# 5 | Closed Sets, Interior, Closure, Boundary

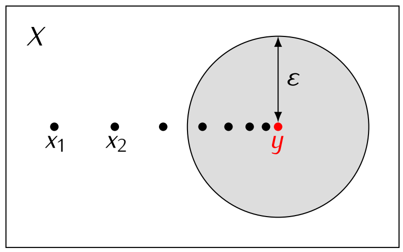
**5.1 Definition.** Let $X$ be a topological space. A set $A \subseteq X$ is a *closed set* if the set $X \smallsetminus A$ is open.

**5.5 Proposition.** *Let $X$ be a topological space.*

1) *The sets $X$, $\varnothing$ are closed.*
2) *If $A_i \subseteq X$ is a closed set for $i \in I$ then $\bigcap_{i \in I} A_i$ is closed.*
3) *If $A_1$, $A_2$ are closed sets then the set $A_1 \cup A_2$ is closed.*

**5.7 Definition.** Let $(X, \varrho)$ be a metric space, and let $\{x_n\}$ be a sequence of points in $X$. We say that $\{x_n\}$ *converges* to a point $y \in X$ if for every $\varepsilon > 0$ there exists $N > 0$ such that $\varrho(y, x_n) < \varepsilon$ for all $n > N$. We write: $x_n \to y$.

Equivalently: $x_n \to y$ if for every $\varepsilon > 0$ there exists $N > 0$ such that $x_n \in B(y, \varepsilon)$ for all $n > N$.



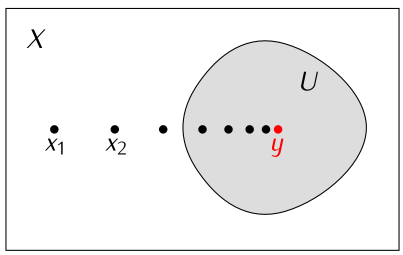

**5.8 Proposition.** *Let $(X, \varrho)$ be a metric space and let $A \subseteq X$. The following conditions are equivalent:*

1) *The set $A$ is closed in $X$.*
2) *If $\{x_n\} \subseteq A$ and $x_n \to y$ then $y \in A$.*

*Proof.* Exercise. □

**5.10 Definition.** Let $X$ be a topological space and $y \in X$. If $U \subseteq X$ is an open set such that $y \in U$ then we say that $U$ is an *open neighborhood of* $y$.

**5.11 Definition.** Let $X$ be a topological space. A sequence $\{x_n\} \subseteq X$ *converges* to $y \in X$ if for every open neighborhood $U$ of $y$ there exists $N > 0$ such that $x_n \in U$ for $n > N$.




**5.12 Note.** In general topological spaces a sequence may converge to many points at the same time.

**5.13 Proposition.** *Let* $(X, \varrho)$ *be a metric space and let* $\{x_n\}$ *be a sequence in* $X$*. If* $x_n \to y$ *and* $x_n \to z$ *for some* $y, z \in X$ *then* $y = z$*.*

*Proof.* Exercise. □

**5.14 Proposition.** *Let $X$ be a topological space and let $A \subseteq X$ be a closed set. If $\{x_n\} \subseteq A$ and $x_n \to y$ then $y \in A$.*

*Proof.* Exercise. $\square$

**5.16 Example.** Let $X = \mathbb{R}$ with the following topology:

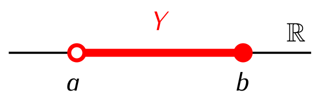
$$\mathcal{T} = \{U \subseteq \mathbb{R} \mid U = \varnothing \text{ or } U = (\mathbb{R} \smallsetminus S) \text{ for some countable set } S \subseteq \mathbb{R}\}$$

Closed sets in $X$ are the whole space $\mathbb{R}$ and all countable subsets of $\mathbb{R}$. If $\{x_n\} \subseteq X$ is a sequence then $x_n \to y$ if and only if there exists $N > 0$ such that $x_n = y$ for all $n > N$ (exercise). It follows that if $A$ is any (closed or not) subset of $X$, $\{x_n\} \subseteq A$, and $x_n \to y$ then $y \in A$.

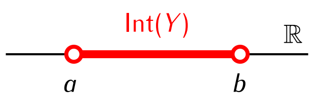
**5.17 Definition.** Let $X$ be a topological space and let $Y \subseteq X$.

- The *interior of* $Y$ is the set $\mathrm{Int}(Y) := \bigcup \{U \mid U \subseteq Y \text{ and } U \text{ is open in } X\}$.
- The *closure of* $Y$ is the set $\overline{Y} := \bigcap \{A \mid Y \subseteq A \text{ and } A \text{ is closed in } X\}$.
- The *boundary of* $Y$ is the set $\mathrm{Bd}(Y) := \overline{Y} \cap \overline{(X \smallsetminus Y)}$.

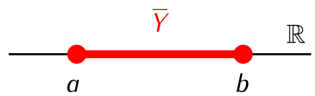
**5.18 Example.** Consider the set $Y = (a, b]$ in $\mathbb{R}$:



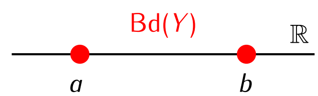

We have:




$\mathrm{Int}(Y) = (a, b)$

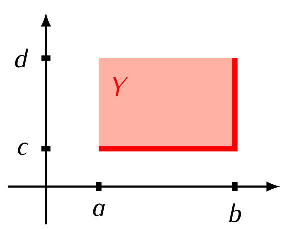



$\overline{Y} = [a, b]$

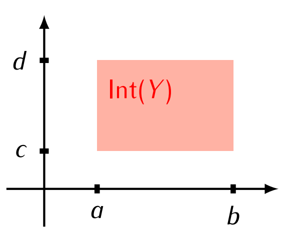



$\mathrm{Bd}(Y) = \{a, b\}$

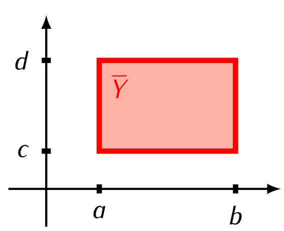
**5.19 Example.** Consider the set $Y = \{(x_1, x_2) \in \mathbb{R}^2 \mid a < x_1 \leq b,\ c \leq x_2 < d\}$ in $\mathbb{R}^2$:



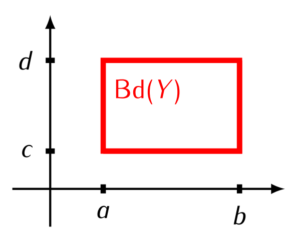

We have:




$\mathrm{Int}(Y) = (a, b) \times (c, d)$




$\overline{Y} = [a, b] \times [c, d]$




$\mathrm{Bd}(Y) = [a, b] \times \{c, d\}$
$\cup \{a, b\} \times [c, d]$

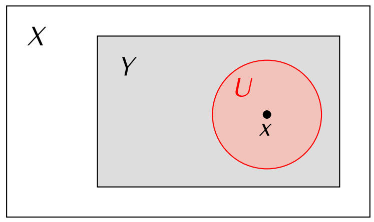
**5.20 Proposition.** *Let $X$ be a topological space and let $Y \subseteq X$.*

1) *The set* $\mathrm{Int}(Y)$ *is open in $X$. It is the biggest open set contained in $Y$: if $U$ is open and $U \subseteq Y$ then* $U \subseteq \mathrm{Int}(Y)$.
2) *The set $\overline{Y}$ is closed in $X$. It is the smallest closed set that contains $Y$: if $A$ is closed and $Y \subseteq A$ then $\overline{Y} \subseteq A$.*

*Proof.* Exercise. □

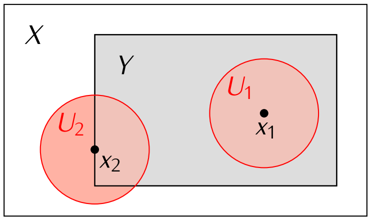
**5.21 Proposition.** *Let $X$ be a topological space, let $Y \subseteq X$, and let $x \in X$. The following conditions are equivalent:*

1) $x \in \operatorname{Int}(Y)$
2) *There exists an open neighborhood $U$ of $x$ such that $U \subseteq Y$.*



**5.22 Proposition.** *Let $X$ be a topological space, let $Y \subseteq X$, and let $x \in X$. The following conditions are equivalent:*

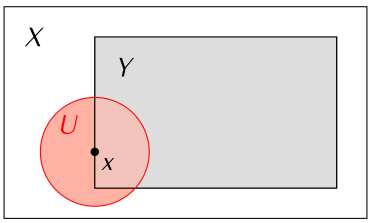
1) $x \in \overline{Y}$
2) *For every open neighborhood $U$ of $x$ we have $U \cap Y \neq \varnothing$.*




*Proof.* Exercise. □

**5.23 Proposition.** *Let $X$ be a topological space, let $Y \subseteq X$, and let $x \in X$. The following conditions are equivalent:*

1) $x \in \mathrm{Bd}(Y)$
2) *For every open neighborhood $U$ of $x$ we have $U \cap Y \neq \varnothing$ and $U \cap (X \smallsetminus Y) \neq \varnothing$.*



**5.24 Definition.** Let $X$ be a topological space. A set $Y \subseteq X$ is *dense in* $X$ if $\overline{Y} = X$.

**5.25 Proposition.** *Let $X$ be a topological space and let $Y \subseteq X$. The following conditions are equivalent:*

*1) $Y$ is dense in $X$*

*2) If $U \subseteq X$ is an open set and $U \neq \varnothing$ then $U \cap Y \neq \varnothing$.*

**5.26 Example.** The set of rational numbers $\mathbb{Q}$ is dense in $\mathbb{R}$.