

Lecture 2: Foundations of Concept Learning

Cognitive Systems - Machine Learning

Part I: Basic Approaches to Concept Learning

Version Space, Candidate Elimination, Inductive Bias

last change October 22, 2010

Definition of Concept Learning

- **Learning** involves acquiring general concepts from a specific set of training examples D
 - Each **concept** c can be thought of as a boolean-valued function defined over a larger set
i.e. a function defined over all animals, whose value is true for birds and false for other animals
- ⇒ **Concept learning**: Inferring a boolean-valued function from training examples

A Concept Learning Task - Informal

- example target concept
Enjoy: “days on which Aldo enjoys his favorite sport”
- set of example days D , each represented by a set of attributes

Example	<i>Sky</i>	<i>AirTemp</i>	<i>Humidity</i>	<i>Wind</i>	<i>Water</i>	<i>Forecast</i>	<i>Enjoy</i>
1	Sunny	Warm	Normal	Strong	Warm	Same	Yes
2	Sunny	Warm	High	Strong	Warm	Same	Yes
3	Rainy	Cold	High	Strong	Warm	Change	No
4	Sunny	Warm	High	Strong	Cool	Change	Yes

- the task is to learn to predict the value of *Enjoy* for an arbitrary day, based on the values of its other attributes

A Concept Learning Task - Informal

- Hypothesis representation

- ▶ Each hypothesis h consists of a **conjunction of constraints on the instance attributes**, that is, in this case a vector of six attributes
 - ▶ Possible constraints:
 - ⇒ ? : any value is acceptable
 - ⇒ single required value for the attribute
 - ⇒ \emptyset : no value is acceptable
 - ▶ if some instance x satisfies all the constraints of hypothesis h , then h classifies x as a positive example ($h(x) = 1$)
- ⇒ **most general** hypothesis: $\langle ?, ?, ?, ?, ?, ? \rangle$
- ⇒ **most specific** hypothesis: $\langle \emptyset, \emptyset, \emptyset, \emptyset, \emptyset, \emptyset \rangle$

A Concept Learning Task - Formal

Given:

- Instances X : Possible days, each described by the attributes
 - ▶ *Sky* (with values *Sunny*, *Cloudy* and *Rainy*)
 - ▶ *AirTemp* (with values *Warm* and *Cold*)
 - ▶ *Humidity* (with values *Normal* and *High*)
 - ▶ *Wind* (with values *Strong* and *Weak*)
 - ▶ *Water* (with values *Warm* and *Cool*)
 - ▶ *Forecast* (with values *Same* and *Change*)
- Hypotheses H where each $h \in H$ is described as a conjunction of constraints on the above attributes
- Target Concept $c : \text{Enjoy} : X \Rightarrow \{0, 1\}$
- Training examples D : positive and negative examples of the table above

Determine:

- A hypothesis $h \in H$ such that $(\forall x \in X)[h(x) = c(x)]$

A Concept Learning Task - Example

- **example hypothesis** $h_e = \langle \text{Sunny}, ?, ?, ?, \text{Warm}, ? \rangle$

⇒ According to h_e Aldo enjoys his favorite sport whenever the *sky* is sunny and the *water* is warm (independent of the other weather conditions!)

example 1: $\langle \text{Sunny}, \text{Warm}, \text{Normal}, \text{Strong}, \text{Warm}, \text{Same} \rangle$

This example satisfies h_e , because the *sky* is sunny and the *water* is warm. Hence, Aldo would enjoy his favorite sport on this day.

example 4: $\langle \text{Sunny}, \text{Warm}, \text{High}, \text{Normal}, \text{Cool}, \text{Change} \rangle$

This example does **not** satisfy h_e , because the *water* is cool. Hence, Aldo would not enjoy his favorite sport on this day.

⇒ h_e is **not** consistent with the training examples D

Concept Learning as Search

- concept learning as search through the space of hypotheses H (implicitly defined by the hypothesis representation) with the goal of finding the hypothesis that best fits the training examples
- most practical learning tasks involve very large, even **infinite hypothesis spaces**
- many concept learning algorithms organize the search through the hypothesis space by relying on the **general-to-specific ordering**

FIND-S

- exploits general-to-specific ordering
- finds a maximally specific hypothesis h consistent with the observed training examples D

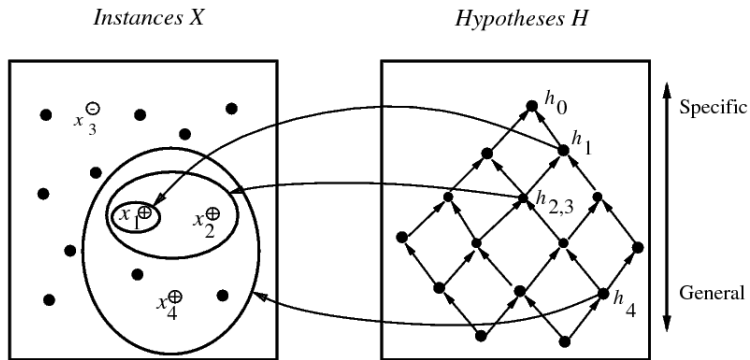
Algorithm

- 1 Initialize h to the most specific hypothesis in H
- 2 For each positive training instance x
 - ▶ if the constraint a_i is satisfied by x then do nothing
else replace a_i with the next more general constraint satisfied by x
- 3 Output hypothesis h

FIND-S – Example

- Initialize $h \leftarrow \langle \emptyset, \emptyset, \emptyset, \emptyset, \emptyset, \emptyset \rangle$
- example 1: $\langle \mathbf{Sunny}, \mathbf{Warm}, \mathbf{Normal}, \mathbf{Strong}, \mathbf{Warm}, \mathbf{Same} \rangle$
 $\Rightarrow h \leftarrow \langle \mathit{Sunny}, \mathit{Warm}, \mathit{Normal}, \mathit{Strong}, \mathit{Warm}, \mathit{Same} \rangle$
- example 2: $\langle \mathit{Sunny}, \mathit{Warm}, \mathbf{High}, \mathit{Strong}, \mathit{Warm}, \mathit{Same} \rangle$
 $\Rightarrow h \leftarrow \langle \mathit{Sunny}, \mathit{Warm}, ?, \mathit{Strong}, \mathit{Warm}, \mathit{Same} \rangle$
- example 3: $\langle \mathit{Rainy}, \mathit{Cold}, \mathit{High}, \mathit{Strong}, \mathit{Warm}, \mathit{Change} \rangle$
This example can be omitted because it is negative.
Notice that the current hypothesis is already consistent with this example, because it correctly classifies it as negative!
- example 4: $\langle \mathit{Sunny}, \mathit{Warm}, \mathit{High}, \mathit{Strong}, \mathbf{Cool}, \mathbf{Change} \rangle$
 $\Rightarrow h \leftarrow \langle \mathit{Sunny}, \mathit{Warm}, ?, \mathit{Strong}, ?, ? \rangle$

FIND-S - Example



$x_1 = \langle \text{Sunny Warm Normal Strong Warm Same} \rangle, +$
 $x_2 = \langle \text{Sunny Warm High Strong Warm Same} \rangle, +$
 $x_3 = \langle \text{Rainy Cold High Strong Warm Change} \rangle, -$
 $x_4 = \langle \text{Sunny Warm High Strong Cool Change} \rangle, +$

$h_0 = \langle \emptyset, \emptyset, \emptyset, \emptyset, \emptyset, \emptyset \rangle$
 $h_1 = \langle \text{Sunny Warm Normal Strong Warm Same} \rangle$
 $h_2 = \langle \text{Sunny Warm ? Strong Warm Same} \rangle$
 $h_3 = \langle \text{Sunny Warm ? Strong Warm Same} \rangle$
 $h_4 = \langle \text{Sunny Warm ? Strong ? ?} \rangle$

Remarks on FIND-S

- in each step, h is consistent with the training examples observed up to this point
- unanswered questions:
 - ▶ Has the learner converged to the correct target concept?

No way to determine whether FIND-S found the only consistent hypothesis h or whether there are many other consistent hypotheses as well
 - ▶ Why prefer the most specific hypothesis?
 - ▶ Are the training examples consistent?

FIND-S is only correct if D itself is consistent. That is, D has to be free of classification errors.
 - ▶ What if there are several maximally specific consistent hypotheses?

CANDIDATE-ELIMINATION

- CANDIDATE-ELIMINATION addresses several limitations of the FIND-S algorithm
- **key idea**: description of the set of all hypotheses consistent with D without explicitly enumerating them
- performs poorly with noisy data
- useful conceptual framework for introducing fundamental issues in machine learning

Version Spaces

- to incorporate the key idea mentioned above, a compact representation of all consistent hypotheses is necessary
- **Version space** $VS_{H,D}$, with respect to hypothesis space H and training data D , is the subset of hypotheses from H consistent with D .

$$VS_{H,D} \equiv \{h \in H \mid \text{Consistent}(h, D)\}$$

- $VS_{H,D}$ can be represented by the **most general** and the **most specific** consistent hypotheses in form of **boundary sets** within the partial ordering

Version Spaces

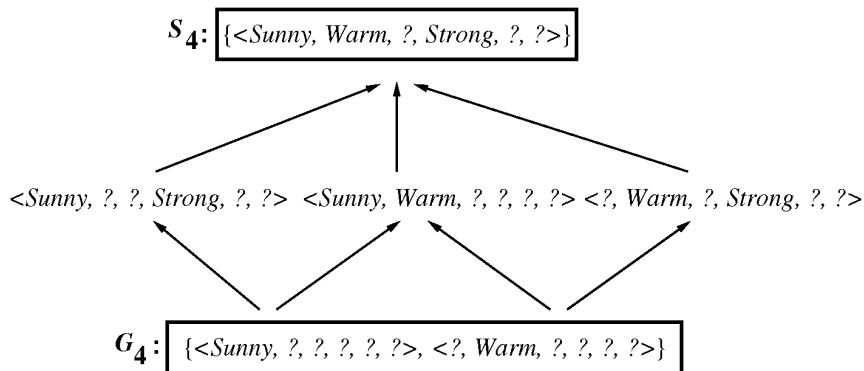
- The **general boundary set** G , with respect to hypothesis space H and training data D , is the set of maximally general members of H consistent with D .

$$G \equiv \{g \in H \mid \text{Consistent}(g, D) \wedge (\neg \exists g' \in H)[(g' >_g g) \wedge \text{Consistent}(g', D)]\}$$

- The **specific boundary set** S , with respect to hypothesis space H and training data D , is the set of minimally general (i.e., maximally specific) members of H consistent with D .

$$S \equiv \{s \in H \mid \text{Consistent}(s, D) \wedge (\neg \exists s' \in H)[(s >_g s') \wedge \text{Consistent}(s', D)]\}$$

Version Spaces



Initialize G to the set of maximally general hypotheses in H

Initialize S to the set of maximally specific hypotheses in H

For each training example $d \in D$, do

- **If d is a positive example**

- ▶ Remove from G any hypothesis inconsistent with d
- ▶ For each hypothesis s in S that is inconsistent with d
 - Remove s from S
 - Add to S all minimal generalizations h of s such that h is consistent with d and some member of G is more general than h
 - Remove from S any hypothesis that is more general than another hypothesis in S

- **If d is a negative example**

- ▶ Remove from S any hypothesis inconsistent with d
- ▶ For each hypothesis g in G that is inconsistent with d
 - Remove g from G
 - Add to G all minimal specializations h of g such that h is consistent with d and some member of S is more specific than h
 - Remove from G any hypothesis that is less general than another hypothesis in G

Illustrative Example

- Initialization of the Boundary sets

- $G_0 \leftarrow \{ \langle ?, ?, ?, ?, ?, ? \rangle \}$
- $S_0 \leftarrow \{ \langle \emptyset, \emptyset, \emptyset, \emptyset, \emptyset, \emptyset \rangle \}$

- example 1: $\langle \mathbf{Sunny, Warm, Normal, Strong, Warm, Same} \rangle$

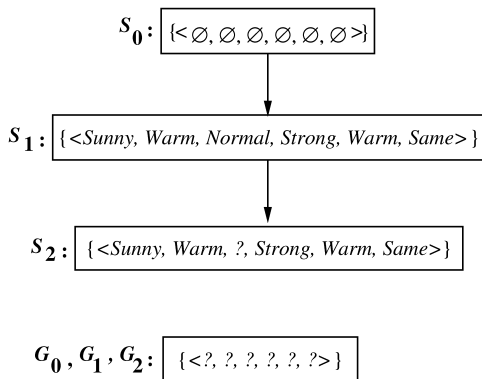
S is overly specific, because it wrongly classifies example 1 as false. So S has to be revised by moving it to the **least more general hypothesis** that covers example 1 and is **still more special** than another hypothesis in G .

- $\Rightarrow S_1 = \{ \langle \mathit{Sunny, Warm, Normal, Strong, Warm, Same} \rangle \}$
- $\Rightarrow G_1 = G_0$

- example 2: $\langle \mathit{Sunny, Warm, \mathbf{High}, Strong, Warm, Same} \rangle$

- $\Rightarrow S_2 = \{ \langle \mathit{Sunny, Warm, ?, Strong, Warm, Same} \rangle \}$
- $\Rightarrow G_2 = G_1 = G_0$

Illustrative Example



Training examples:

1. $\langle \text{Sunny}, \text{Warm}, \text{Normal}, \text{Strong}, \text{Warm}, \text{Same} \rangle, \text{Enjoy Sport} = \text{Yes}$
2. $\langle \text{Sunny}, \text{Warm}, \text{High}, \text{Strong}, \text{Warm}, \text{Same} \rangle, \text{Enjoy Sport} = \text{Yes}$

Illustrative Example

- example 3: $\langle \mathbf{Rainy}, \mathbf{Cold}, High, Strong, Warm, \mathbf{Change} \rangle$

G is overly general, because it wrongly classifies example 3 as true. So G has to be revised by moving it to the **least more specific hypotheses** that covers example 3 and is **still more general** than another hypothesis in S .

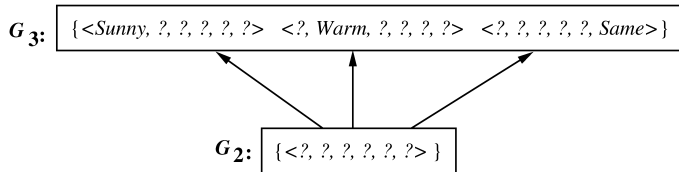
There are several alternative minimally more specific hypotheses.

$$\Rightarrow S_3 = S_2$$

$$\Rightarrow G_3 = \{ \langle \mathbf{Sunny}, ?, ?, ?, ?, ? \rangle, \langle ?, \mathbf{Warm}, ?, ?, ?, ? \rangle, \langle ?, ?, ?, ?, ?, \mathbf{Same} \rangle \}$$

Illustrative Example

S_2, S_3 : { <Sunny, Warm, ?, Strong, Warm, Same> }



Training Example:

3. <Rainy, Cold, High, Strong, Warm, Change>, EnjoySport=No

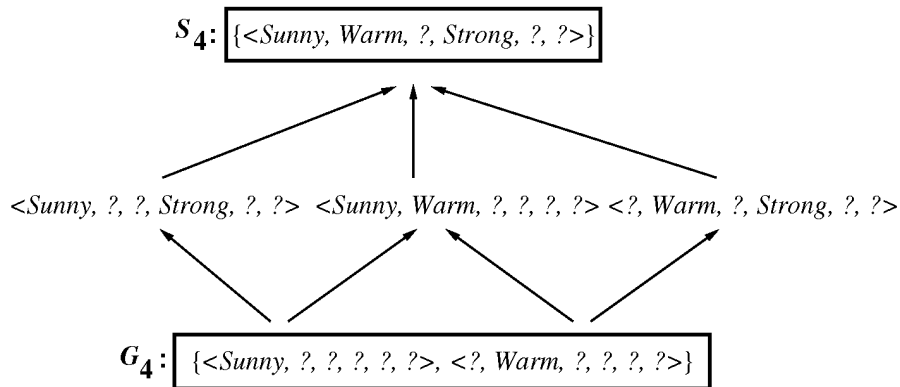
Illustrative Example

- example 4: $\langle \textit{Sunny}, \textit{Warm}, \textit{High}, \textit{Strong}, \mathbf{Cool}, \mathbf{Change} \rangle$

$$\Rightarrow S_4 = \{ \langle \textit{Sunny}, \textit{Warm}, ?, \textit{Strong}, ?, ? \rangle \}$$

$$\Rightarrow G_4 = \{ \langle \textit{Sunny}, ?, ?, ?, ?, ? \rangle, \langle ?, \textit{Warm}, ?, ?, ?, ? \rangle \}$$

Illustrative Example



Remarks

- Will the algorithm converge to the correct hypothesis?
 - ▶ convergence is assured provided there are no errors in D and the H includes the target concept
 - ▶ G and S contain only the same hypothesis
- How can partially learned concepts be used?
 - ▶ some unseen examples can be classified unambiguously as if the target concept had been fully learned
 - **positive** iff it satisfies every member of S
 - **negative** iff it doesn't satisfy any member of G
 - ▶ otherwise an instance x is classified by majority (if possible)

Inductive Bias

- fundamental property of inductive learning
 - ▶ a learner that makes no a priori assumptions regarding the identity of the target concept has no rational basis for classifying unseen examples
 - ▶ e.g., learning the *EnjoySport* concept was based on the assumption that the target concept could be represented as a conjunction of attribute values
- inductive bias \approx policy by which the learner generalizes beyond the observed training data to infer the classification of new instances
- Consider a concept learning algorithm L for the set of instances X . Let c be an arbitrary concept defined over X , and $D_c = \{ \langle x, c(x) \rangle \}$ an arbitrary set of training examples of c . Let $L(x_i, D_c)$ denote the classification assigned to the instance x_i by L after training on the data D_c . The **inductive bias** of L is any minimal set of assertions B such that
$$(\forall x_i \in X)[(B \wedge D_c \wedge x_i) \vdash L(x_i, D_c)]$$

Kinds of Inductive Bias

- **Restriction Bias** (aka Language Bias)

- ▶ entire H is searched by learning algorithm
- ▶ hypothesis representation **not expressive enough** to encompass all possible concepts
- ▶ e.g. CANDIDATE-ELIMINATION: for the hypothesis language used in the “enjoy”-example H only includes conjunctive concepts

- **Preference Bias** (aka Search Bias)

- ▶ hypothesis representation encompasses all possible concepts
- ▶ learning algorithm does not consider each possible hypothesis
- ▶ e.g. use of heuristics, greedy strategies

⇒ Preference Bias more desirable, because it assures

$$(\exists h \in H)[(\forall x \in X)[h(x) = c(x)]]$$

An Unbiased Learner

- an unbiased $H = 2^{|X|}$ would contain every teachable function
 - for such a H ,
 - ▶ G would always contain the **negation of the disjunction of observed negative examples**
 - ▶ S would always contain the **disjunction of the observed positive examples**
 - hence, only observed examples will be classified correctly
- ⇒ in order to converge to a single target concept, every $x \in X$ has to be in D
- ⇒ the learning algorithm is unable to generalize beyond observed training data

FIND-S / CANDIDATE ELIMINATION

Supervised Learning	unsupervised learning
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Approaches:

Concept / Classification	Policy Learning
symbolic	statistical / neuronal network
inductive	analytical

Learning Strategy:

⇒ **learning from examples**

Inductive System vs. Theorem Prover

