



## MSML610: Advanced Machine Learning

# Machine Learning Theories

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**References:**

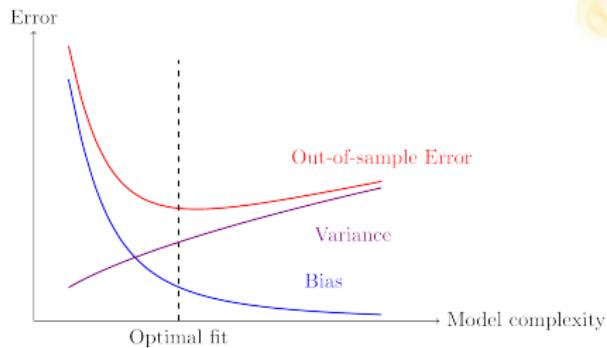
- Abu-Mostafa et al.: “*Learning From Data*” (2012)



- ***Is Machine Learning Even Possible?***
- Growth Function
- The VC Dimension
- Overfitting
- Bias Variance Analysis
- Learning Curves
- Learn-Validation Approach

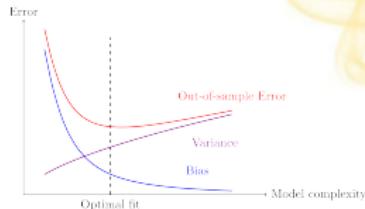
# A Simple Visual ML Experiment (1/2)

- Consider the supervised classification problem
- **Input**
  - A 9 bit vector represented as a  $3 \times 3$  array
- **Training set**
  - The blue row  $\underline{x}_1, \underline{x}_2, \underline{x}_3$  for  $f(\underline{x}) = -1$
  - The green row  $\underline{x}_4, \underline{x}_5, \underline{x}_6$  for  $f(\underline{x}) = +1$
- **Test set**
  - For the red pattern  $\underline{x}_0$ , is  $f(\underline{x}_0) = -1$  or  $+1$ ?



# A Simple Visual ML Experiment (2/2)

- **Model 1**
  - $f(\underline{x}) = +1$  when  $\underline{x}$  has an axis of symmetry
  - $f(\underline{x}) = -1$  when  $\underline{x}$  is not symmetric
  - The test set is symmetrical  $\Rightarrow f(\underline{x}_0) = +1$
- **Model 2**
  - $f(\underline{x}) = +1$  when the top left square  $\underline{x}$  is empty
  - $f(\underline{x}) = -1$  when the top left square  $\underline{x}$  is full
  - The test set has top left square full  
 $\Rightarrow f(\underline{x}_0) = -1$
- Many functions fit the 6 training examples
  - Some have a value of -1 on the test point, others +1
  - Which one is it?
- How can a limited data set reveal enough information to define the entire target function?
  - **Is machine learning possible?**



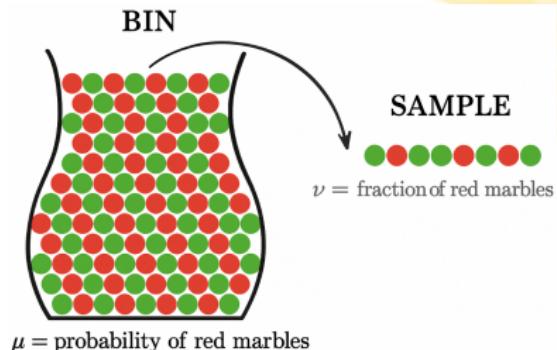
# Is Machine Learning Possible?

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- The function can assume **any value outside data**
  - E.g., with summer temperature data, the function could assume a different value for winter
- **How to learn an unknown function?**
  - Estimating at unseen points seems impossible in general
  - Requires assumptions or models about behavior
- Difference between:
  - **Possible**
    - No knowledge of the unknown function
    - E.g., could be linear, quadratic, or sine wave outside known data
  - **Probable**
    - Some knowledge of the unknown function from domain knowledge or historical data patterns
    - E.g., if historical weather data forms a sinusoidal pattern, unknown points likely follow that pattern

# Supervised Learning: Bin Analogy (1/2)

- Consider a bin with red and green marbles
  - We want to estimate  $\Pr(\text{pick a red marble}) = \mu$  where the value of  $\mu$  is unknown
  - We pick  $N$  marbles independently with replacement
  - The fraction of red marbles is  $\nu$



- Does  $\nu$  say anything about  $\mu$ ?
  - "No"
    - In strict terms, we don't know anything about the marbles we didn't pick
    - The sample can be mostly green, while the bin is mostly red
    - This is *possible*, but *not probable*
  - "Yes"
    - Under certain conditions, the sample frequency is close to the real frequency
- Possible vs probable
  - It is **possible** that we don't know anything about the marbles in the bin
  - It is **probable** that we know something
  - Hoeffding inequality makes this intuition formal

# Hoeffding Inequality

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- Consider a Bernoulli random variable  $X$  with probability of success  $\mu$
- Estimate the mean  $\mu$  using  $N$  samples with  $\nu = \frac{1}{N} \sum_i X_i$
- The **probably approximately correct** (PAC) statement holds:

$$\Pr(|\nu - \mu| > \varepsilon) \leq \frac{2}{e^{2\varepsilon^2 N}}$$

- **Remarks:**

- Valid for all  $N$  and  $\varepsilon$ , not an asymptotic result
- Holds only if you sample  $\nu$  and  $\mu$  at random and in the same way
- If  $N$  increases, it is exponentially small that  $\nu$  will deviate from  $\mu$  by more than  $\varepsilon$
- The bound does not depend on  $\mu$
- Trade-off between  $N$ ,  $\varepsilon$ , and the bound:
  - Smaller  $\varepsilon$  requires larger  $N$  for the same probability bound
  - Since  $\nu \in [\mu - \varepsilon, \mu + \varepsilon]$ , you want small  $\varepsilon$  with a large probability
- It is a statement about  $\nu$  and not  $\mu$  although you use it to state something about  $\nu$  (like for a confidence interval)

## Supervised Learning: Bin Analogy (2/2)

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- Let's connect the bin analogy, Hoeffding inequality, and feasibility of machine learning
  - You know  $f(\underline{x})$  at points  $\underline{x} \in \mathcal{X}$
  - You choose an hypothesis  $h : \mathcal{X} \rightarrow \mathcal{Y} = \{0, 1\}$
  - Each point  $\underline{x} \in \mathcal{X}$  is a marble
  - You color **red** if the hypothesis is correct  $h(\underline{x}) = f(\underline{x})$ , **green** otherwise
  - The in-sample error  $E_{in}(h)$  corresponds to  $\nu$
  - The marbles of unknown color corresponds to  $E_{out}(h) = \mu$
  - $\underline{x}_1, \dots, \underline{x}_n$  are picked randomly and independently from a distribution over  $\mathcal{X}$  which is the same as for  $E_{out}$
- Hoeffding inequality holds and bounds the error going from in-sample to out-of-sample

$$\Pr(|E_{in} - E_{out}| > \varepsilon) \leq c$$

- Generalization over unknown points (i.e., marbles) is possible
- **Machine learning is possible!**

# Validation vs Learning: Bin Analogy

- You have learned that for a given  $h$ , in-sample performance  $E_{in}(h) = \nu$  needs to be close to out-of-sample performance  $E_{out}(h) = \mu$ 
  - This is the **validation setup**, after you have already learned a model
- In a **learning setup** you have  $h$  to choose from  $M$  hypotheses
  - You need a bound on the out-of-sample performance of the chosen hypothesis  $h \in \mathcal{H}$ , regardless of which hypothesis you choose
  - You need a Hoeffding counterpart for the case of choosing from multiple hypotheses

$$\forall g \in \mathcal{H} = \{h_1, \dots, h_M\} \quad \Pr(|E_{in}(g) - E_{out}(g)| > \varepsilon)$$

$$\leq \Pr\left(\bigcup_{i=1}^M (|E_{in}(h_i) - E_{out}(h_i)| > \varepsilon)\right)$$

$$\leq \sum_{i=1}^M \Pr(|E_{in}(h_i) - E_{out}(h_i)| > \varepsilon) \quad (\text{by the union bound})$$

$$\leq 2M \exp(-2\varepsilon^2 N) \quad (\text{by Hoeffding})$$

# Validation vs Learning: Coin Analogy

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- In a **validation set-up**, you have a coin and want to determine if it is fair
- Assume the coin is unbiased:  $\mu = 0.5$
- Toss the coin 10 times
- How likely is that you get 10 heads (i.e., the coin looks biased  $\nu = 0$ )?

$$\Pr(\text{coin shows } \nu = 0) = 1/2^{10} = 1/1024 \approx 0.1\%$$

- **Conclusion:** the probability that the out-of-sample performance ( $\nu = 0.0$ ) is completely different from the in-sample perf ( $\mu = 0.5$ ) is very low

# Validation vs Learning: Coin Analogy

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- In a **learning set-up**, you have many coins and you need to choose one and determine if it's fair
- If you have 1000 fair coins, how likely is it that at least one appears totally biased using 10 experiments?
  - I.e., out-of-sample performance is completely different from in-sample performance

$$\begin{aligned}\Pr(\text{at least one coin has } \nu = 0) &= 1 - \Pr(\text{all coins have } \nu \neq 0) \\ &= 1 - (\Pr(\text{a coin has } \nu \neq 0))^{10} \\ &= 1 - (1 - \Pr(\text{a coin has } \nu = 0))^{10} \\ &= 1 - (1 - 1/2^{10})^{1000} \\ &\approx 0.63\%\end{aligned}$$

- **Conclusion:** It is probable, more than 50%

# Validation vs Learning: Hoeffding Inequality

- In **validation / testing**

- Use Hoeffding to assess how well our  $g$  (the *chosen hypothesis*) approximates  $f$  (the *unknown hypothesis*):

$$\Pr(|E_{in} - E_{out}| > \varepsilon) \leq 2 \exp(-2\varepsilon^2 N)$$

where:

$$E_{in}(g) = \frac{1}{N} \sum_i e(g(\underline{x}_i), f(\underline{x}_i))$$

$$E_{out}(g) = \mathbb{E}_{\underline{x}}[e(g(\underline{x}), f(\underline{x}))]$$

- Since the hypothesis  $g$  is final and fixed, Hoeffding inequality guarantees that you can learn since it gives a bound for  $E_{out}$  to track  $E_{in}$

- In **learning**

- Need to account that our hypothesis is the best of  $M$  hypotheses, so:

$$\Pr(|E_{in} - E_{out}| > \varepsilon) \leq 2M \exp(-2\varepsilon^2 N)$$

- The bound for  $E_{out}$  from Hoeffding is weak

- **Questions:**

- Is the bound weak because it needs to be?

- Is it possible to replace it with a stricter bound?



# Intuition Why Bound for Hoeffding Is Weak

- The Hoeffding inequality and the union bound applied to training set

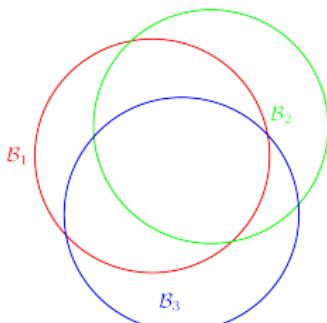
$$\Pr(|E_{in} - E_{out}| > \varepsilon) \leq 2M \exp(-2\varepsilon^2 N)$$

is **artificially** too loose

- $M$  was coming from the bad event:

$$\begin{aligned}\mathcal{B}_i &= \text{"hypothesis } h_i \text{ does not generalize out-of-sample"} \\ &= "|E_{in}(h_i) - E_{out}(h_i)| > \varepsilon"\end{aligned}$$

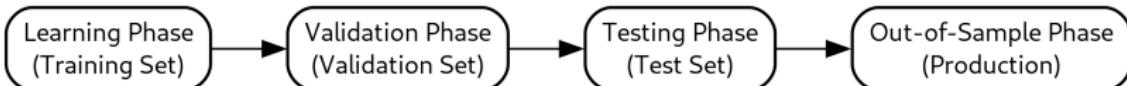
- Since  $g \in \{h_1, h_2, \dots, h_M\}$  then  
 $\Pr(\mathcal{B}) \leq \Pr(\bigcup_i \mathcal{B}_i) \leq \sum_i \Pr(\mathcal{B}_i)$
- The union bound assumes the events are disjoint, leading to a conservative estimate if events overlap
- In reality**, bad events are extremely overlapping because bad hypotheses are extremely similar



# Training vs Testing: College Course Analogy (1/2)

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- In machine learning there are several phases



- This set-up is very similar to studying and exams in a college course
  - Students study the material
    - This is the **learning phase**
  - Before the final exam, students receive practice problems and solutions
    - Studying the problems improves performance by understanding what they need to improve
    - This corresponds to the **validation set**

# Training vs Testing: College Course Analogy (2/2)

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- The final exam corresponds to the **testing phase**
  - These problems are different than the problems in the validation set
  - Why not give out exam problems to improve performance?
    - Doing well in the exam isn't the goal
    - The goal is to learn the course material
  - The final exam isn't strictly necessary
    - Gauges how well you've learned
    - Motivates you to study
    - Knowing exam problems in advance wouldn't gauge learning effectively
- What matters is how students do once they graduate and find a job
  - This is the **out-of-sample phase**

- Is Machine Learning Even Possible?
- ***Growth Function***
- The VC Dimension
- Overfitting
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# Dichotomy: Definition

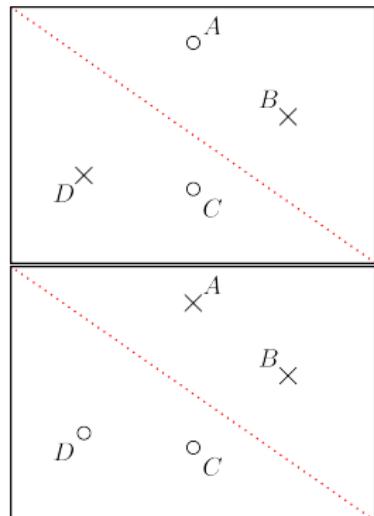
- **Problem:** classify  $N$  (fixed) points  $\underline{x}_1, \dots, \underline{x}_N$  with an hypothesis set  $\mathcal{H}$  of multi-class classifiers
- Consider an assignment  $D$  of the points to certain class  $\underline{d}_1, \dots, \underline{d}_N$
- $D$  is a **dichotomy** for hypothesis set  $\mathcal{H} \iff$  there exists  $h \in \mathcal{H}$  that gets the desired classification  $D$

## Example

- 4 points in a plane  $A, B, C, D$
- Binary classification
- $\mathcal{H} = \{ \text{ bidimensional perceptrons} \}$
- Moving the separating hyperplane, you get different classifications for the points (i.e., dichotomies)

	D1	D2	D3	D4	D...
A	o	x		...	
B	x	x			
C	o	o			
D	x	o		...	

- There are at most  $2^N$  dichotomies
- Certain classifications are not possible (e.g.,



# Dichotomies vs Hypotheses

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- An **hypothesis** classifies each point of  $\mathcal{X}$ :  $\mathcal{X} \rightarrow \{-1, +1\}$
- A **dichotomy** classifies each point of a fixed set:  
 $\{\underline{x}_1, \dots, \underline{x}_N\} \rightarrow \{-1, +1\}$ 
  - Dichotomies are “mini-hypotheses”, i.e., hypotheses restricted to given points
  - A dichotomy depends on:
    - The number of points  $N$
    - Hypothesis set  $\mathcal{H}$  (i.e., the possible models)
    - Where the points are placed
    - How the points are assigned
- The **number of different dichotomies** is indicated by  $|\mathcal{H}(\underline{x}_1, \dots, \underline{x}_N)|$ 
  - The number of dichotomies is always finite, since  $|\mathcal{H}(\underline{x}_1, \dots, \underline{x}_N)| \leq N^K$
  - The number of hypotheses is usually infinite, i.e.,  $|\mathcal{H}| = \infty$
- The “complexity” of  $\mathcal{H}$  is related to the number of hypothesis
- From the training set point of view what matters are dichotomies and not hypotheses

SCIENCE  
ACADEMY Many (infinite) hypotheses can correspond to the same dichotomy



# Growth Function

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- The **growth function** counts the maximum number of possible dichotomies on  $N$  points for a hypothesis set  $\mathcal{H}$ :

$$m_{\mathcal{H}}(N) = \max_{\underline{x}_1, \dots, \underline{x}_N \in \mathcal{X}} |\mathcal{H}(\underline{x}_1, \dots, \underline{x}_N)|$$

- Why growth function?**

- The dichotomies depend on point distribution and assignment
- The growth function considers the maximum by placing points in the most "favorable way" for the hypothesis set
- To compute  $m_{\mathcal{H}}(N)$  by **brute force**:
  - Consider all possible placements of  $N$  points  $\underline{x}_1, \dots, \underline{x}_N$
  - Consider all possible assignments of the points to the classes
  - Consider all possible hypotheses  $h \in \mathcal{H}$
  - Compute the corresponding dichotomy for  $h$  on  $\underline{x}_1, \dots, \underline{x}_N$
  - Count the number of different dichotomies

# What Can Vary in a Dichotomy

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- Given:
  - An hypothesis set  $\mathcal{H}$  (e.g., bidimensional perceptrons)
  - $N$  (fixed) points  $\underline{x}_1, \dots, \underline{x}_N$
  - An assignment  $D$  of the points to certain class  $\underline{d}_1, \dots, \underline{d}_N$
- $D$  is a **dichotomy** for hypothesis set  $\mathcal{H} \iff$  there exists  $h \in \mathcal{H}$  that gets the desired classification  $D$
- There are various quantities in the definition of dichotomy
  - The hypothesis set  $\mathcal{H}$ 
    - It is fixed
  - The number of dimensions of the input space
    - It is fixed through the hypothesis set  $\mathcal{H}$
  - The number of points  $N$ 
    - Input to the growth function  $m_{\mathcal{H}}(N)$
  - How the points are assigned to the classes  $\underline{d}_1, \dots, \underline{d}_N$ 
    - It is a free parameter, removed by how each hypothesis in  $\mathcal{H}$  “splits” the space
  - Where the points are positioned  $\underline{x}_1, \dots, \underline{x}_N$ 
    - It is a free parameter, removed by the growth function through max

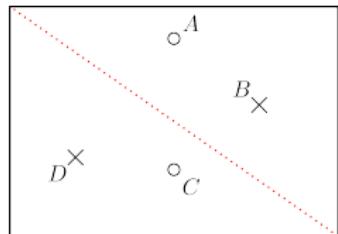
# Growth Function Is Increasing

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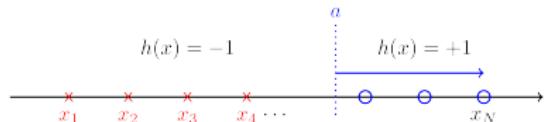
- $m_{\mathcal{H}}(N)$  increases (although not monotonically) with  $N$
- E.g.,
  - The number of dichotomies on  $N = 3$  points  $m_{\mathcal{H}}(3)$  is smaller or equal than the number of dichotomies on  $N = 4$  points
  - In fact we can ignore a new point and get the same classification
- $m_{\mathcal{H}}(N)$  increases with the complexity of  $\mathcal{H}$
- $m_{\mathcal{H}}(N)$  increases with the number of dimensions in the input space (i.e., feature space)

# Growth Function: Examples

- Consider the growth function  $m_{\mathcal{H}}$  for different hypothesis sets  $\mathcal{H}$
- Perceptron on a plane**
  - $m_{\mathcal{H}}(3) = 8$
  - $m_{\mathcal{H}}(4) = 14$  (2 XOR classifications not possible)

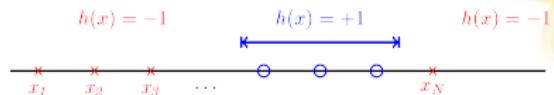


- Positive rays**  $\text{sign}(x - a)$  on  $\mathbb{R}$ 
  - $m_{\mathcal{H}}(N) = N + 1$
  - Origin of rays  $a$  can be placed in  $N + 1$  intervals

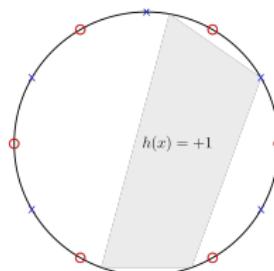


# Growth Function: Examples

- **Positive intervals** on  $\mathbb{R}$   $x \in [a, b]$ 
  - $m_{\mathcal{H}}(N) = \binom{N+1}{2} + 1 \sim N^2$
  - Pick 2 distinct intervals out of  $N+1$ , and there is a dichotomy with 2 points in the same interval



- **Convex sets on a plane**
  - $m_{\mathcal{H}}(N) = 2^N$
  - Place points in a circle and can classify  $N$  points in any way



# Break Point of an Hypothesis Set

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- Given an hypothesis set  $\mathcal{H}$
- A hypothesis set  $\mathcal{H}$  **shatters  $N$  points**  $\iff m_{\mathcal{H}}(N) = 2^N$ 
  - There is a position of  $N$  points and a class assignment that you can classify using  $h \in \mathcal{H}$
  - It does not mean all sets of  $N$  points can be classified in any way
- $k$  is a **break point** for  $\mathcal{H}$   $\iff m_{\mathcal{H}}(k) < 2^k$ 
  - I.e., no data set of size  $k$  can be shattered by  $\mathcal{H}$
  - E.g.,
    - For 2D perceptron: a break point is 4
    - For positive rays: a break point is 2
    - For positive intervals: a break point is 3
    - For convex set on a plane: there is no break point

# Break Point for an Hypothesis Set and Learning

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- If there is a break point for a hypothesis set  $\mathcal{H}$ , it can be shown that:
  - $m_{\mathcal{H}}(N)$  is polynomial in  $N$
  - Instead of Hoeffding's inequality for learning

$$\Pr(|E_{in}(g) - E_{out}(g)| > \varepsilon) \leq 2M e^{-2\varepsilon^2 N}$$

you can use the Vapnik-Chervonenkis inequality:

$$\Pr(\text{bad generalization}) \leq 4m_{\mathcal{H}}(2N) e^{-\frac{1}{8}\varepsilon^2 N}$$

- Since  $m_{\mathcal{H}}(N)$  is polynomial in  $N$ , it will be dominated by the negative exponential, given enough examples
- You can have a generalization bound: machine learning works!
- A hypothesis set can be characterized from the learning point of view by the **existence and value of a break point**

- Is Machine Learning Even Possible?
- Growth Function
- ***The VC Dimension***
- Overfitting
- Bias Variance Analysis
- Learning Curves
- Learn-Validation Approach

# VC Dimension of an Hypothesis Set

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- The **VC dimension of a hypothesis set**  $\mathcal{H}$ , denoted as  $d_{VC}(\mathcal{H})$ , is defined as the largest value of  $N$  for which  $m_{\mathcal{H}}(N) = 2^N$ 
  - I.e., the VC dimension is the most points  $\mathcal{H}$  can shatter
- **Properties** of the VC dimension: if  $d_{VC}(\mathcal{H}) = N$  then
  - Exists a constellation of  $N$  points that can be shattered by  $\mathcal{H}$ 
    - Not all sets of  $N$  points can be shattered
    - If  $N$  points were placed randomly, they could not be necessarily shattered
  - $\mathcal{H}$  can *shatter*  $N$  points for any  $N \leq d_{VC}(\mathcal{H})$
  - The *smallest break point* is  $d_{VC} - 1$
  - The *growth function* in terms of the VC dimension is  $m_{\mathcal{H}} \leq \sum_{i=0}^{d_{VC}} \binom{N}{i}$
  - The VC dimension is the *order of the polynomial bounding*  $m_{\mathcal{H}}$

# VC Dimension: Interpretation

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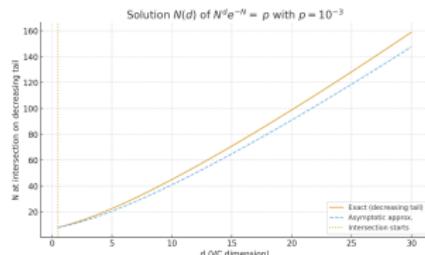
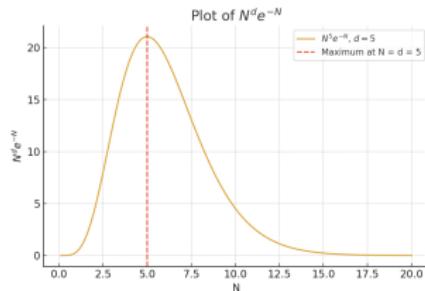
- The VC dimension **measures the complexity** of a hypothesis set in terms of **effective parameters**
- E.g.,
  - A perceptron in a  $d$ -dimensional space has  $d_{VC} = d + 1$
  - In fact  $d_{VC}$  is the number of perceptron parameters!
  - E.g., for a 2D perceptron ( $d = 2$ ), the break point is 2, so  $d_{VC} = 3$
- The VC dimension considers the model as a black box in order to estimate effective parameters
  - How many points  $N$  a model can shatter, not the number of parameters
- Not all parameters contribute to degrees of freedom
  - E.g., combining  $N$  1D perceptrons gives  $2N$  parameters, but the effective degrees of freedom remain 2
- A complex hypothesis  $\mathcal{H}$ :
  - Has more parameters (higher VC dimension  $d_{VC}$ )
  - Requires more examples for training

# VC Generalization Bounds

- How many data points are needed to obtain  $\Pr(|E_{in} - E_{out}| > \varepsilon) \leq \delta?$
- The VC inequality states

$$\Pr(\text{bad generalization}) \leq 4m_{\mathcal{H}}(2N)e^{-\frac{1}{8}\varepsilon^2 N}$$

- $N^d e^{-N}$  abstracts the upper bound term
  - Plot  $N^d e^{-N}$  vs.  $N$ : Power dominates for small  $N$ , exponential for large  $N$  and brings it to 0
  - Vary  $d$  (VC dimension) function peaks for larger  $N$ , then approaches the region of interest  $\leq N^1$
- Plot intersection of  $N^d e^{-N}$  with a probability as a function of  $d$ 
  - Examples  $N$  needed are proportional to  $d$
  - Rule of thumb:  $N \geq 10d_{VC}$  for generalization



# VC Generalization Bounds

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- The VC inequality

$$\Pr(|E_{in} - E_{out}| > \varepsilon) \leq 4m_{\mathcal{H}}(2N)e^{-\frac{1}{8}\varepsilon^2 N}$$

can be used in several ways to relate  $\varepsilon$ ,  $\delta$ , and  $N$ , e.g.,

- Examples
  - "Given  $\varepsilon = 1\%$  error, how many examples  $N$  are needed to get  $\delta = 0.05$ ?"
  - "Given  $N$  examples, what's the probability of an error larger than  $\varepsilon$ ?"
- You can equate  $\delta$  to  $4m_{\mathcal{H}}(2N)e^{\frac{1}{8}\varepsilon^2 N}$  and solve for  $\varepsilon$ , getting

$$\Omega(N, \mathcal{H}, \delta) = \sqrt{\frac{8}{N} \ln \frac{4m_{\mathcal{H}}(2N)}{\delta}}$$

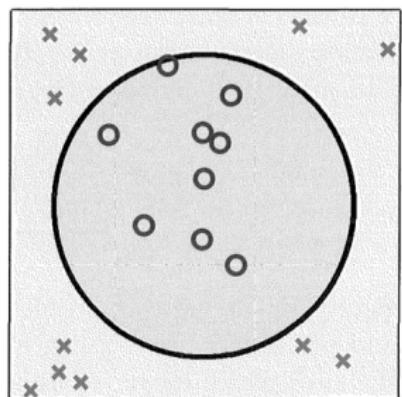
- Then you can say  $|E_{out} - E_{in}| \leq \Omega(N, \mathcal{H}, \delta)$  with probability  $\geq 1 - \delta$ 
  - The generalization bounds are then:  $\Pr(E_{out} \leq E_{in} + \Omega) \geq 1 - \delta$

# How to Void the VC Analysis Guarantee

- Consider the case where data is genuinely non-linear
  - E.g., “o” points in the center and “x” in the corners
- Transform to high-dimensional  $\mathcal{Z}$  with:

$$\Phi : \underline{x} = (x_0, \dots, x_d) \rightarrow \underline{z} = (z_0, \dots, z_{\tilde{d}})$$

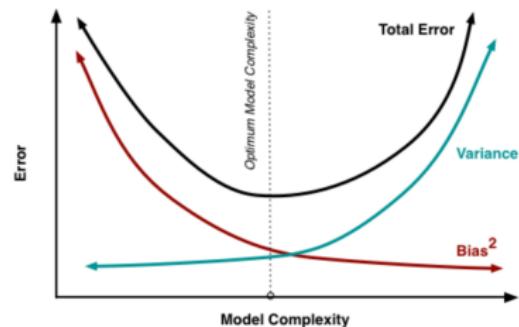
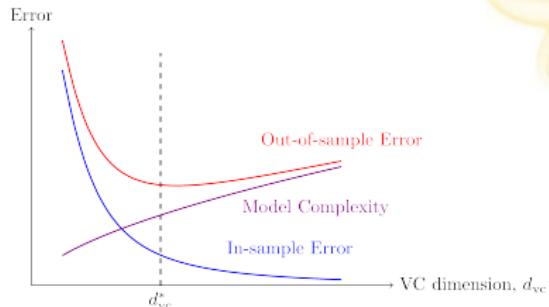
- $d_{VC} \leq \tilde{d} + 1$ ; smaller  $\tilde{d}$  improves generalization
  - Use  $\underline{z} = (1, x_1, x_2, x_1 x_2, x_1^2, x_2^2)$
  - Why not  $\underline{z} = (1, x_1^2, x_2^2)$ ?
  - Why not  $\underline{z} = (1, x_1^2 + x_2^2)$ ?
  - Why not  $\underline{z} = (x_1^2 + x_2^2 - 0.6)$ ?
- Some model coefficients were zero and discarded, leaving machine learning the rest
  - VC analysis is a warranty, forfeited if data is examined before model selection (data snooping)
  - From VC analysis, complexity is that of the initial hypothesis set



- Is Machine Learning Even Possible?
- Growth Function
- The VC Dimension
- ***Overfitting***
- Bias Variance Analysis
- Learning Curves
- Learn-Validation Approach

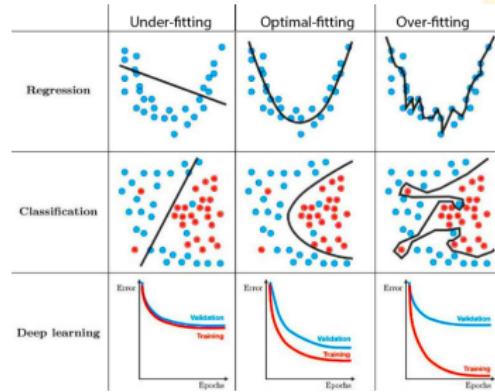
# Overfitting: Definition

- **Overfitting** occurs when the model fits the data more than what is warranted
- Surpass point where  $E_{out}$  is minimal (optimal fit)
  - Model complexity too high for data/noise
  - Noise in training set mistaken for signal
- **Fitting noise instead of signal** is not useless but harmful
  - Model infers in-sample pattern that, when extrapolated out-of-sample, deviates from target function  $\Rightarrow$  poor generalization



# Optimal Fit

- The opposite of overfitting is **optimal fit**
  - Train a model with proper complexity for the data
- The optimal fit:
  - Implies  $E_{out}$  is minimal
  - Does not imply generalization error  $E_{out} - E_{in}$  is minimal
    - E.g., no training implies generalization error equal to 0
- The **generalization error** is the additional error  $E_{out} - E_{in}$  when going from in-sample to out-of-sample



# Overfitting: Diamond Price Example

- Predict diamond price as a function of carat size (regression problem)
- **True relationship**

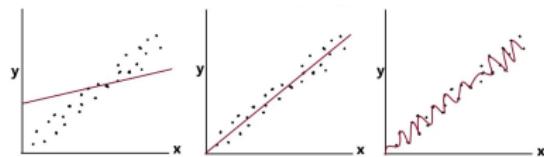
$$\text{price} \sim (\text{carat size})^2 + \varepsilon$$

where:

- Square function: price increases more with rarity
- Noise  $\varepsilon$ : e.g., market noise, missing features

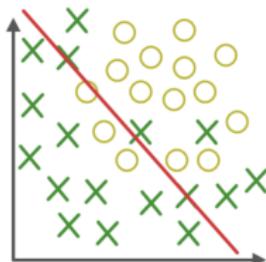
- **Fit with:**

- *Line*
  - Underfit
  - High bias (large error)
  - Low variance (stable model)
- *Polynomial of degree 2*
  - right fit
- *Polynomial of degree 10*
  - Overfit (wiggly curve)
  - Low bias
  - High variance (many degrees of freedom)

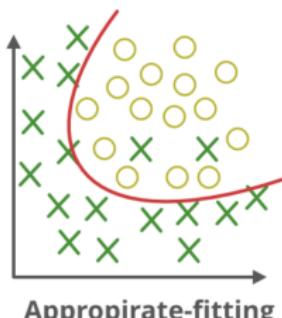


# Overfitting: Classification Example

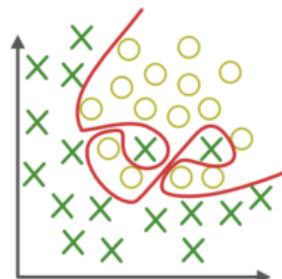
- Assume:
  - You want to separate 2 classes using 2 features  $x_1, x_2$
  - The true class boundary has a parabola shape
- You can use logistic regression and a decision boundary equal to:
  - A line  $\text{logit}(w_0 + w_1x + w_2y)$ 
    - Underfit
    - High bias, low variance
  - A parabola  $\text{logit}(w_0 + w_1x + w_2x^2 + w_3xy + w_4y^2)$ 
    - Right fit
  - A wiggly decision boundary  $\text{logit}(w_0 + \text{high powers of } x_1, x_2)$ 
    - Overfit
    - Low bias, high variance



Under-fitting



Appropriate-fitting



Over-fitting

- Is Machine Learning Even Possible?
- Growth Function
- The VC Dimension
- Overfitting
- ***Bias Variance Analysis***
- Learning Curves
- Learn-Validation Approach

# VC Analysis vs Bias-Variance Analysis

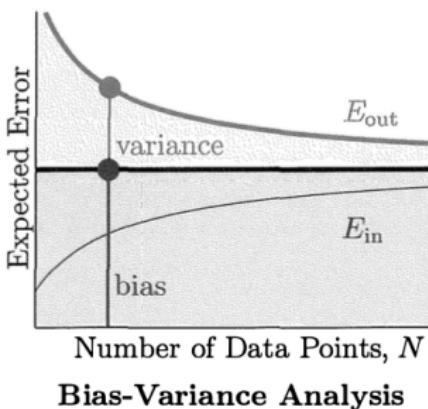
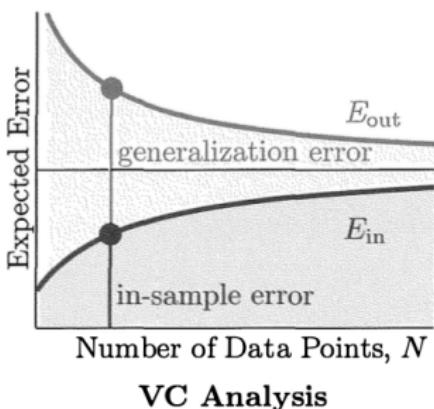
- Both VC analysis and bias-variance analysis are concerned with the hypothesis set  $\mathcal{H}$

- VC analysis:**

$$E_{out} \leq E_{in} + \Omega(\mathcal{H})$$

- Bias-variance analysis**

$$E_{out} = \text{bias} + \text{variance}$$



# Hypothesis Set and Bias-Variance Analysis

---

- **Learning** consists in finding  $g \in \mathcal{H}$  such that  $g \approx f$  where  $f$  is an unknown function
- The **tradeoff in learning** is between:
  - Bias vs variance
  - Overfitting vs underfitting
  - More complex vs less complex  $\mathcal{H} / h$
  - Approximation (in-sample) vs generalization (out-of-sample)

# Decomposing Error in Bias-Variance (1/4)

---

- **Problem**

- Regression set-up: target is a real-valued function
- Hypothesis set  $\mathcal{H} = \{h_1(\underline{x}), h_2(\underline{x}), \dots, h_n(\underline{x})\}$
- Training data  $\mathcal{D}$  with  $N$  examples
- Squared error  $E_{out} = \mathbb{E}[(g(\underline{x}) - f(\underline{x}))^2]$
- Choose the best function  $g \in \mathcal{H}$  that approximates unknown  $f$

- **Question**

- What is the out-of-sample error  $E_{out}(g)$  as function of  $\mathcal{H}$  for a training set of  $N$  examples?

## Decomposing Error in Bias-Variance (2/4)

---

- The final hypothesis  $g$  depends on training set  $D$ , so make the dependency explicit  $g^{(D)}$ :

$$E_{out}(g^{(D)}) \triangleq \mathbb{E}_{\underline{x}}[(g^{(D)}(\underline{x}) - f(\underline{x}))^2]$$

- Interested in:
  - Hypothesis set  $\mathcal{H}$  rather than specific  $h$
  - Training set  $D$  of  $N$  examples, rather than a specific  $D$
- Remove dependency from  $D$  by averaging over all possible training sets  $D$  with  $N$  examples:

$$E_{out}(\mathcal{H}) \triangleq \mathbb{E}_D[E_{out}(g^{(D)})] = \mathbb{E}_D[\mathbb{E}_{\underline{x}}[(g^{(D)}(\underline{x}) - f(\underline{x}))^2]]$$

# Decomposing Error in Bias-Variance (3/4)

- Switch the order of the expectations since the quantity is non-negative:

$$E_{out}(\mathcal{H}) = \mathbb{E}_{\underline{x}}[\mathbb{E}_D[(g^{(D)}(\underline{x}) - f(\underline{x}))^2]]$$

- Focus on  $\mathbb{E}_D[(g^{(D)}(\underline{x}) - f(\underline{x}))^2]$  which is a function of  $\underline{x}$
- Define the *average hypothesis* over all training sets as:

$$\bar{g}(\underline{x}) \triangleq \mathbb{E}_D[g^{(D)}(\underline{x})]$$

- Add and subtract it inside the  $\mathbb{E}_D$  expression:

$$\begin{aligned} E_{out}(\mathcal{H}) &= \mathbb{E}_{\underline{x}} \left[ \mathbb{E}_D \left[ (g^{(D)}(\underline{x}) - f(\underline{x}))^2 \right] \right] \\ &= \mathbb{E}_{\underline{x}} \mathbb{E}_D[(g^{(D)} - \bar{g} + \bar{g} - f)^2] \\ &= \mathbb{E}_{\underline{x}} \mathbb{E}_D[(g^{(D)} - \bar{g})^2 + (\bar{g} - f)^2 + 2(g^{(D)} - \bar{g})(\bar{g} - f)] \\ &\quad (\mathbb{E}_D \text{ is linear and } (\bar{g} - f) \text{ doesn't depend on } D) \\ &= \mathbb{E}_{\underline{x}} [\mathbb{E}_D[(g^{(D)} - \bar{g})^2] + (\bar{g} - f)^2 + 2\mathbb{E}_D[(g^{(D)} - \bar{g})](\bar{g} - f)] \end{aligned}$$

# Decomposing Error in Bias-Variance (4/4)

- The cross term:

$$\mathbb{E}_D[(g^{(D)} - \bar{g})(\bar{g} - f)]$$

disappears since applying the expectation on  $D$ , it is equal to:

$$(g^{(D)} - \mathbb{E}_D[\bar{g}])(\bar{g} - f) = 0 \cdot (\bar{g} - f) = 0 \cdot \text{constant}$$

- Finally:

$$\begin{aligned} E_{out}(\mathcal{H}) &= \mathbb{E}_{\underline{x}}[\mathbb{E}_D[(g^{(D)} - \bar{g})^2] + (\bar{g}(\underline{x}) - f(\underline{x}))^2]] \\ &= \mathbb{E}_{\underline{x}}[\mathbb{E}_D[(g^{(D)} - \bar{g})^2]] + \mathbb{E}_{\underline{x}}[(\bar{g} - f)^2] \quad (\mathbb{E}_{\underline{x}} \text{ is linear}) \\ &= \mathbb{E}_{\underline{x}}[\text{var}(\underline{x})] + \mathbb{E}_{\underline{x}}[\text{bias}(\underline{x})^2] \\ &= \text{variance} + \text{bias} \end{aligned}$$

# Interpretation of Average Hypothesis

---

- The **average hypothesis** over all training sets

$$\bar{g}(\underline{x}) \triangleq \mathbb{E}_D[g^{(D)}(\underline{x})]$$

can be interpreted as the “best” hypothesis from  $\mathcal{H}$  training on  $N$  samples

- Note:  $\bar{g}$  is not necessarily  $\in \mathcal{H}$
- In fact it’s like **ensemble learning**:
  - Consider all the possible data sets  $D$  with  $N$  samples
  - Learn  $g$  from each  $D$
  - Average all the hypotheses

# Interpretation of Variance and Bias Terms

- The out-of-sample error can be decomposed as:

$$E_{out}(\mathcal{H}) = \text{bias}^2 + \text{variance}$$

- Bias term**

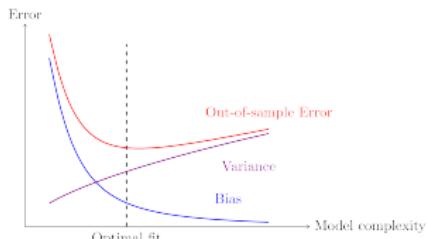
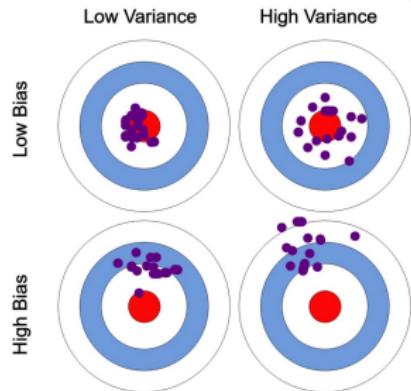
$$\text{bias}^2 = \mathbb{E}_{\underline{x}}[(\bar{g}(\underline{x}) - f(\underline{x}))^2]$$

- Does not depend on learning as it is not a function of the data set  $D$
- Measures how limited  $\mathcal{H}$  is
  - i.e., the ability of  $\mathcal{H}$  to approximate the target with infinite training sets

- Variance term**

$$\text{variance} = \mathbb{E}_{\underline{x}} \mathbb{E}_D[(g^{(D)}(\underline{x}) - \bar{g}(\underline{x}))^2]$$

- Measures variability of the learned hypothesis from  $D$  for any  $\underline{x}$ 
  - With infinite training sets, we could focus on the “best”  $g$ , which is  $\bar{g}$
  - But we have only one data set  $D$  at a time, incurring a cost

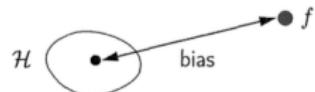


# Variance and Bias Term Varying Cardinality of $\mathcal{H}$

- If hypothesis set **has a single function**:

$$\mathcal{H} = \{h \neq f\}$$

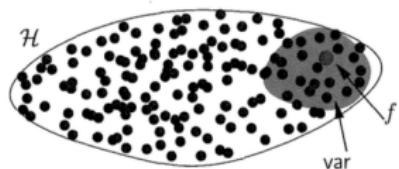
- Large bias
  - $h$  might be far from  $f$
- Variance = 0
  - No cost in choosing hypothesis



- If hypothesis set **has many functions**:

$$\mathcal{H} = \{\text{many hypotheses } h\}$$

- Bias can be 0
  - E.g., if  $f \in \mathcal{H}$
- Large variance
  - Depending on data set  $D$ , end up far from  $f$
  - Larger  $\mathcal{H}$ , farther  $g$  from  $f$



# Bias-Variance Trade-Off: Numerical Example

---

- **Machine learning problem:**
  - Target function  $f(x) = \sin(\pi x)$ ,  $x \in [-1, 1]$
  - Noiseless target
  - You have  $f(\underline{x})$  for  $N = 2$  points
- **Two hypotheses sets  $\mathcal{H}$ :**
  - Constant model:  $\mathcal{H}_0 : h(x) = b$
  - Linear model:  $\mathcal{H}_1 : h(x) = ax + b$
- **Which model is best?**
  - Depends on the perspective!
  - Best for *approximation*: minimal error approximating the sinusoid
  - Best for *learning*: learn the unknown function with minimal error from 2 points

# Bias-Variance Trade-Off: Numerical Example

- **Approximation**

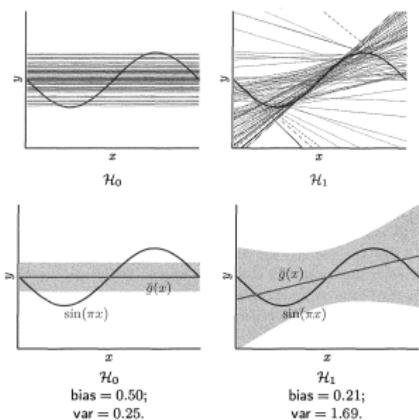
- $E_{out}(g_0) = 0.5$ 
  - $g_0$  is a constant and approximates the sinusoid poorly (higher bias)
- $E_{out}(g_1) = 0.2$ 
  - $g_1$  is a line and has more degrees of freedom (lower bias)
- The line model *approximates better* than the constant model

- **Learning**

- Algorithm:
  - Pick 2 points as training set  $D$
  - Learn  $g$  from  $D$
  - Compute  $\mathbb{E}_D[E_{out}(g)]$
- Average over all data sets  $D$ :

$$E_{out} = \text{bias}^2 + \text{variance}$$

- $E_{out}(g_0) = 0.5 + 0.25 = 0.75$ 
  - $g_0$  is more stable given the data set (lower variance)
- $E_{out}(g_1) = 0.2 + 1.69 = 1.9$ 
  - $g_1$  heavily depends on the training set (higher variance)

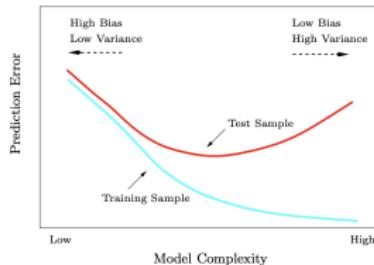


SCIENCE The constant model *learns better* than  
ACADEMY the line model



# Bias-Variance Curves

- **Bias-variance curves** are plots of  $E_{out}$  increasing the complexity of the model
- Typical **shape** of bias-variance curves
  - $E_{in}$  and  $E_{out}$  start from the same point
  - $E_{in}$ 
    - Is decreasing with increasing model complexity
    - Can even go to 0
    - Is shaped like an hyperbole
  - $E_{out}$ 
    - Is always larger than  $E_{in}$
    - Is the sum of bias and variance
    - Has a bowl shape
    - Reaches a minimum for optimal fit
    - Before the minimum there is a “high bias / underfitting” regime
    - After the minimum there is a “high variance / overfitting” regime



# How to Measure the Model Complexity

---

- Number of features
- Parameters for model form / degrees of freedom, e.g.,
  - VC dimension  $d_{VC}$
  - Degree of polynomials
  - $k$  in KNN
  - $\nu$  in NuSVM
- Regularization param  $\lambda$
- Training epochs for neural network

# Bias-Variance Curves and Regularization

- We can use a complex model together with regularization to learn at the same time:
  - The model coefficients  $\underline{w}$
  - The model “complexity” (e.g., VC dimension), which is related to the regularization parameter  $\lambda$
- For each different values of  $\lambda = \{10^{-1}, 1.0, 10\}$  we optimize:

$$\underline{w}(\lambda) = \operatorname{argmin}_{\underline{w}} E_{\text{aug}}(\underline{w}) = E_{\text{in}}(\underline{w}) + \Omega(\lambda)$$

- $\underline{w}(\lambda)$  is the optimal model as function of  $\lambda$
- Then estimate  $E_{\text{out}}$  using  $\underline{w}(\lambda)$  and  $\lambda$ 
  - Small  $\lambda$  means
    - Complex model (with respect to data)
    - Low bias
    - High variance
  - Large  $\lambda$  means
    - Simple model
    - High bias
    - Low variance
- There will be an intermediate value of  $\lambda$  that optimizes the trade-off between bias and variance

# Bias-Variance Decomposition with a Noisy Target

- We can extend the bias-variance decomposition to the noisy target

$$y = \underline{\mathbf{w}}^T \underline{\mathbf{x}} + \varepsilon$$

- With similar hypothesis and a similar analysis we conclude that:

$$\begin{aligned} E_{out}(\mathcal{H}) &= \mathbb{E}_{D, \underline{\mathbf{x}}} [(g^{(D)} - \bar{g})^2] + \mathbb{E}_{\underline{\mathbf{x}}} [(\bar{g} - f)^2] + \mathbb{E}_{\varepsilon, \underline{\mathbf{x}}} [(f - y)^2] \\ &= \text{variance} + \text{bias } (= \text{deterministic noise}) + \text{stochastic noise} \end{aligned}$$

- **Interpretation:**

- The error is the sum of 3 contributions
  1. Variance: from the set of hypotheses to the centroid of the hypothesis set
  2. Bias: from the centroid of the hypothesis set to the noiseless function
  3. Noise: from the noiseless function to the real function

# Bias as Deterministic Noise

---

- The bias term can be interpreted as “deterministic noise”
  - Bias is the part of the target function that our hypothesis set cannot capture:

$$h^*(\underline{x}) - f(\underline{x})$$

where

- $h^*(\cdot)$  is the best approximation of  $f(\underline{x})$  in the hypothesis set  $\mathcal{H}$
  - E.g.,  $\bar{g}(x)$
- The hypothesis set  $\mathcal{H}$  cannot learn the deterministic noise since it is outside of its ability, and thus it behaves like noise

# Deterministic vs Stochastic Noise in Practice

---

- In bias-variance analysis, the error for a noisy target is decomposed into:
  - Bias (deterministic noise)
  - Variance
  - Stochastic noise
- **Deterministic noise:**
  - Fixed for a particular  $\underline{x}$
  - Depends on  $\mathcal{H}$
  - Independent of  $\varepsilon$  or  $D$
- **Stochastic noise:**
  - Not fixed for  $\underline{x}$
  - Independent of  $D$  or  $\mathcal{H}$
- In an actual machine learning problem, there's no difference between stochastic and deterministic noise, since  $\mathcal{H}$  and  $D$  are fixed
  - E.g., from the training set alone, we cannot tell if the data is from a *noiseless complex* target or a *noisy simple* target

# Deterministic vs Stochastic Noise Example

- 2 targets:
  - Noisy low-order target (5-th order polynomial)
  - Noiseless high-order target (50-th order polynomial)
  - Generate  $N = 15$  data points from them
- 2 models:
  - $\mathcal{H}_2$  low-order hypothesis (2nd order polynomial)
  - $\mathcal{H}_{10}$  high-order hypothesis (10-th order polynomial)
- When learning a model there is no difference between deterministic and stochastic noise
- In fact the learning algorithm only sees the samples in the training set and one cannot distinguish the two different sources
- For noisy low-order target: going from fitting the 2nd order to the 10-th order polynomial we see that  $\downarrow E_{in}$  (we have more degrees of freedoms) and  $\uparrow\uparrow E_{out}$  (since the 10-th polynomial fits the noise)
- For noiseless high-order target: exactly the same phenomenon!

# Amount of Data and Model Complexity

---

- The lesson learned from bias-variance analysis is that one must match the *model complexity*:
  - To the *data resources*
  - To the *signal to noise ratio*
  - **Not** to the *target complexity*
- The rule of thumb is:

$$dvc \text{ (degrees of freedom of the model)} = N \text{ (number of data points)} / 10$$

- In other words, 10 data points needed to fit a degree of freedom
- If the data is noisy, you need even more data

# Bias-Variance Curves for Neural Networks

---

- For neural networks one can plot  $E_{in}$  and  $E_{out}$  as function of the training epochs
- One starts with random weights
- Both  $E_{in}$  and  $E_{out}$ :
  - Are large
  - Start exactly from the same value
    - No generalization error
    - Since the model is random, it has no optimistic bias on the training set
- As learning proceeds:
  - $E_{in}$  and  $E_{out}$  decrease
  - The generalization error  $E_{out} - E_{in}$  increases
- It is like the VC dimension is increasing from 0 towards all the available degrees of freedom while exploring the weight space

# Overfitting as a Function of Data Resources, Model Complexity, Noise

---

- We can measure overfitting as  $\frac{E_{out} - E_{in}}{E_{out}}$ 
  - $\uparrow$  data resources ( $N$ )  $\implies \downarrow$  overfitting
  - $\uparrow$  model complexity ( $d_{vc}$ )  $\implies \uparrow$  overfitting
  - $\uparrow$  stochastic noise ( $\sigma^2$ ) / deterministic noise (target complexity)  
 $\implies \uparrow$  overfitting
- There is an error to which both  $E_{in}$  and  $E_{out}$  converge for  $N \rightarrow \infty$ 
  - Irreducible error
  - This error depends on stochastic and deterministic noise
  - There is no variance (since  $N = \infty$ )

- Is Machine Learning Even Possible?
- Growth Function
- The VC Dimension
- Overfitting
- Bias Variance Analysis
- ***Learning Curves***
- Learn-Validation Approach

# Learning Curves vs Bias-Variance Curves

---

- Learning curves are the dual of the bias-variance curves
- For bias-variance curves

$$E_{in}, E_{out} = f(d_{VC}|N)$$

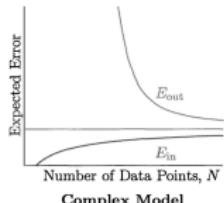
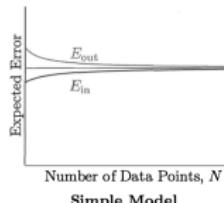
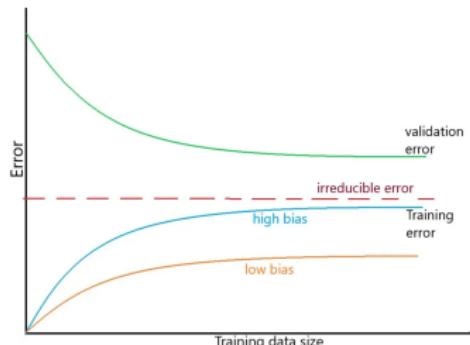
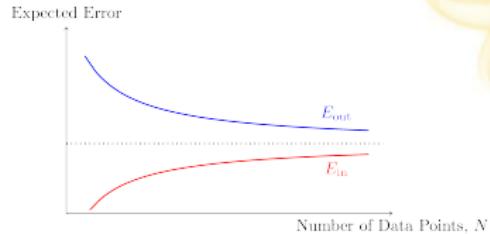
- Keep the training / test set fixed (number of examples  $N$ )
- Vary the model in terms of:
  - Model complexity  $d$
  - Number of features  $p$
  - Regularization amount  $\lambda$
- For learning curves

$$E_{in}, E_{out} = f(N|d_{VC})$$

- Fix the model
- Vary the size  $N$  of training set

# Typical Form of Learning Curves

- Learning curves plot  $E_{in}$  and  $E_{out}$  error as a function of data amount
- **Small  $N$** 
  - With small data  $N$ ,  $E_{in}$  might be small (even 0) depending on model capacity (VC dimension)
  - The model is likely overfitted, memorizing examples, generalizing poorly, and  $E_{out}$  is large
- **Increasing  $N$** 
  - $E_{in}$  increases as the model cannot fit all data
  - $E_{out}$  decreases as the model fits better and generalizes better ( $E_{out} - E_{in}$  decreases)
  - Asymptotically,  $E_{in}$  reaches a minimum (not 0 if noise), while  $E_{out}$  starts increasing, entering overfitting regime
  - $E_{out} \geq E_{in}$  for any  $N$



# High-Bias vs High-Variance Regime

---

- From the learning curve we can see two regimes:
  - High-variance regime for small  $N$ 
    - $E_{in}$  is small
    - $E_{out} > E_{in}$
    - More data helps; gap between  $E_{in}$  and  $E_{out}$  decreases
    - Small data set  $D$ ; high dependency on  $D$
  - **High-bias regime for large  $N$** 
    - $E_{in}$  is large; flattens for large  $N$
    - Best model fitted; more data won't help
    - $E_{out}$  can be close to  $E_{in}$  (good generalization) or not

- Is Machine Learning Even Possible?
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- ***Learn-Validation Approach***
  - Train / Test
  - Cross-Validation

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  - *Train / Test*
  - Cross-Validation

# Estimating Out-Of-Sample Error with One Point

- Pick an out-of-sample point  $(\underline{x}', y)$
- The error of the model  $h$  is:

$$E_{val}(h) = e(h(\underline{x}'), y)$$

where the error can be:

- Squared error  $(h(\underline{x}) - y)^2$
  - Binary error  $I[h(\underline{x}) - y]$
  - ...
- The error on an out-of-sample point is an unbiased estimate of  $E_{out}$ , since

$$\mathbb{E}[E_{val}(h)] = \mathbb{E}[e(h(\underline{x}), y)] = E_{out}$$

by definition

- The quality of the estimate depends on  $\mathbb{V}[e(h(\underline{x}), y)]$ , which in an



# Estimating Out-Of-Sample Error with $K$ Points

- To improve the estimate, use a validation set, i.e.,  $K$  points instead of one point  $(\underline{x}_1, y_1), \dots, (\underline{x}_K, y_K)$  drawn IID
- Compute the error on the validation set as:

$$E_{val}(h) = \frac{1}{K} \sum_{i=1}^K e(h(\underline{x}_i), y_i)$$

- The validation error is an unbiased estimate of out-of-sample error since:

$$\mathbb{E}[E_{val}(h)] = E_{out}(h)$$

- The error is:

$$\mathbb{V}[E_{val}(h)] = \frac{1}{K^2} \sum_i \mathbb{V}[e(h(\underline{x}_i), y_i)] + \text{covariances}$$

$$= \frac{1}{K^2} \sum_i \mathbb{V}[e(h(\underline{x}_i), y_i)] \quad (\text{covariances are 0 because } \underline{x}$$

$$= \frac{K\sigma^2}{K^2} = \frac{\sigma^2}{K}$$

# Trade-Off Between Training and Validation Set Size

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- **Problem:** to better estimate  $E_{val}$ , we need points from the training set:

$$D_{val} = \{K \text{ points}\}$$

$$D_{train} = \{N - K \text{ points}\}$$

- We know:

$$\uparrow K \implies \mathbb{V}[E_{val}] \implies |E_{val} - E_{out}| \downarrow \text{ (most reliable estimate)}$$

but

$$\uparrow K \implies \downarrow N - K \implies E_{in}, E_{out} \uparrow \text{ (worse model)}$$

- If  $K$  is too big, we get a reliable estimate of a bad number!
- **Solution:**



SCIENCE Rule of thumb: 70-30 or 80-20 split between train and validation  
ACADEMY

- 20%-30% of data for validation

# $E_{Out}$ From VC Analysis vs Learn-Validation Approach

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- In general:

$$E_{out}(h) = E_{in}(h) + \text{generalization error}$$

- VC analysis
  - Estimates generalization error as “overfit penalty” in terms of hypothesis set complexity
- Learn-validation
  - Estimates  $E_{out}$  directly by holding out data as validation set:

$$E_{val} \approx E_{out}$$

- Use learn-validation approach at different points of the modeling flow: e.g., validation / test sets

# Reusing Validation / Test Set for Training

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- Never use  $D_{val}$  for training, at least during research
  - If  $D_{val}$  affects learning (e.g., model selection), this data set is biased and optimistic and cannot assess the model
- **Algorithm**
  1. Train with  $N - K$  points to learn  $g^-$
  2. Use  $K$  points to compute  $E_{val}[g^-]$  estimating  $E_{out}[g^-]$
  3. Once the model form is finalized, use all  $N$  data points (including validation, test set) to re-train to get  $g$ 
    - $E_{val}[g] < E_{val}[g^-]$  since  $g$  is learned on a larger data set than  $g^-$  and is thus better
  4. Deliver to customers:
    - Final hypothesis  $g$
    - Upper bound of out-of-sample performance  $E_{val}[g^-]$

# Learn-Validation Approach: Pros and Cons

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- **Pros**
  - Estimate  $E_{out}$  using  $E_{val}$
  - Simple to compute, no complexity from VC analysis
- **Cons**
  - Cannot use all data for learning and validation; need a compromise
  - Learned model and  $E_{val}$  depend on the split; different splits can give different results

- Is Machine Learning Even Possible?
- Growth Function
- The VC Dimension
- Overfitting
- Bias Variance Analysis
- Learning Curves
- Learn-Validation Approach
  - Train / Test
  - ***Cross-Validation***

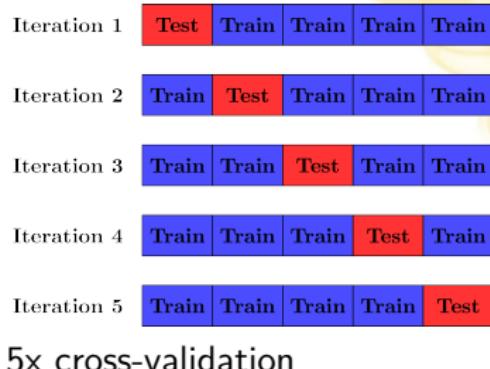
# Cross-validation

- Divide the dataset into  $K$  folds, each with  $\frac{N}{K}$  samples
- Each fold should reflect the full dataset's statistics
  - E.g., stratified sampling
- There are  $K$  iterations  $i = 1, \dots, K$ :
  - In the  $i$ -th iteration, train on all folds except  $i$  (use  $\frac{K-1}{K}N$  points) and get  $g^{(-i)}(\underline{x})$
  - Validate on the  $i$ -th fold (use  $\frac{N}{K}$  points) to compute

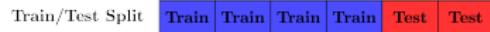
$$E_{val}^{(i)} = E_{val}[g^{(-i)}(\underline{x})]$$

- Average the  $K$  error rates and compute bounds:

$$E_{val} = \frac{1}{K} \sum_i E_{val}^{(i)}$$



5x cross-validation



Train / test validation

# Cross-Validation: Pros and Cons

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- **Pros**

- Efficient data usage (all data used for learning and validation)
- Better estimate of  $E_{val}$  than separate training/validation sets
- Folds can be stratified

- **Cons**

- Computationally intensive:  $K$  learning phases
- Dependency on fold selection
- Errors  $E_{val}$  are not independent (coupling through common training samples)
  - Experimentally not completely correlated

# Repeated Cross-Validation

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- Cross-validation results depend on fold selection
  - To remove this dependency, repeat cross-validation multiple times (e.g., 10) and average results
- Note: “10x 10-fold cross-validation” is different than “1x 100-fold cross-validation”

# Leave-One-Out Cross-Validation

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- Leave-one-out (LOO) cross-validation
  - There are  $N$  training sessions
  - Each session trains on  $N - 1$  points and validates on 1 point
  - Like “ $N$ -fold cross-validation,” where  $N$  is the number of examples in the dataset
- Train:
  - For  $i$ -th fold,  $N - 1$  samples for training  $\implies g_i^- \approx g$
- Validate / estimate:
  - Estimate the validation error on a single point (bad):

$$E_{val}[g_i^-] = e(g_i^-(\underline{\mathbf{x}}_i), y_i) \not\approx E_{out}[g_i^-]$$

- Average  $E_{val}$  over the points as estimate of  $E_{out}$  (good):

$$E_{val} = \frac{1}{N} \sum_i E_{val}[g_i^-]$$

# Leave-One-Out Cross-Validation: Pros and Cons

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- **Pros**
  - Max data used for training
  - Deterministic procedure (no fold selection dependency)
- **Cons**
  - High computational cost (as many learning phases as data points)
  - Cannot be stratified
  - Higher correlation between cross-validation estimates

# Bootstrap

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- **Algorithm**
  - Pick  $N$  samples with replacement from a data set with  $N$  instances to build training set
  - Pick the elements never chosen to build the test set ("out-of-bag" samples)
  - Training set contains 63.2% of all the samples, 36.8% in the test set
- **Pros**
  - Works for small data sets since it "expands" the data
- **Cons**
  - Not flexible
  - Smaller percentage of instances are used for training set than 10-fold cross validation