

# MATH 16210 (Honors Calculus II IBL) Notes

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## 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  $x \not\leq r$ . But since  $r \in A$  and  $x \in \mathbb{Q}$ , it must be that  $x \not\leq r$ . 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  $x \in A$ ,  $x \leq 0$ .  $\square$

*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.  $\square$

**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,  $B = \{x \in \mathbb{Q} \mid x < q + 1\}$ <sup>[1]</sup> 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  $B$ .  $\square$

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

<sup>1</sup>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<sup>[2]</sup> 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  $i : \mathbb{Q} \rightarrow \mathbb{R}$ . 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  $A < i(p) < B$ .

<sup>2</sup>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.  $\square$

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.  $\square$

**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  $\frac{p}{n} \in [\frac{p}{n}]$  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.  $\square$

**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.  $\square$

**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.  $\square$

## 6.2 Discussion

- 1/12:
- Upper limit at signing up for 4-5 across the script.
  - Lemma 6.2 is probably more straightforward using a contradiction argument.
  - Briefly restate the algebra of Exercise 4.24 in Exercise 6.3c.
- 1/14:
- Turning in Script 5 journals is optional — it will boost your grade a bit if you do.
    - Your journal grade will be whichever is higher: the average of all your journal grades with and without Script 5.
    - Script 5 will probably be due Wednesday, 1/20.
  - In Lemma 6.6, do we need to prove that the union of arbitrarily many Dedekind cuts is, itself, a Dedekind cut? Yes.