

## Announcements

- PS1 due tomorrow  
7/29 1 pm
- type on # 5

# Econ 204 2022

## Lecture 4

### Outline

#### O. Sequences in $\mathbb{R}$ (cont.)

1. Open and Closed Sets
2. Continuity in Metric Spaces

$$x_n = \begin{cases} 1 & n \text{ even} \\ 1 + \frac{1}{n} & n \text{ odd} \end{cases}$$

$$\{3, 2, 1, 1, \dots\}$$

## Lim Sups and Lim Infs

$$\{1 - \frac{1}{n}\}$$

Consider a sequence  $\{x_n\}$  of real numbers. Let

$$\begin{aligned} \alpha_n &= \sup\{x_k : k \geq n\} \\ &= \sup\{x_n, x_{n+1}, x_{n+2}, \dots\} \\ \beta_n &= \inf\{x_k : k \geq n\} \\ &= \inf\{x_n, x_{n+1}, x_{n+2}, \dots\} \end{aligned}$$

Either  $\alpha_n = +\infty$  for all  $n$ , or  $\alpha_n \in \mathbf{R}$  and  $\alpha_1 \geq \alpha_2 \geq \alpha_3 \geq \dots$ .

Either  $\beta_n = -\infty$  for all  $n$ , or  $\beta_n \in \mathbf{R}$  and  $\beta_1 \leq \beta_2 \leq \beta_3 \leq \dots$ .

## Lim Sups and Lim Infs

**Definition 9.**

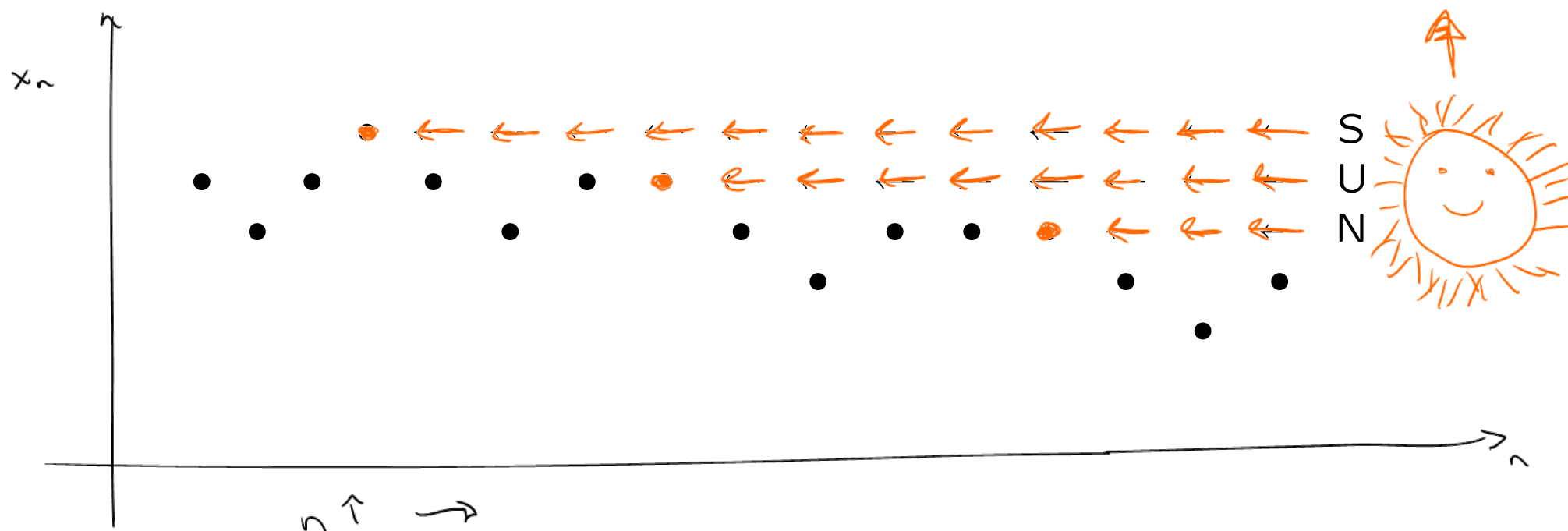
$$\begin{aligned}\limsup_{n \rightarrow \infty} x_n &= \begin{cases} +\infty & \text{if } \alpha_n = +\infty \text{ for all } n \\ \lim \alpha_n & \text{otherwise.} \end{cases} \\ \liminf_{n \rightarrow \infty} x_n &= \begin{cases} -\infty & \text{if } \beta_n = -\infty \text{ for all } n \\ \lim \beta_n & \text{otherwise.} \end{cases}\end{aligned}$$

**Theorem 7.** *Let  $\{x_n\}$  be a sequence of real numbers. Then*

$$\begin{aligned}\lim_{n \rightarrow \infty} x_n &= \gamma \in \mathbf{R} \cup \{-\infty, \infty\} \\ \Leftrightarrow \limsup_{n \rightarrow \infty} x_n &= \liminf_{n \rightarrow \infty} x_n = \gamma\end{aligned}$$

# Increasing and Decreasing Subsequences

**Theorem 8** (Theorem 3.2, Rising Sun Lemma). *Every sequence of real numbers contains an increasing subsequence or a decreasing subsequence or both.*



*Proof.* Let

$$S = \{s \in \mathbf{N} : x_s > x_n \quad \forall n > s\}$$

Either  $S$  is infinite, or  $S$  is finite. *(or empty)*

If  $S$  is infinite, let

$$\begin{aligned} n_1 &= \min S \\ n_2 &= \min (S \setminus \{n_1\}) \\ n_3 &= \min (S \setminus \{n_1, n_2\}) \\ &\vdots \\ n_{k+1} &= \min (S \setminus \{n_1, n_2, \dots, n_k\}) \end{aligned}$$

Then  $n_1 < n_2 < n_3 < \cdots$ .

$$\begin{array}{ll}
 x_{n_1} > x_{n_2} & \text{since } n_1 \in S \text{ and } n_2 > n_1 \\
 x_{n_2} > x_{n_3} & \text{since } n_2 \in S \text{ and } n_3 > n_2 \\
 & \vdots \\
 x_{n_k} > x_{n_{k+1}} & \text{since } n_k \in S \text{ and } n_{k+1} > n_k \\
 & \vdots
 \end{array}$$

so  $\{x_{n_k}\}$  is a strictly decreasing subsequence of  $\{x_n\}$ .

If  $S$  is finite and nonempty, let  $n_1 = (\max S) + 1$ ; if  $S = \emptyset$ , let  $n_1 = 1$ . Then

$$\begin{array}{ll}
 n_1 \notin S & \text{so } \exists n_2 > n_1 \text{ s.t. } x_{n_2} \geq x_{n_1} \\
 n_2 \notin S & \text{so } \exists n_3 > n_2 \text{ s.t. } x_{n_3} \geq x_{n_2} \\
 & \vdots \\
 n_k \notin S & \text{so } \exists n_{k+1} > n_k \text{ s.t. } x_{n_{k+1}} \geq x_{n_k} \\
 & \vdots
 \end{array}$$

so  $\{x_{n_k}\}$  is a (weakly) increasing subsequence of  $\{x_n\}$ .



## Bolzano-Weierstrass Theorem

**Theorem 9** (Thm. 3.3, Bolzano-Weierstrass). *Every bounded sequence of real numbers contains a convergent subsequence.*

*Proof.* Let  $\{x_n\}$  be a bounded sequence of real numbers. By the Rising Sun Lemma, find an increasing or decreasing subsequence  $\{x_{n_k}\}$ . If  $\{x_{n_k}\}$  is increasing, then by Theorem 3.1',

$$\lim x_{n_k} = \sup\{x_{n_k} : k \in \mathbf{N}\} \leq \sup\{x_n : n \in \mathbf{N}\} < \infty$$

since the sequence is bounded; since the limit is finite, the subsequence converges. Similarly, if the subsequence is decreasing, it converges. □



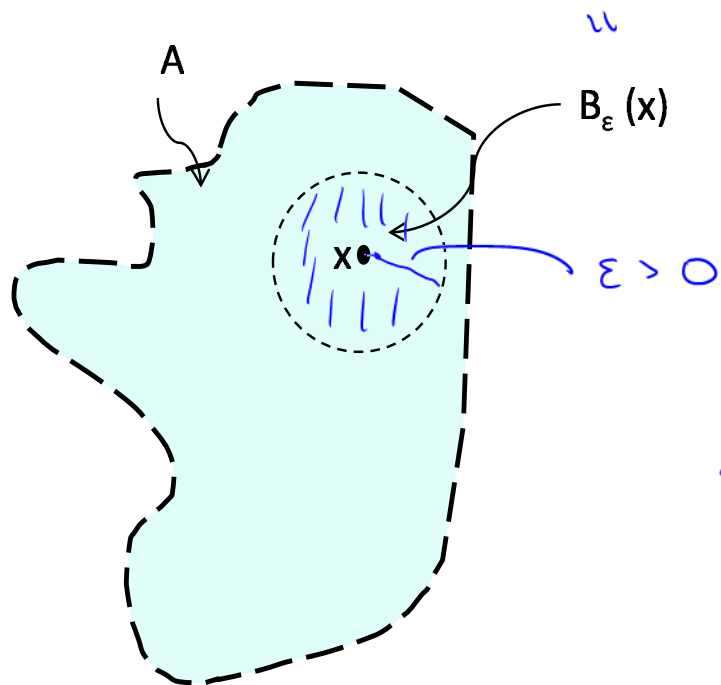
# Open and Closed Sets

**Definition 1.** *Let  $(X, d)$  be a metric space. A set  $A \subseteq X$  is open if*

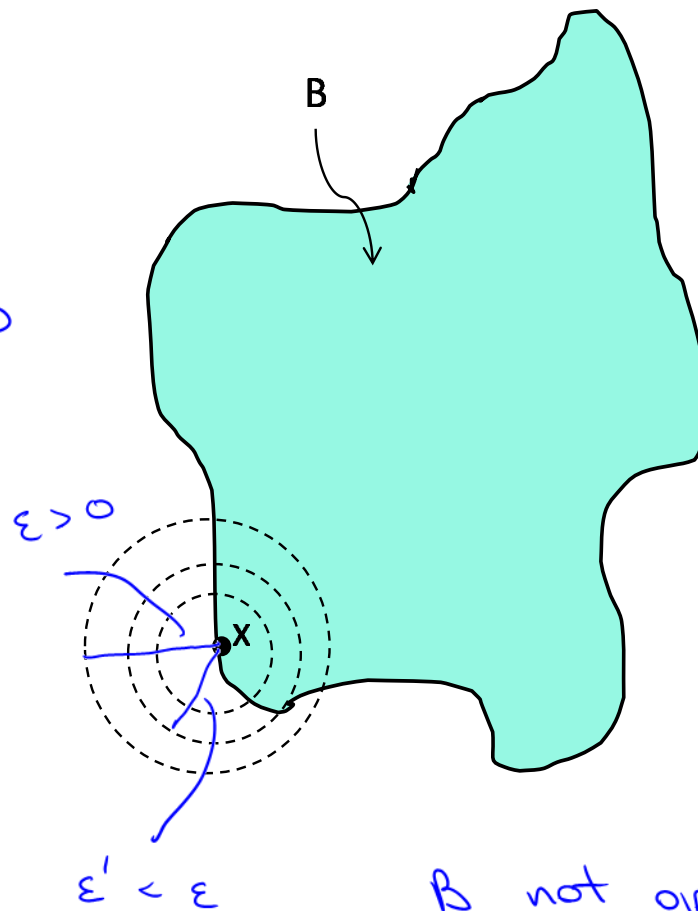
$$\forall x \in A \ \exists \varepsilon > 0 \text{ s.t. } B_\varepsilon(x) \subseteq A$$

*A set  $C \subseteq X$  is closed if  $X \setminus C$  is open.*

$$\{y \in X : d(y, x) < \varepsilon\}$$



A open



B not open:

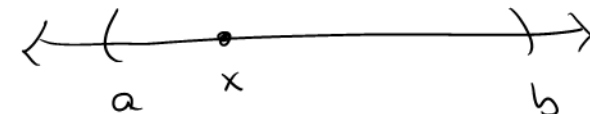
$\nexists \varepsilon > 0$  s.t.  $B_\varepsilon(x) \subseteq B$

# Open and Closed Sets

$(a, +\infty)$

**Example:**  $(a, b)$  is open in the metric space  $\mathbf{E}^1$  ( $\mathbf{R}$  with the usual Euclidean metric). Given  $x \in (a, b)$ ,  $a < x < b$ . Let

$$\varepsilon = \min\{x - a, b - x\} > 0$$



Then

$$\begin{aligned} -\varepsilon &\geq -(x - a) \\ \varepsilon &\leq b - x \end{aligned}$$

$$\begin{aligned} y \in B_\varepsilon(x) &\Rightarrow y \in (x - \varepsilon, x + \varepsilon) \\ &\subseteq (x - (x - a), x + (b - x)) \\ &= (a, b) \end{aligned}$$

so  $B_\varepsilon(x) \subseteq (a, b)$ , so  $(a, b)$  is open.

Notice that  $\varepsilon$  depends on  $x$ ; in particular,  $\varepsilon$  gets smaller as  $x$  nears the boundary of the set.

$$(X, d)$$

$$[a, +\infty)$$

## Open and Closed Sets

**Example:** In  $\mathbb{E}^1$ ,  $[a, b]$  is closed.  $\mathbb{R} \setminus [a, b] = (-\infty, a) \cup (b, \infty)$  is a union of two open sets, which must be open.

**Example:** In the metric space  $X = [0, 1]$ ,  $[0, 1]$  is open. With  $[0, 1]$  as the underlying metric space,  $[0, 1]$  is open. *with standard metric*

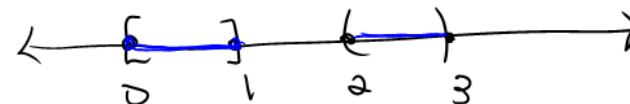
$$\varepsilon \in (0, 1) : B_\varepsilon(0) = \{x \in [0, 1] : |x - 0| < \varepsilon\} = [0, \varepsilon) \subseteq [0, 1]$$

$x \in X$

Thus, openness and closedness depend on the underlying metric space as well as on the set.

# Open and Closed Sets

**Example:** Most sets are neither open nor closed. For example, in  $\mathbb{E}^1$ ,  $[0, 1] \cup (2, 3)$  is neither open nor closed.



**Example:** An open set may consist of a single point. For example, if  $X = \mathbb{N}$  and  $d(m, n) = |m - n|$ , then

$$B_{1/2}(1) = \{m \in \mathbb{N} : |m - 1| < 1/2\} = \{1\}$$

Since 1 is the only element of the set  $\{1\}$  and  $B_{1/2}(1) = \{1\} \subseteq \{1\}$ , the set  $\{1\}$  is open.

# Open and Closed Sets

**Example:** In any metric space  $(X, d)$  both  $\emptyset$  and  $X$  are open, and both  $\emptyset$  and  $X$  are closed.

To see that  $\emptyset$  is open, note that the statement

$$\forall x \in \emptyset \exists \varepsilon > 0 B_\varepsilon(x) \subseteq \emptyset$$

is vacuously true since there aren't any  $x \in \emptyset$ . To see that  $X$  is open, note that since  $B_\varepsilon(x)$  is by definition  $\{z \in X : d(z, x) < \varepsilon\}$ , it is trivially contained in  $X$ .

Since  $\emptyset$  is open,  $X$  is closed; since  $X$  is open,  $\emptyset$  is closed.

↓  
 $X \sim \emptyset$

↓  
 $X \sim X$

# Open and Closed Sets

**Example:** Open balls are open sets.

Fix  $x \in X$ ,  $\varepsilon > 0$ .  $B_\varepsilon(x)$  is open:

Suppose  $y \in B_\varepsilon(x)$ . Then  $d(x, y) < \varepsilon$ . Let  $\delta = \varepsilon - d(x, y) > 0$ . If  $d(z, y) < \delta$ , then

$$\begin{array}{c} \updownarrow \\ z \in B_\delta(y) \end{array}$$

$$\begin{aligned} d(z, x) &\leq d(z, y) + d(y, x) \\ &< \delta + d(x, y) \\ &= \varepsilon - d(x, y) + d(x, y) \\ &= \varepsilon \end{aligned}$$

so  $B_\delta(y) \subseteq B_\varepsilon(x)$ , so  $B_\varepsilon(x)$  is open.



# Open and Closed Sets

**Theorem 1** (Thm. 4.2). *Let  $(X, d)$  be a metric space. Then*

- 1.  $\emptyset$  and  $X$  are both open, and both closed.*
- 2. The union of an arbitrary (finite, countable, or uncountable) collection of open sets is open.*
- 3. The intersection of a finite collection of open sets is open.*

*Proof.* 1. We have already shown this.



2. Suppose  $\{A_\lambda\}_{\lambda \in \Lambda}$  is a collection of open sets.

$$x \in \bigcup_{\lambda \in \Lambda} A_\lambda \Rightarrow \exists \lambda_0 \in \Lambda \text{ s.t. } x \in A_{\lambda_0} \quad \text{--- open}$$

$$\Rightarrow \exists \varepsilon > 0 \text{ s.t. } B_\varepsilon(x) \subseteq A_{\lambda_0} \subseteq \bigcup_{\lambda \in \Lambda} A_\lambda$$

so  $\bigcup_{\lambda \in \Lambda} A_\lambda$  is open.

3. Suppose  $A_1, \dots, A_n \subseteq X$  are open sets. If  $x \in \bigcap_{i=1}^n A_i$ , then

$$x \in A_1, x \in A_2, \dots, x \in A_n$$

so

$$\begin{array}{ccccccc} & \uparrow & \uparrow & \dots & \uparrow & & \\ & \text{open} & \text{open} & & \text{open} & & \\ \exists \varepsilon_1 > 0, \dots, \varepsilon_n > 0 \text{ s.t. } & B_{\varepsilon_1}(x) \subseteq A_1, & \dots, & B_{\varepsilon_n}(x) \subseteq A_n \end{array}$$

Let\*

$$\varepsilon = \min\{\varepsilon_1, \dots, \varepsilon_n\} > 0$$

Then

$$B_\varepsilon(x) \subseteq B_{\varepsilon_1}(x) \subseteq A_1, \dots, B_\varepsilon(x) \subseteq B_{\varepsilon_n}(x) \subseteq A_n$$

so

$$B_\varepsilon(x) \subseteq \bigcap_{i=1}^n A_i$$

which proves that  $\bigcap_{i=1}^n A_i$  is open.



\*Note this is where we need the fact that we are taking a finite intersection. The infimum of an infinite set of positive numbers could be zero. And the intersection of an infinite collection of open sets need not be open.

$$\{u \in X : u \subseteq A \text{ } u \text{ open}\}$$

$$A^\circ$$

## Interior, Closure, Exterior and Boundary

**Definition 2.** • The interior of  $A$ , denoted  $\text{int } A$ , is the largest open set contained in  $A$  (the union of all open sets contained in  $A$ ).

$$A \text{ not open} \Leftrightarrow \text{int } A \subsetneq A$$

- The closure of  $A$ , denoted  $\bar{A}$ , is the smallest closed set containing  $A$  (the intersection of all closed sets containing  $A$ )

$$A \text{ not closed} \Leftrightarrow A \subsetneq \bar{A}$$

- The exterior of  $A$ , denoted  $\text{ext } A$ , is the largest open set contained in  $X \setminus A$ .

$$(\text{ext } A = \text{int } (X \setminus A))$$

- The boundary of  $A$ , denoted  $\partial A = \overline{(X \setminus A)} \cap \bar{A}$

$$(\partial A = \bar{A} \setminus \text{int } A)$$

$$\{u \subseteq X : u \subseteq A, u \text{ open}\}$$

$$\cup \quad u$$

$$u \subseteq A, u \text{ open}$$

# Interior, Closure, Exterior and Boundary

$\mathbb{R}$  with standard metric:

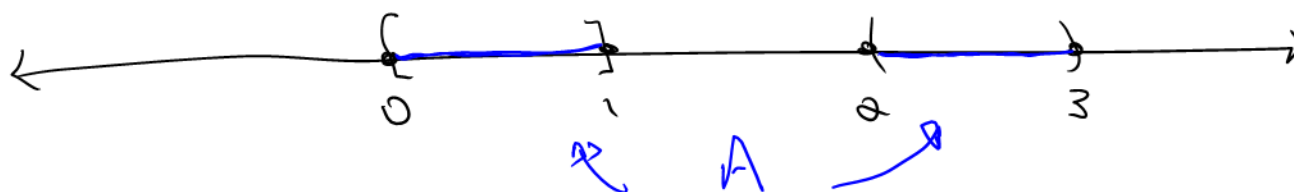
**Example:** Let  $A = [0, 1] \cup (2, 3)$ . Then

$$\text{int } A = (0, 1) \cup (2, 3)$$

$$\bar{A} = [0, 1] \cup [2, 3]$$

$$\begin{aligned} \text{ext } A &= \text{int}(X \setminus A) \\ &= (-\infty, 0) \cup (1, 2) \cup (3, +\infty) \end{aligned}$$

$$\begin{aligned} \partial A &= \overline{(X \setminus A)} \cap \bar{A} \\ &= ((-\infty, 0] \cup [1, 2] \cup [3, +\infty)) \cap ([0, 1] \cup [2, 3]) \\ &= \{0, 1, 2, 3\} \end{aligned}$$



## Sequences and Closed Sets

**Theorem 2** (Thm. 4.13). *A set  $A$  in a metric space  $(X, d)$  is closed if and only if*

$$\{x_n\} \subset A, x_n \rightarrow x \in X \Rightarrow x \in A$$

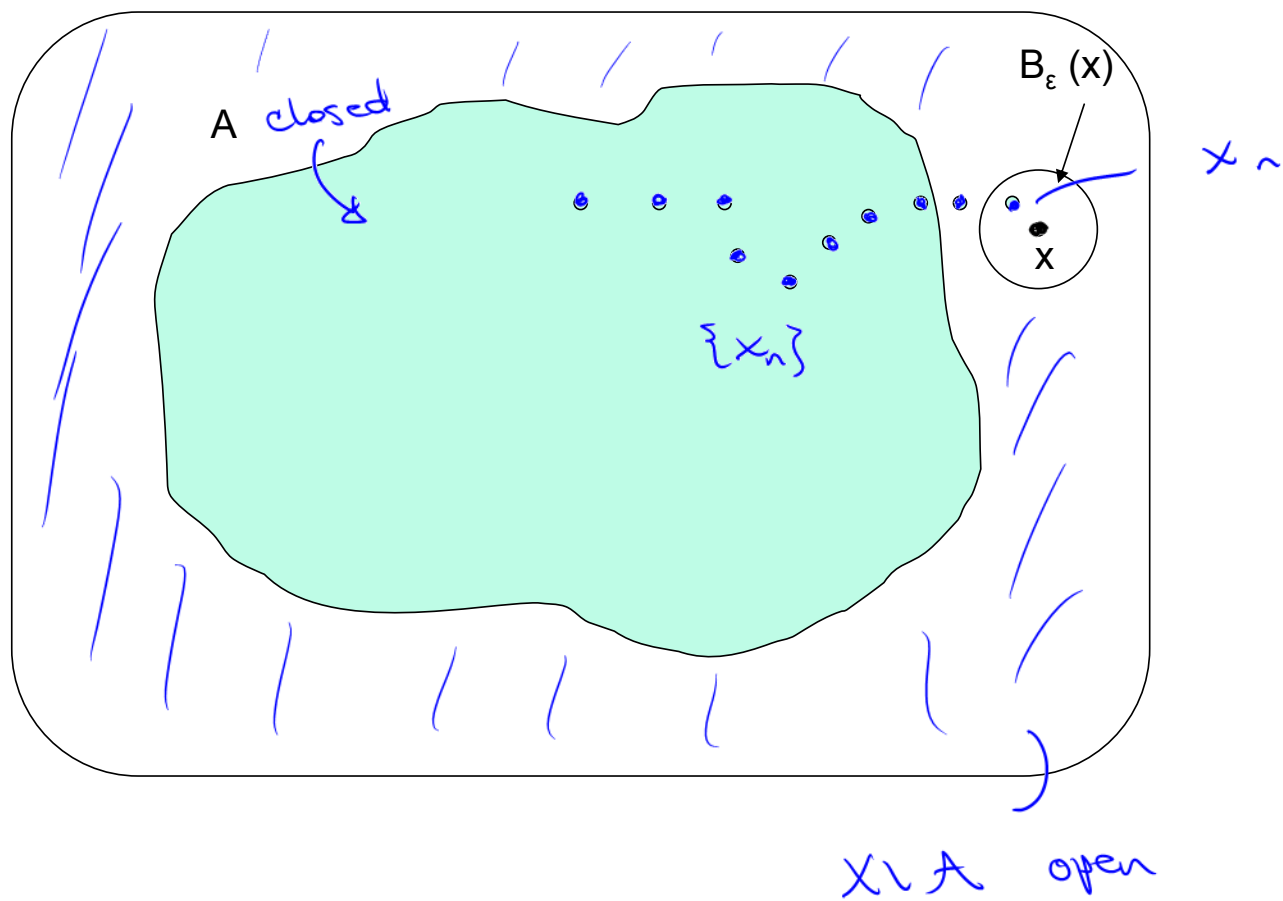
$\Rightarrow$ : *Proof.* Suppose  $A$  is closed. Then  $X \setminus A$  is open. Consider a convergent sequence  $x_n \rightarrow x \in X$ , with  $x_n \in A$  for all  $n$ . If  $x \notin A$ ,  $x \in X \setminus A$ , so there is some  $\varepsilon > 0$  such that  $B_\varepsilon(x) \subseteq X \setminus A$  (why?). Since  $x_n \rightarrow x$ , there exists  $N(\varepsilon)$  such that

$$\begin{aligned} n > N(\varepsilon) &\Rightarrow x_n \in B_\varepsilon(x) \\ &\Rightarrow x_n \in X \setminus A \\ &\Rightarrow x_n \notin A \end{aligned}$$

contradiction. Therefore,

$$\{x_n\} \subset A, x_n \rightarrow x \in X \Rightarrow x \in A$$

X





⇐ : Conversely, suppose

$$\{x_n\} \subset A, x_n \rightarrow x \in X \Rightarrow x \in A$$

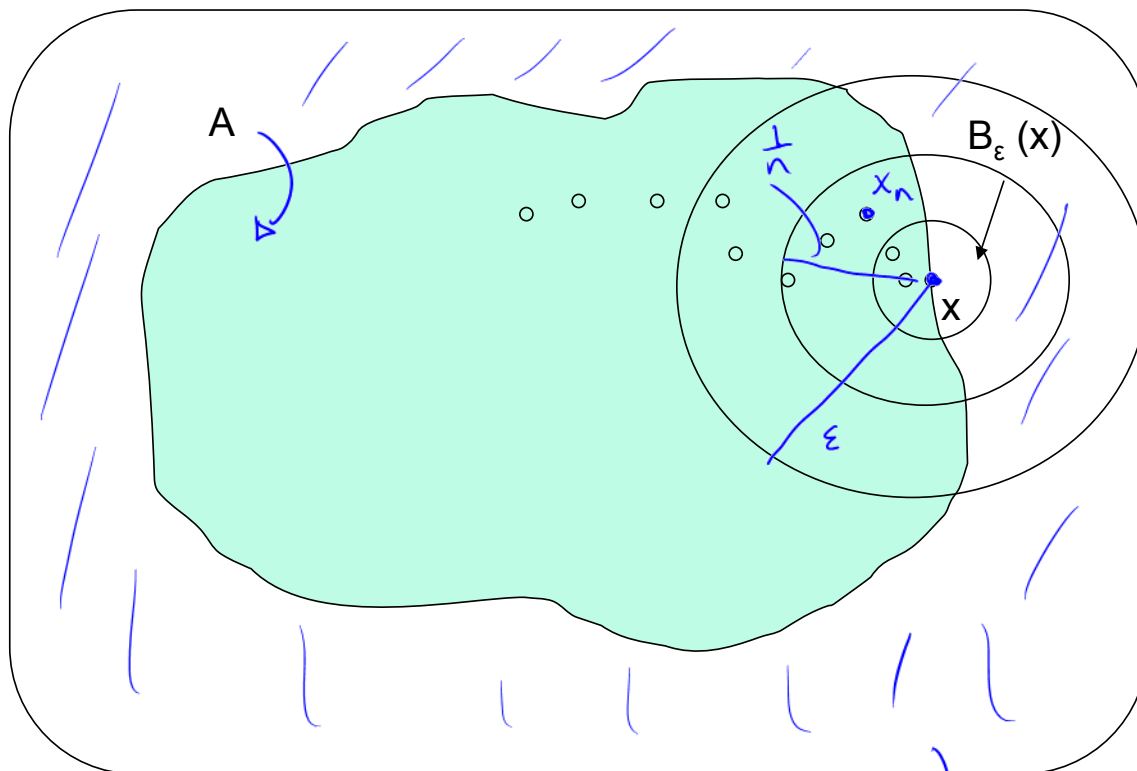
We need to show that  $A$  is closed, i.e.  $X \setminus A$  is open. Suppose not, so  $X \setminus A$  is not open. Then there exists  $x \in X \setminus A$  such that for every  $\varepsilon > 0$ ,

$$B_\varepsilon(x) \not\subset X \setminus A$$

so there exists  $y \in B_\varepsilon(x)$  such that  $y \notin X \setminus A$ . Then  $y \in A$ , hence

$$B_\varepsilon(x) \cap A \neq \emptyset \quad \forall \varepsilon > 0$$

$X$



$x \in X \setminus A$

$X \setminus A$

Construct a sequence  $\{x_n\}$  as follows: for each  $n$ , choose

$$x_n \in B_{\frac{1}{n}}(x) \cap A$$

Given  $\varepsilon > 0$ , we can find  $N(\varepsilon)$  such that  $N(\varepsilon) > \frac{1}{\varepsilon}$  by the Archimedean Property. So  $n > N(\varepsilon) \Rightarrow \frac{1}{n} < \frac{1}{N(\varepsilon)} < \varepsilon$  and  $x_n \in B_{\frac{1}{n}}(x) \subseteq B_\varepsilon(x)$ . Thus  $x_n \rightarrow x$ . Then  $\{x_n\} \subseteq A$ ,  $x_n \rightarrow x$ , so  $\underline{x \in A}$ , contradiction. Therefore,  $X \setminus A$  is open, so  $A$  is closed.  $\square$

## Continuity in Metric Spaces

**Definition 3.** Let  $(X, d)$  and  $(Y, \rho)$  be metric spaces. A function  $f : X \rightarrow Y$  is continuous at a point  $x_0 \in X$  if

$$\forall \varepsilon > 0 \exists \delta(x_0, \varepsilon) > 0 \text{ s.t. } d(x, x_0) < \delta(x_0, \varepsilon) \Rightarrow \rho(f(x), f(x_0)) < \varepsilon$$

$f$  is continuous if it is continuous at every element of its domain.

Note that  $\delta$  can depend on  $x_0$  and  $\varepsilon$ .

# Continuity in Metric Spaces

Continuity at  $x_0$  requires:

- $f(x_0)$  is defined; and
- either
  - $x_0$  is an isolated point of  $X$ , i.e.  $\exists \varepsilon > 0$  s.t.  $B_\varepsilon(x_0) = \{x_0\}$ ;  
or
  - $\lim_{x \rightarrow x_0} f(x)$  exists and equals  $f(x_0)$

# Continuity in Metric Spaces

Suppose  $f : X \rightarrow Y$  and  $A \subseteq Y$ . Define

$$f^{-1}(A) = \{x \in X : f(x) \in A\}$$

**Theorem 3** (Theorem 6.14). *Let  $(X, d)$  and  $(Y, \rho)$  be metric spaces, and  $f : X \rightarrow Y$ . Then  $f$  is continuous if and only if*

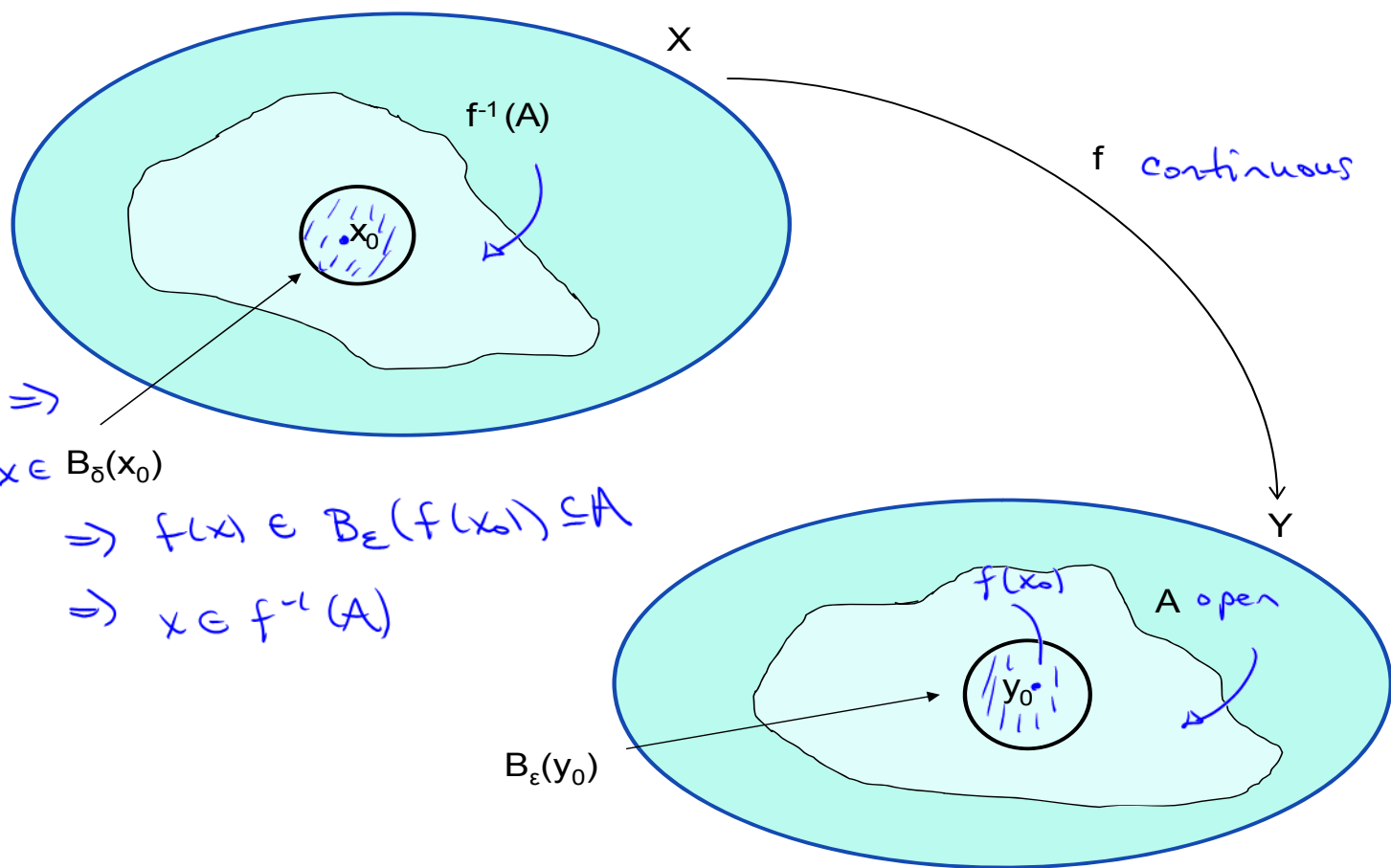
$$f^{-1}(A) \text{ is open in } X \ \forall A \subseteq Y \text{ s.t. } A \text{ is open in } Y$$

Alternatively,  $f$  is continuous  $\iff f^{-1}(C)$  is closed in  $X$  for every closed  $C \subseteq Y$ .

$\Rightarrow$ : *Proof.* Suppose  $f$  is continuous. Given  $A \subseteq Y$ ,  $A$  open, we must show that  $f^{-1}(A)$  is open in  $X$ . Suppose  $x_0 \in f^{-1}(A)$ . Let  $y_0 = f(x_0) \in A$ . Since  $A$  is open, we can find  $\varepsilon > 0$  such that  $B_\varepsilon(y_0) \subseteq A$ . Since  $f$  is continuous, there exists  $\delta > 0$  such that

$$\begin{aligned} x \in B_\delta(x_0) &\Rightarrow d(x, x_0) < \delta \Rightarrow \rho(f(x), f(x_0)) < \varepsilon \\ &\Rightarrow f(x) \in B_\varepsilon(y_0) \subseteq A \\ &\Rightarrow f(x) \in A \\ &\Rightarrow x \in f^{-1}(A) \end{aligned}$$

so  $B_\delta(x_0) \subseteq f^{-1}(A)$ , so  $f^{-1}(A)$  is open.



$f \text{ cont} \Rightarrow$   
 $\exists \delta > 0 \text{ s.t. } x \in B_{\delta}(x_0)$   
 $\Rightarrow f(x) \in B_{\epsilon}(f(x_0)) \subseteq A$   
 $\Rightarrow x \in f^{-1}(A)$



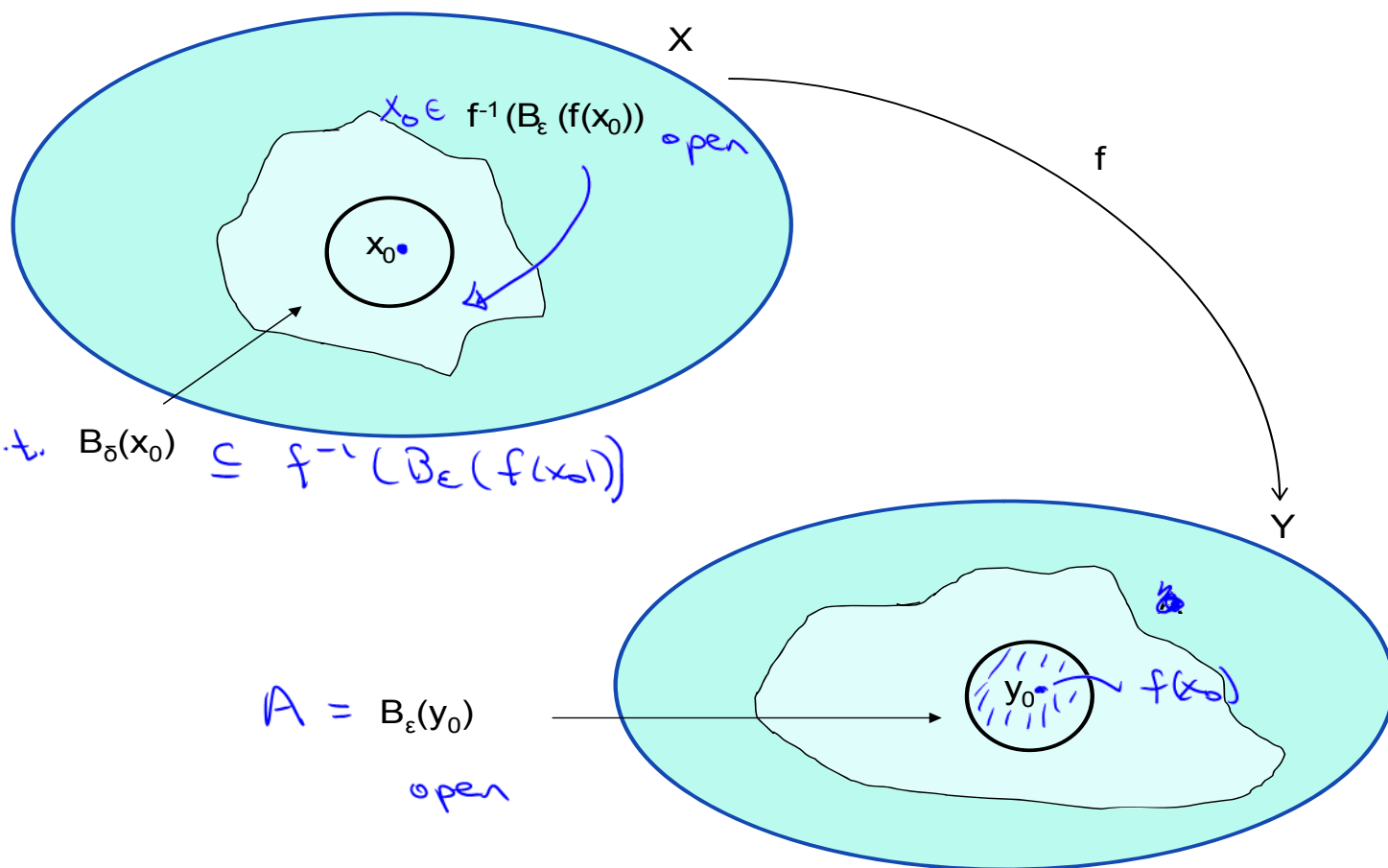
$\Leftarrow$  : Conversely, suppose

$f^{-1}(A)$  is open in  $X \ \forall A \subseteq Y$  s.t.  $A$  is open in  $Y$

We need to show that  $f$  is continuous. Let  $x_0 \in X$ ,  $\varepsilon > 0$ . Let  $A = B_\varepsilon(f(x_0))$ .  $A$  is an open ball, hence an open set, so  $f^{-1}(A)$  is open in  $X$ .  $x_0 \in f^{-1}(A)$ , so there exists  $\delta > 0$  such that  $B_\delta(x_0) \subseteq f^{-1}(A)$ .

$$\begin{aligned} \underline{d(x, x_0) < \delta} &\Rightarrow x \in B_\delta(x_0) \\ &\Rightarrow x \in f^{-1}(A) \\ &\Rightarrow f(x) \in A (= B_\varepsilon(f(x_0))) \\ &\Rightarrow \underline{\rho(f(x), f(x_0)) < \varepsilon} \end{aligned}$$

Fix  $x_0 \in X$ ,  $\varepsilon > 0$



$\Rightarrow \exists \delta > 0$  s.t.  $B_\delta(x_0) \subseteq f^{-1}(B_\varepsilon(f(x_0)))$

$A = B_\varepsilon(y_0)$   
open

Thus, we have shown that  $f$  is continuous at  $x_0$ ; since  $x_0$  is an arbitrary point in  $X$ ,  $f$  is continuous.  $\square$

# Continuity in Metric Spaces

The composition of continuous functions is continuous:

**Theorem 4** (Slightly weaker version of Thm. 6.10). *Let  $(X, d_X)$ ,  $(Y, d_Y)$  and  $(Z, d_Z)$  be metric spaces. If  $f : X \rightarrow Y$  and  $g : Y \rightarrow Z$  are continuous, then  $g \circ f : X \rightarrow Z$  is continuous.*

*Proof.* Suppose  $A \subseteq Z$  is open. Since  $g$  is continuous,  $g^{-1}(A)$  is open in  $Y$ ; since  $f$  is continuous,  $f^{-1}(\underbrace{g^{-1}(A)}_{\text{open}})$  is open in  $X$ .

We claim that

$$f^{-1}(g^{-1}(A)) = (g \circ f)^{-1}(A)$$

Observe

$$\begin{aligned}x \in f^{-1}(g^{-1}(A)) &\Leftrightarrow f(x) \in g^{-1}(A) \\&\Leftrightarrow g(f(x)) \in A \\&\Leftrightarrow (g \circ f)(x) \in A \\&\Leftrightarrow x \in (g \circ f)^{-1}(A)\end{aligned}$$

which establishes the claim. This shows that  $(g \circ f)^{-1}(A)$  is open in  $X$ , so  $g \circ f$  is continuous.  $\square$

## Uniform Continuity

**Definition 4** (Uniform Continuity). *Let  $(X, d)$  and  $(Y, \rho)$  be metric spaces. A function  $f : X \rightarrow Y$  is uniformly continuous if*

$$\forall \varepsilon > 0 \exists \delta(\varepsilon) > 0 \text{ s.t. } \forall x_0 \in X, d(x, x_0) < \delta(\varepsilon) \Rightarrow \rho(f(x), f(x_0)) < \varepsilon$$

Notice the important contrast with continuity:  $f$  is continuous means

$$\forall x_0 \in X, \varepsilon > 0 \exists \delta(x_0, \varepsilon) > 0 \text{ s.t. } d(x, x_0) < \delta(x_0, \varepsilon) \Rightarrow \rho(f(x), f(x_0)) < \varepsilon$$

# Uniform Continuity

**Example:** Consider  $f : (0, 1] \rightarrow \mathbf{R}$  given by

$$f(x) = \frac{1}{x}, \quad x \in (0, 1]$$

$f$  is continuous (why?). We will show that  $f$  is **not** uniformly continuous.

Let  $\varepsilon_0 = 1$ . Take any  $\delta > 0$  with  $\delta \leq 1$ . Set  $x = \frac{\delta}{3}$  and  $y = \frac{\delta}{6}$ . So

$$|x - y| = \frac{\delta}{6} < \delta$$

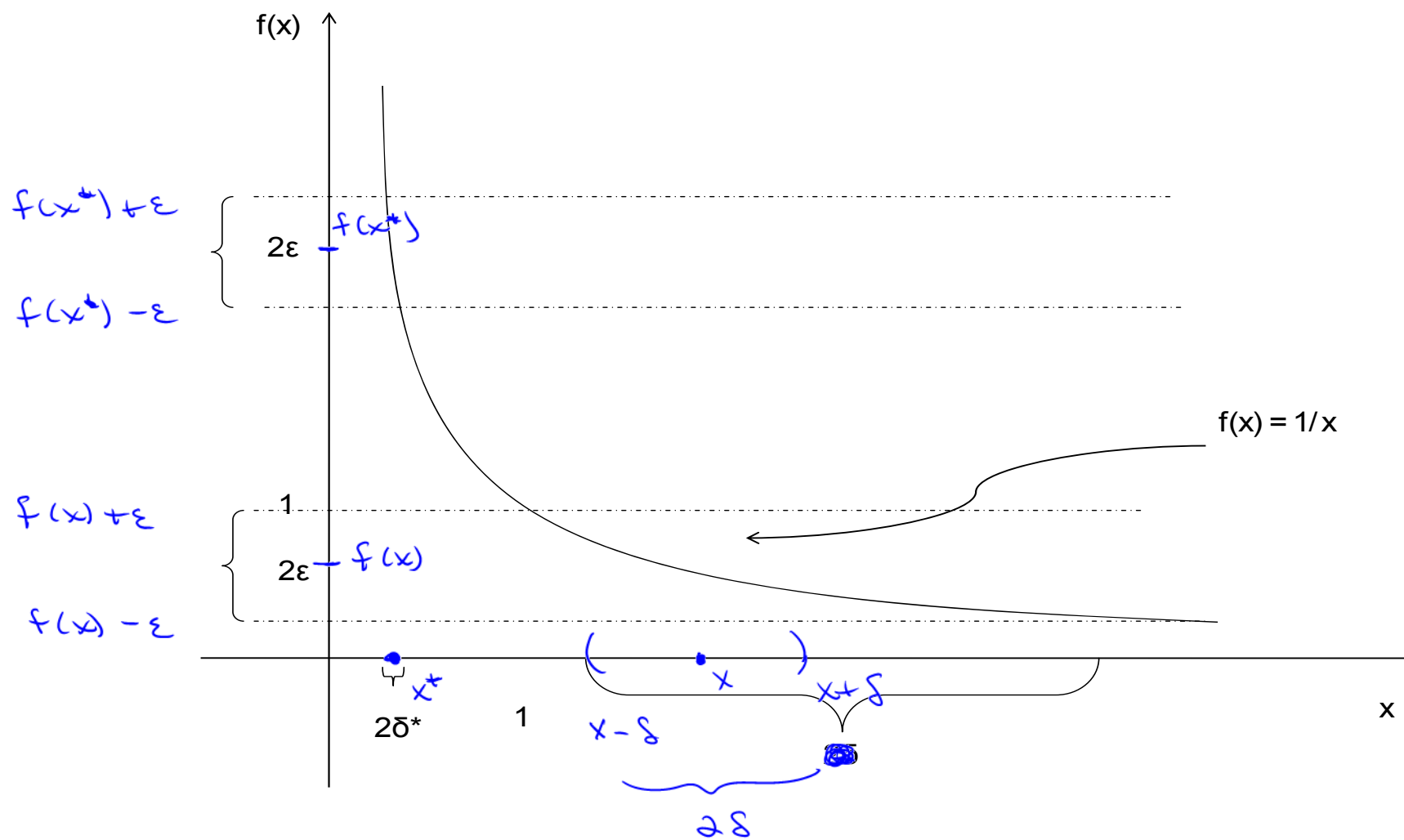
But

$$|f(x) - f(y)| = \frac{|x - y|}{|xy|} = \left| \frac{\delta/6}{\delta^2/18} \right|$$

$$\stackrel{\text{u}}{\frac{1}{x}} \quad \stackrel{=}{\frac{1}{y}} = \frac{3}{\delta} > 1 = \varepsilon_0$$



Fix  $\varepsilon > 0$ .



## Uniform Continuity

**Example:** If  $f : \mathbf{R} \rightarrow \mathbf{R}$  and  $f'(x)$  is defined and ~~uniformly~~ bounded on an interval  $[a, b]$ , then  $f$  is uniformly continuous on  $[a, b]$ . However, even a function with an unbounded derivative may be uniformly continuous. Consider

$$f(x) = \sqrt{x}, \quad x \in [0, 1]$$

$f$  is continuous (why?). We will show that  $f$  is uniformly continuous. Given  $\varepsilon > 0$ , let  $\delta = \varepsilon^2$ . Then given any  $x_0 \in [0, 1]$ ,

$|x - x_0| < \delta$  implies by the Fundamental Theorem of Calculus

$$\begin{aligned} |f(x) - f(x_0)| &= \left| \int_{x_0}^x \frac{1}{2\sqrt{t}} dt \right| \\ &\leq \int_0^{|x-x_0|} \frac{1}{2\sqrt{t}} dt \\ &= \sqrt{|x - x_0|} \\ &< \sqrt{\delta} \\ &= \sqrt{\varepsilon^2} \\ &= \varepsilon \end{aligned}$$

Thus,  $f$  is uniformly continuous on  $[0, 1]$ , even though  $f'(x) \rightarrow \infty$  as  $x \rightarrow 0$ .

# Lipschitz Continuity

**Definition 5.** Let  $X, Y$  be normed vector spaces,  $E \subseteq X$ . A function  $f : X \rightarrow Y$  is Lipschitz on  $E$  if

$$\exists K > 0 \text{ s.t. } \|f(x) - f(z)\|_Y \leq K\|x - z\|_X \quad \forall x, z \in E$$

$f$  is locally Lipschitz on  $E$  if

$$\forall x_0 \in E \exists \varepsilon > 0 \text{ s.t. } f \text{ is Lipschitz on } B_\varepsilon(x_0) \cap E$$

$$f \text{ Lipschitz} \Rightarrow \exists K > 0 \text{ s.t. } \forall x \neq y,$$

$$\frac{\|f(x) - f(y)\|}{\|x - y\|} \leq K$$

# Notions of Continuity

Lipschitz continuity is stronger than either continuity or uniform continuity:

Lipschitz  $\Rightarrow$  locally Lipschitz  $\Rightarrow$  continuous

Lipschitz  $\Rightarrow$  uniformly continuous

Every  $C^1$  function  $f: \mathbb{R}^m \rightarrow \mathbb{R}^n$  is locally Lipschitz. (Recall that a function  $f: \mathbb{R}^m \rightarrow \mathbb{R}^n$  is said to be  $C^1$  if all its first partial derivatives exist and are continuous.)

# Homeomorphisms

**Definition 6.** *Let  $(X, d)$  and  $(Y, \rho)$  be metric spaces. A function  $f : X \rightarrow Y$  is called a homeomorphism if it is one-to-one, onto, continuous, and its inverse function is continuous.*

Topological properties are invariant under homeomorphism:

# Homeomorphisms

Suppose that  $f$  is a homeomorphism and  $U \subset X$ . Let  $g = f^{-1} : Y \rightarrow X$ .

$$y \in g^{-1}(U) \Leftrightarrow g(y) \in U$$

$$\Leftrightarrow y \in f(U)$$

$$U \text{ open in } X \Rightarrow g^{-1}(U) \text{ is open in } (f(X), \rho)$$

$$\Rightarrow f(U) \text{ is open in } (f(X), \rho)$$

This says that  $(X, d)$  and  $(f(X), \rho|_{f(X)})$  are identical in terms of properties that can be characterized solely in terms of open sets; such properties are called “topological properties.”