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CSCI4230 Computational Learning Theory
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Spring 2019
Based on *Rocco Servedio's* notes

Notes 5: VC dimension

1. VAPNIK-CHERVONENKIS DIMENSION

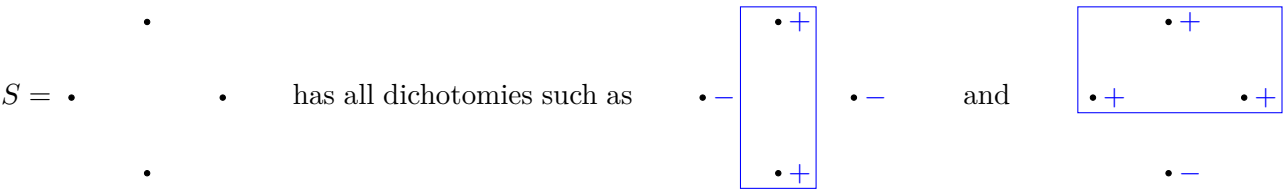
Related to mistake lower bounds in Online Learning

Usually an integer, telling us how expressive a concept class \mathcal{C} is

Given concept class \mathcal{C} over instance space X , subset $S \subseteq X$ is **shattered** by \mathcal{C} if all “dichotomies” of S can be induced by \mathcal{C} , i.e.:

$$\forall T \subseteq S, \exists c \in \mathcal{C} \text{ s.t. } c \cap S = T$$

$X = \text{the plane} = \mathbb{R}^2$ $\mathcal{C} = \text{axis-aligned rectangles}$



$\text{VCDim}(\mathcal{C})$ is the size of the largest subset $S \subseteq X$ shattered by \mathcal{C}

$\text{VCDim}(\mathcal{C}) = d$ if and only if

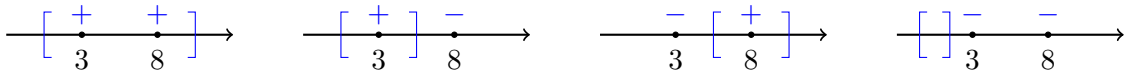
- (1) some subset $S \subseteq X$ with $|S| = d$ is shattered by \mathcal{C} ; and
- (2) all subsets of size $d + 1$ is not shattered by \mathcal{C}

$\text{VCDim}(\mathcal{C})$ can be ∞

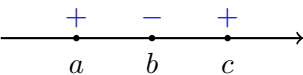
Example: Closed intervals of the real line

$X = \mathbb{R}$ $\mathcal{C} = \text{closed intervals} = \{[a, b] \mid a, b \in \mathbb{R}\}$ where $[a, b] = \{x \in \mathbb{R} \mid a \leq x \text{ and } x \leq b\}$

Every two points (e.g. 3 and 8) can be shattered $\implies \text{VCDim}(\mathcal{C}) \geq 2$



No three points ($a < b < c$) can be shattered $\implies \text{VCDim}(\mathcal{C}) \leq 2$



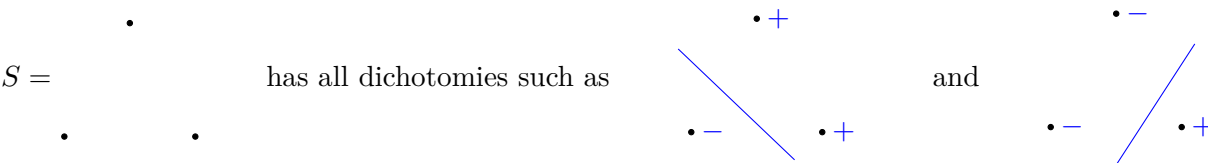
Example: Halfspaces in the plane

$X = \mathbb{R}^2$

$\mathcal{C} = \text{LTF}$

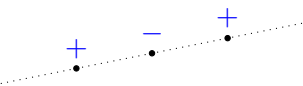
Any three non-collinear points can be shattered

$\implies \text{VCDim}(\mathcal{C}) \geq 3$



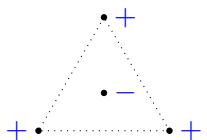
No four points can be shattered $\implies \text{VCDim}(\mathcal{C}) \leq 3$

Case 1: contains three collinear points



Case 2: No three points collinear

Case 2a: Some point inside the triangle formed by three other points

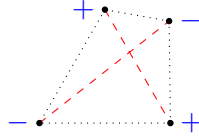


Case 2b: Four points form a convex quadrilateral

\iff

the **two diagonals** cross

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endpoints of two diagonals get different labels

Example: $X = \{0, 1\}^n$ $\mathcal{C} = \{\text{monotone conjunction}\}$ e.g. $c(x) = x_2 \wedge x_5 \wedge x_7 \in \mathcal{C}$
 $\text{VCDim}(\mathcal{C}) \geq n$: $S = \{a_j = \text{vector with 0 at position } j \text{ and 1 everywhere else} \mid 1 \leq j \leq n\}$

$$\text{e.g. } n = 4 \quad S = \begin{Bmatrix} 0111, \\ 1011, \\ 1101, \\ 1110 \end{Bmatrix}, \quad T = \begin{Bmatrix} 0111, \\ 1101, \\ 1110 \end{Bmatrix} \text{ induced by } c(x) = x_2$$

Every subset $T \subseteq S$ is induced by $c \in \mathcal{C}$ containing precisely variables x_j s.t. $a_j \notin T$
 $\text{VCDim}(\mathcal{C}) \leq n$: because $|\mathcal{C}| = 2^n$ and
Observation: $\text{VCDim}(\mathcal{C}) \geq d$ implies $|\mathcal{C}| \geq 2^d$

2. ONLINE MISTAKE LOWERBOUNDS FROM VC DIMENSION

Claim 2.1. *Any deterministic algorithm for learning \mathcal{C} makes $\geq \text{VCDim}(\mathcal{C})$ mistakes on some sample sequence*

Proof. $S = \{x^1, \dots, x^d\}$ be shattered set of size $d = \text{VCDim}(\mathcal{C})$

Instance sequence is x^1, \dots, x^d

On sample x^i , algorithm predicts $b_i \in \{0, 1\}$

Can find $c \in \mathcal{C}$ s.t. $c(x^i) = \bar{b}_i$ for all $1 \leq i \leq n$ (opposite of all predictions) \square

Claim 2.2. *Some fixed sample sequence causes every randomized algorithm for learning \mathcal{C} to make $\geq \text{VCDim}(\mathcal{C})/2$ mistakes in expectation*

Previous claim follows from the next claim (via Yao's minimax principle, not covered in this course)

Claim 2.3. *Some distribution of random sample sequences causes every deterministic algorithm for learning \mathcal{C} to make $\geq \text{VCDim}(\mathcal{C})/2$ mistakes in expectation*

Proof. $S = \{x^1, \dots, x^d\}$ be shattered set of size $d = \text{VCDim}(\mathcal{C})$

Sample sequence is $(x^1, y^1), \dots, (x^d, y^d)$, where y^1, \dots, y^d are uniformly random bits

Any algorithm predicting d uniformly random bits makes $d/2$ mistakes in expectation

For every choice of random bits y^1, \dots, y^d , some $c \in \mathcal{C}$ correctly labels all instances x^1, \dots, x^d \square

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