$ (since $1 \in \mathbb{Q}$ and $1^2 = 1 < 2$ implies $1 \in B$, implies $1 \in A$) and $1 > 0 \geq p$, a contradiction. Now suppose that $p > 0$. Definition 3.3 tells us that $p \in A$, but the condition that $p > 0$ means $p \notin B$, so we must have $p \in C$. However, by the proof of Exercise 4.24, $\frac{2(p+1)}{p+2}$ will be an element of $B$ (and therefore $A$) that is greater than $p$ no matter how large $p$ is, a contradiction. □

**Definition 6.4.** If $A, B \in \mathbb{R}$, we say that $A < B$ if $A$ is a proper subset of $B$.

**Exercise 6.5.** Show that $\mathbb{R}$ satisfies Axioms 1, 2, and 3.

*Proof.* By Exercise 6.3a, $\{x \in \mathbb{Q} \mid x < 0\} \in \mathbb{R}$ since $0 \in \mathbb{Q}$. Therefore, Axiom 1 is immediately satisfied.

Axiom 2 asserts that $\mathbb{R}$ must have an ordering $<$. As such, it will suffice to verify that the ordering given by Definition 6.4 satisfies the stipulations of Definition 3.1. To prove that $<$ satisfies the trichotomy, it will suffice to show that for all $A, B \in \mathbb{R}$, exactly one of the following holds: $A < B$, $B < A$, or $A = B$.

We first show that *no more than one* of the three statements can simultaneously be true. Let $A, B$ be arbitrary elements of $\mathbb{R}$. We divide into three cases. First, suppose for the sake of contradiction that $A < B$ and $B < A$. By Definition 6.4, this implies that $A \subsetneq B$ and $B \subsetneq A$. Thus, by Definition 1.3, $A \subset B$, $B \subset A$, and $A \neq B$. But by Theorem 1.7, $A \subset B$ and $B \subset A$ implies that $A = B$, a contradiction. Second, suppose for the sake of contradiction that $A < B$ and $A = B$. By Definition 6.4, the former statement implies that $A \subsetneq B$. Thus, by Definition 1.3, $A \neq B$, a contradiction. The proof of the third case ($B < A$ and $A = B$) is symmetric to that of the second case.

We now show that *at least one* of the three statements is always true. Let $A, B$ be arbitrary elements of $\mathbb{R}$, and suppose for the sake of contradiction that $A \not< B$, $B \not< A$, and $A \neq B$. Since $A \not< B$ and $B \not< A$, we have by Definition 6.4 that $A \not\subsetneq B$ and $B \not\subsetneq A$. Thus, by Definition 1.3, $A \not\subset B$ or $A = B$, and $B \not\subset A$ or $A = B$. But $A \neq B$ by hypothesis, so it must be that $A \not\subset B$ and $B \not\subset A$. It follows from the first statement by Definition 1.3 that there exists an object $x \in A$ such that $x \notin B$, and there exists an object $y \in B$ such that $y \notin A$. Since $x \notin B$, Lemma 6.2 implies that $x$ is an upper bound of $B$. Consequently, by Definition 5.6, $p \leq x$ for all $p \in B$, including $y$. Similarly, $p \leq y$ for all $p \in A$, including $x$. Thus, we have $y \leq x$ and $x \leq y$, implying that $x = y$. But since $y \in B$, this implies that $x \in B$, a contradiction.

To prove that $<$ is transitive, it will suffice to show that for all $A, B, C \in \mathbb{R}$, if $A < B$ and $B < C$, then $A < C$. Let $A, B, C$ be arbitrary elements of $\mathbb{R}$ for which it is true that $A < B$ and $B < C$. By Definition 6.4, we have $A \subsetneq B$ and $B \subsetneq C$. Thus, by Script 1, $A \subsetneq C$. Therefore, by Definition 6.4, $A < C$.

Axiom 3 asserts that $\mathbb{R}$ must have no first or last point. We will take this one argument at a time

Suppose for the sake of contradiction that $\mathbb{R}$ has some first point $A$. Then by Definition 3.3, $A \leq X$ for every $X \in \mathbb{R}$. Now since $A$ is a Dedekind cut, Definition 6.1 tells us that $A \neq \emptyset$. Thus, by Definition 1.8, there exists some $q \in A$. Additionally, $A \subset \mathbb{Q}$ by Definition 6.1, so $q \in A$ implies that $q \in \mathbb{Q}$. It follows by Exercise 6.3a that $B = \{x \in \mathbb{Q} \mid x < q\}$ is a Dedekind cut. We now seek to prove that $B \subsetneq A$. To do this, Definition 1.3 tells us that it will suffice to show that $B \neq A$ and $B \subset A$. To show that $B \neq A$, Definition 1.2 tells us that it will suffice to find an element of $A$ that is not an element of $B$. Conveniently, $q$ is clearly such an object. To show that $B \subset A$, Definition 1.3 tells us that we must confirm that every element of $B$ is an element of $A$. Let $p$ be an arbitrary element of $B$. Then by the definition of $B$, $p \in \mathbb{Q}$ and $p < q$. It follows by Definition 6.1b (which clearly applies to $A$) that $p \in A$, as desired. Having proven that $B \subsetneq A$, Definition 6.4 tells us that $B < A$. But this contradicts the previously demonstrated fact that $A \leq X$ for every $X \in \mathbb{R}$, including $B$.

Suppose for the sake of contradiction that $\mathbb{R}$ has some last point $A$. Then by Definition 3.3, $X \leq A$ for every $X \in \mathbb{R}$. Now since $A$ is a Dedekind cut, Definition 6.1 tells us that $A \neq \mathbb{Q}$. Thus, by Definition 1.2, there exists some $q \in \mathbb{Q}$ such that $q \notin A$. It follows by Lemma 6.2 that $q$ is an upper bound of $A$. Consequently, by Definition 5.6, $x \leq q$ for all $x \in A$. Additionally, by Exercise 6.3a, $B = \{x \in \mathbb{Q} \mid x < q+1\}$[1] is a Dedekind cut. We now seek to prove that $A \subsetneq B$. As before, this means we must show that $A \neq B$ and $A \subset B$. To show that $A \neq B$, Definition 1.2 tells us that it will suffice to find an element of $B$ that is not an element of $A$. Since $x \leq q$ for all $x \in A$ and $q < q + 0.5 < q + 1$, $q + 0.5 \notin A$ and $q + 0.5 \in B$ is the desired object. To show that $A \subset B$, Definition 1.3 tells us that we must confirm that every element of $A$ is an element of $B$. Let $p$ be an arbitrary element of $A$. As an element of $A$, we know that $p \leq q$. Thus, $p < q + 1$, so $p \in B$, as desired. Having proven that $A \subsetneq B$, Definition 6.4 tells us that $A < B$. But this contradicts the previously demonstrated fact that $X \leq A$ for every $X \in \mathbb{R}$, including $B$. ☐

1/14: **Lemma 6.6.** *A nonempty subset of* $\mathbb{R}$ *that is bounded above has a supremum.*

*Proof.* Let $X$ be an arbitrary nonempty subset of $\mathbb{R}$ that is bounded above. To prove that $\sup X$ exists, we will show that $\sup X = U = \bigcup\{Y \mid Y \in X\}$. To show this, Definition 5.7 tells us that it will suffice to demonstrate that $U \in \mathbb{R}$, $U$ is an upper bound of $X$, and if $U'$ is an upper bound of $X$, then $U \leq U'$. Let's begin.

To demonstrate that $U \in \mathbb{R}$, Definition 6.1 tells us that it will suffice to confirm that $U \neq \emptyset$; $U \neq \mathbb{Q}$; if $r \in U$ and $s \in \mathbb{Q}$ satisfy $s < r$, then $s \in U$; and if $r \in U$, then there is some $s \in U$ with $s > r$.

As the union of a nonempty subset of nonempty sets, Script 1 implies that $U \neq \emptyset$.

To demonstrate that $U \neq \mathbb{Q}$, Definition 1.2 tells us that it will suffice to find a point $p \in \mathbb{Q}$ such that $p \notin U$. Since $X$ is bounded above, we have by Definition 5.6 that there exists a Dedekind cut $V \in \mathbb{R}$ such that $Y \leq V$ for all $Y \in X$. It follows by Definition 6.4 that $Y \subset V$ for all $Y \in X$. Thus, by Script 1, $U \subset V$. Now since $V$ is a Dedekind cut, we know by Definition 6.1 that $V \subset \mathbb{Q}$ and $V \neq \mathbb{Q}$, meaning that there exists a point $p \in \mathbb{Q}$ such that $p \notin V$. Consequently, since $U \subset V$, $p \notin U$, as desired.

To demonstrate that if $r \in U$ and $s \in \mathbb{Q}$ satisfy $s < r$, then $s \in U$, we let $r \in U$ and $s \in \mathbb{Q}$ be arbitrary elements of their respective sets that satisfy $s < r$ and seek to verify that $s \in U$. Since $r \in U$, Definition 1.13 tells us that $r \in Y$ for some $Y \in X$. Thus, since $Y$ is a Dedekind cut, $s \in \mathbb{Q}$ and $s < r$ implies that $s \in Y$. Therefore, $s \in U$.

To demonstrate that if $r \in U$, then there is some $s \in U$ with $s > r$, we let $r \in U$ and seek to find such an $s$. Since $r \in U$, Definition 1.13 tells us that $r \in Y$ for some $Y \in X$. Thus, since $Y$ is a Dedekind cut, there exists a point $s \in Y$ with $s > r$. Therefore, $s \in U$.

To demonstrate that $U$ is an upper bound of $X$, Definition 5.6 tells us that it will suffice to confirm that $Y \leq U$ for all $Y \in X$. To confirm this, Definition 6.4 tells us that it will suffice to verify that $Y \subset U$ for all $Y \in X$. But by an extension of Theorem 1.7b, this is true.

Now suppose for the sake of contradiction that there exists an upper bound $U'$ of $X$ such that $U' < U$. It follows by Definitions 6.4 and 1.3 that there exists a point $p \in U$ such that $p \notin U'$. Thus, by the former statement and Definition 1.13, $p \in Y$ for some $Y \in X$. Additionally, since $U'$ is an upper bound of $X$, we

[1] Note that we add 1 to $q$ to treat the case that $q = \sup A$, a case in which we would have $B = A$ if $B$ were defined as $\{x \in \mathbb{Q} \mid x < q\}$.

have by Definitions 5.6 and 6.4 that $Y \subset U'$ for all $Y \in X$. But this implies by Definition 1.3 that $p \in U'$, a contradiction. $\square$

1/19: **Exercise 6.7.** Show that $\mathbb{R}$ satisfies Axiom 4.

*Proof.* Suppose for the sake of contradiction that $\mathbb{R}$ does not satisfy Axiom 4. It follows that $\mathbb{R}$ is not connected, implying by Definition 4.22 that $\mathbb{R} = A \cup B$ where $A, B$ are disjoint, nonempty, open sets. Since $A, B$ are disjoint and nonempty, we know that there exist distinct objects $a \in A$ and $b \in B$. WLOG, let $a < b$.

We now seek to prove that the set $A \cap \underline{ab}$ is nonempty and bounded above. To prove that $A \cap \underline{ab}$ is nonempty, Definition 1.8 tells us that it will suffice to find an element of $A \cap \underline{ab}$. Since $a \in A$ and $A$ is open, we have by Theorem 4.10 that there exists a region $\underline{cd}$ such that $a \in \underline{cd}$ and $\underline{cd} \subset A$. It follows by Definitions 3.10 and 3.6 that $a < d$, implying by Lemma 6.10[2] that there exists some point $x \in \mathbb{R}$ such that $c < a < x < d < b$ (note that $d < b$ since if $b < d$, then $b \in \underline{cd}$ would contradict the fact that $\underline{cd} \subset A$). Consequently, $x \in \underline{cd}$, meaning that $x \in A$, and $x \in \underline{ab}$. Therefore, $x \in A \cap \underline{ab}$, as desired. To prove that $A \cap \underline{ab}$ is bounded above, Definition 5.6 tells us that it will suffice to show that $b$ is an upper bound of $A \cap \underline{ab}$. To show this, Definition 5.6 tells us that it will suffice to confirm that $y \leq b$ for all $y \in A \cap \underline{ab}$. Let $y$ be an arbitrary element of $A \cap \underline{ab}$. Then by Definition 1.6, $y \in A$ and $y \in \underline{ab}$. It follows from the latter statement by Definitions 3.10 and 3.6 that $y < b$, i.e., $y \leq b$, as desired.

Having established that $A \cap \underline{ab} \subset \mathbb{R}$ is nonempty and bounded above, we can invoke Lemma 6.6 to learn that $A \cap \underline{ab}$ has a supremum $\sup(A \cap \underline{ab})$. We now divide into two cases ($\sup(A \cap \underline{ab}) \in A$ and $\sup(A \cap \underline{ab}) \in B$; it follows from the definitions of $A$ and $B$ that exactly one of these cases is true). Suppose first that $\sup(A \cap \underline{ab}) \in A$. Then since $A$ is open, we have by Theorem 4.10 that there exists a region $\underline{ef}$ such that $\sup(A \cap \underline{ab}) \in \underline{ef}$ and $\underline{ef} \subset A$. It follows from the former condition that $\sup(A \cap \underline{ab}) < f$. Thus, by Lemma 6.10, there exists an object $z \in \mathbb{R}$ such that $e < \sup(A \cap \underline{ab}) < z < f < b$ (note that $f < b$ for the same reason that $d < b$). Consequently, $z \in \underline{ef}$, implying that $z \in A$, and $z \in \underline{ab}$. Thus, we have found an element of $A \cap \underline{ab}$ that is greater than $\sup(A \cap \underline{ab})$, contradicting Definitions 5.7 and 5.6. The proof is symmetric in the other case. $\square$

1/14: **Definition 6.8.** Let $C$ be a continuum satisfying Axioms 1-4. Consider a subset $X \subset C$. We say that $X$ is **dense** in $C$ if every $p \in C$ is a limit point of $X$.

**Lemma 6.9.** *A subset $X \subset C$ is dense in $C$ if and only if $\overline{X} = C$.*

*Proof.* Suppose first that $X \subset C$ is dense in $C$. To prove that $\overline{X} = C$, Definition 1.2 tells us that it will suffice to show that every point $p \in \overline{X}$ is an element of $C$ and vice versa. Clearly, every element of $\overline{X}$ is an element of $C$. On the other hand, let $p$ be an arbitrary element of $C$. Since $X$ is dense in $C$, Definition 6.8 tells us that $p \in LP(X)$. Therefore, by Definitions 1.5 and 4.4, $p \in \overline{X}$.

Now suppose that $\overline{X} = C$. To prove that $X$ is dense in $C$, Definition 6.8 tells us that it will suffice to show that every $p \in C$ is a limit point of $X$. Let $p$ be an arbitrary element of $C$. By Corollary 5.4, this implies that $p \in LP(C)$. It follows that $p \in LP(\overline{X})$. Thus, by Definition 4.4, $p \in LP(X \cup LP(X))$. Consequently, by Theorem 3.20, $p \in LP(X)$ or $p \in LP(LP(X))$. We now divide into two cases. If $p \in LP(X)$, then we are done. On the other hand, if $p \in LP(LP(X))$, the lemma from Theorem 4.6 asserts that $p \in LP(X)$, and we are done again. $\square$

Our next goal is to prove that $\mathbb{Q}$ is dense in $\mathbb{R}$. Just to make sense of that statement, we need to decide how to think of $\mathbb{Q}$ as a subset of $\mathbb{R}$. For every rational number $q \in \mathbb{Q}$, define the corresponding real number as the Dedekind cut

$$i(q) = \{x \in \mathbb{Q} \mid x < q\}$$

For example, $\mathbf{0} = i(0)$. It can be verified that this gives a well-defined injective function $i : \mathbb{Q} \to \mathbb{R}$. We identify $\mathbb{Q}$ with its image $i(\mathbb{Q}) \subset \mathbb{R}$ so that the rational numbers $\mathbb{Q}$ are a subset of the real numbers $\mathbb{R}$. (Similarly, $\mathbb{N}$ and $\mathbb{Z}$ can be understood as subsets of $\mathbb{R}$.)

**Lemma 6.10.** *Given $A, B \in \mathbb{R}$ with $A < B$, there exists $p \in \mathbb{Q}$ such that $A < i(p) < B$.*

[2] We may use this lemma since it does not depend on this result, Definition 6.8, or Lemma 6.9.

*Proof.* Since $A < B$, Definition 6.4 tells us that $A \subsetneq B$. Thus, by Definition 1.3, there exists a point $q$ such that $q \in B$ and $q \notin A$. Since $q \in B$ where $B$ is a Dedekind cut, we have by Definition 6.1 that there exists a point $p \in B$ with $p > q$. Additionally, since $q \notin A$ implies that $q$ is an upper bound of $A$ by Lemma 6.2, we know by Definition 5.6 that $x \leq q$ for all $x \in A$. It follows since $q < p$ that $x \leq p$ for all $x \in A$, meaning by Definition 5.6 and Lemma 6.2 that $p \notin A$. Having established that $p, q \in B$, $p, q \notin A$, and $q < p$, we are now ready to prove that $A < i(p) < B$. Definition 6.4 tells us that we may do so by showing that $A \subsetneq i(p)$ and $i(p) \subsetneq B$. We will take this one argument at a time.

To show that $A \subsetneq i(p)$, Definition 1.3 tells us that it will suffice to verify that every element of $A$ is an element of $i(p)$ and that there exists an element of $i(p)$ that is not an element of $A$. We treat the former statement first. As previously mentioned, $x \leq p$ for all $x \in A$. This combined with the fact that $p \notin A$ implies that $x < p$ for all $x \in A$. Thus, by the definition of $i(p)$, $x \in i(p)$ for all $x \in A$, as desired. As to the latter statement, since $q < p$, we have by the definition of $i(p)$ that $q \in i(p)$. However, we also know that $q \notin A$, as desired.

To show that $i(p) \subsetneq B$, we must verify symmetric arguments to before. For the former statement, let $r$ be an arbitrary element of $i(p)$. Then by the definition of $i(p)$, $r < p$. Since $p \in B$ and $r \in \mathbb{Q}$ satisfy $r < p$, we have by Definition 6.1 that $r \in B$, as desired. As to the latter statement, $p$ is clearly an element of $B$ that is not an element of $i(p)$, as desired. □

1/19: **Theorem 6.11.** *$i(\mathbb{Q})$ is dense in $\mathbb{R}$.*

*Proof.* To prove that $i(\mathbb{Q})$ is dense in $\mathbb{R}$, Definition 6.8 tells us that it will suffice to show the every point $X \in \mathbb{R}$ is a limit point of $i(\mathbb{Q})$. Let $X$ be an arbitrary element of $\mathbb{R}$. To show that $X \in LP(i(\mathbb{Q}))$, Definition 3.13 tells us that it will suffice to verify that for every region $\underline{AB}$ with $X \in \underline{AB}$, we have $\underline{AB} \cap (i(\mathbb{Q}) \setminus \{X\}) \neq \emptyset$. Let $\underline{AB}$ be an arbitrary region with $X \in \underline{AB}$. It follows by Definitions 3.10 and 3.6 that $A < X < B$. Thus, by Lemma 6.10, there exists $p \in \mathbb{Q}$ such that $A < i(p) < X < B$. By Definitions 3.6 and 3.10, $i(p) \in \underline{AB}$. By Definition 1.18, $i(p) \in i(\mathbb{Q})$. By Exercise 6.5, $i(p) < X$ implies that $i(p) \neq X$. Combining the last three results with Definitions 1.11 and 1.6, we have that $i(p) \in \underline{AB} \cap (i(\mathbb{Q}) \setminus \{X\})$, as desired. □

**Corollary 6.12** (The Archimedean Property)**.** *Let $A \in \mathbb{R}$ be a positive real number. Then there exist nonzero natural numbers $n, m \in \mathbb{N}$ such that $i(\frac{1}{n}) < A < i(m)$.*

*Proof.* We will first prove that there exists a nonzero natural number $n$ such that $i(\frac{1}{n}) < A$. We will then prove that there exists a nonzero natural number $m$ such that $A < i(m)$. Let's begin.

Since $A \in \mathbb{R}$ is positive, we know that $0 < A$. Thus, by Lemma 6.10, there exists $\frac{p}{n} \in \mathbb{Q}$ such that $0 < i(\frac{p}{n}) < A$. As permitted by Exercise 3.9b, we choose $\frac{p}{n} \in \left[\frac{p}{n}\right]$ to be an object such that $0 < n$ (this means that $n \in \mathbb{N}$). Consequently, by Scripts 2 and 3, we know that $0 < \frac{1}{n} \leq \frac{p}{n}$. It follows that $i(\frac{1}{n}) \leq i(\frac{p}{n})$ since $x \in i(\frac{1}{n})$ implies $x < \frac{1}{n} \leq \frac{p}{n}$ implies $x \in i(\frac{p}{n})$, implies $i(\frac{1}{n}) \subset i(\frac{p}{n})$. Therefore, $i(\frac{1}{n}) \leq i(\frac{p}{n}) < A$, as desired.

Suppose for the sake of contradiction that no natural number $m$ exists such that $A < i(m)$. Then $A \geq i(m)$ for all $m \in \mathbb{N}$. Thus, by Definition 6.4, $i(m) \subset A$ for all $m \in \mathbb{N}$. Now let $\frac{p}{q}$ be an arbitrary element of $\mathbb{Q}$, again with a positive denominator. It follows by Scripts 2 and 3 that $\frac{p}{q} < 1$ if $p \leq 0$ and $\frac{p}{q} < p$ if $p > 0$. Either way, $\frac{p}{q} < m$ for some nonzero natural number $m \in \mathbb{N}$, meaning that $\frac{p}{q} \in i(m)$ for some $m \in \mathbb{N}$. This implies that $\frac{p}{q} \in A$. But by Definition 1.3, this means that $\mathbb{Q} \subset A$, implying that $A = \mathbb{Q}$ by Theorem 1.7a. This contradicts Definition 6.1. □

**Corollary 6.13.** *$i(\mathbb{N})$ is an unbounded subset of $\mathbb{R}$.*

*Proof.* Suppose for the sake of contradiction that $i(\mathbb{N})$ is bounded above. Then by Definition 5.6, there exists a point $A \in \mathbb{R}$ such that $i(n) \leq A$ for all $n \in \mathbb{N}$. Note that $A$ is a positive real number since $0 = i(0) \leq A$. But by Corollary 6.12, $A < i(n)$ for some $n \in \mathbb{N}$, a contradiction. □

**Corollary 6.14.** *If $A \in \mathbb{R}$ is a real number, then there is an integer $n$ such that $i(n-1) \leq A < i(n)$.*

*Proof.* Suppose for the sake of contradiction that there exists a real number $A$ for which there does not exist an integer $n$ such that $i(n-1) \leq A$ and $A < i(n)$. In other words, for all integers $n$, $i(n-1) > A$ or $A \geq i(n)$. We now divide into two cases. Suppose first that $i(n-1) > A$ for all $n \in \mathbb{Z}$, and suppose for the sake of contradiction that $p \in A$. Then by Scripts 2 and 3, there exists a natural number $m < p$. Thus, $i(m) < A$, a contradiction. The proof is symmetric in the other case. $\square$