Learning Theory

Questions suitable for Theoretical Analysis

- How hard is a given learning task?
- How many training examples are needed?
- How many errors should we expect during and after training?
- How large is the risk of failing to learn?

Assumptions:

- Concept Learning
- Training and test data from same distribution $\mathcal{D}$

What kind of errors can occur?

- The result of leaning can be bad
  The resulting hypothesis makes too many errors
- Learning itself can fail
  The learning algorithm may not find any reasonable hypothesis

How bad hypotheses are we prepared to accept?

True Error — the probability that a given hypothesis gives the wrong answer

$$\mathrm{error}_{\mathcal{D}}(h) \equiv P_{x \in \mathcal{D}}\left[h(x) \neq c(x)\right]$$

A hypothesis h is called approximately correct (ganska rätt) if

$$\mathrm{error}_{\mathcal{D}}(h) < \epsilon$$

How often may learning fail?

Risk that learning does not find an approximately correct hypothesis

$$P_L\left[\mathrm{error}_{\mathcal{D}}(h) \geq \epsilon\right]$$

The algorithm L is said to probably (troligen) find a solution if

$$P_L\left[\mathrm{error}_{\mathcal{D}}(h) \geq \epsilon\right] < \delta$$

PAC-learning

Probably Approximately Correct

Given

C	the concept to learn
ϵ	limit on the error
δ	limit on the risk
n	size of the examples

PAC-learnable: Time to find a solution grows polynomially with respect to $\text{size}(C)$, n, $\frac{1}{\epsilon}$ and $\frac{1}{\delta}$

Analysis of a Consistent Learner

- Assumtion: no errors in training examples
- Examples are drawn from the distribution $\mathcal{D}$
- The solution is consistent with all training examples
- "Dangerous Hypotheses":

$$\text{error}_{\mathcal{D}}(h) \geq \epsilon$$

We do not want learning to produce a dangerous hypothesis!

How large is the risk that a dangerous hypothesis is consistent with all training examples?

- Probability that one hypothesis h is contradicted by one example

$$\text{error}_{\mathcal{D}}(h)$$

- Probability that h is not contradicted

$$1 - \text{error}_{\mathcal{D}}(h)$$

- Risk that a *dangerous hypothesis* $(\text{error}_{\mathcal{D}}(h) \geq \epsilon)$ is not contradicted by a randomly drawn example

$$\leq (1 - \epsilon)$$

- Risk that a *dangerous hypothesis* is not contradicted by one randomly drawn example

$$\leq (1 - \epsilon)$$

- Risk that a *dangerous hypothesis* is not contradicted my m randomly drawn examples

$$\leq (1 - \epsilon)^m$$

- How large is the risk that any dangerous hypothesis in H happens to be consistent with all examples:

$$\leq |H| \cdot (1 - \epsilon)^m$$

$$\leq |H| \cdot e^{-\epsilon m}$$

How many training examples are needed?

How many examples m are needed to make the risk of ending up with a dangerous hypothesis less than δ?

$$\delta \geq |H| \cdot e^{-\epsilon m}$$

$$e^{\epsilon m} \geq \frac{|H|}{\delta}$$

$$m \geq \frac{1}{\epsilon}\left[\ln |H| + \ln \frac{1}{\delta}\right]$$

Important relation:

$$m \geq \frac{1}{\epsilon}\left[\ln |H| + \ln \frac{1}{\delta}\right]$$

Is this PAC-learnable?

Potential problem: $|H|$ might be too large

Learning Conjunctions
Example: $\text{Sunny} \wedge \neg\text{Windy} \wedge \text{Humid}$
n attributes $\Rightarrow 3^n$ possible concepts $\Rightarrow |H| = 3^n$

$$m \geq \frac{1}{\epsilon}\left[n \ln 3 + \ln \frac{1}{\delta}\right]$$

- Linear w.r.t. $\frac{1}{\epsilon}$
- Linear w.r.t. n
- Logarithmic w.r.t. $\frac{1}{\delta}$

Seems PAC-learnable!
Further, *time for each example* must be polynomial.
Find-S: Ok

Unbiased Learning
All subsets of X are hypotheses

$$|X| = 2^n$$

$$|H| = 2^{2^n}$$

$$m \geq \frac{1}{\epsilon}\left[2^n \ln 2 + \ln \frac{1}{\delta}\right]$$

Not PAC-learnable!
However, this estimate is an upper bound
We have not proven that m actually grows exponentially w.r.t. n
However, in this case it *is* true

Problem with $|H|$

- Gives too pessimistic estimates
- Can't be used when $|H| = \infty$

Vapnik — Chervonenkis observation:

The important thing is not the *number of* hypotheses, but how they can form subsets in X

Scattering

A finite set S is scattered (splittras) by the hypotheses H if every subset of S is described by a $h \in H$

The size of S is a measure of the expressive power of H

VC Dimension

$\mathrm{VC}(H)$

Size of the largest subset of X which can be scattered by H

Example:

H Intervals on the real axis
X Real numbers

- Can 2 points be scattered?
- Can 3 points be scattered?

Conclusion: $\mathrm{VC}(H) = 2$

Example:

H Separating hyperplane
X Points in $\Re^r$

- When $r = 1$

$$\mathrm{VC}(H) = 2$$

- When $r = 2$

$$\mathrm{VC}(H) = 3$$

- Generally

$$\mathrm{VC}(H) = r + 1$$

Number of Training Examples

Previous estimate

$$m \geq \frac{1}{\epsilon}\left[\ln|H| + \ln\frac{1}{\delta}\right]$$

New estimate

$$m \geq \frac{1}{\epsilon}\left[4\log_2\frac{2}{\delta} + 8\mathrm{VC}(H)\cdot\log_2\frac{13}{\epsilon}\right]$$

Much better (smaller)

Alternative Performance Measure for Learning Algorithms:

How many errors does the algorithm make during learning

Find-S

- Only learns when making errors
- Worst case: generalises only one attribute each time
- First example only chooses one specific hypothesis
- Maximally $n+1$ changes

Will maximally make $n+1$ errors

Candidate Elimination

- We must force the algorithm to guess
- Suppose we use a majority vote among all hypotheses remaining in *Version Space*
- Wrong answer only when at least half of VS give the wrong answer
- For each error made, at least half of VS disappears

Maximally $\log_2 |H|$ errors

Optimal Learning

- Best algorithm
- Worst case
  Trickiest concept, worst order of examples

Number of errors while learning concept C

$$\mathrm{Opt}(C)$$

Theoretical Limit

$$\mathrm{VC}(C) \leq \mathrm{Opt}(C) \leq \log_2 |C|$$