

Basic Machine Learning: Linear Models

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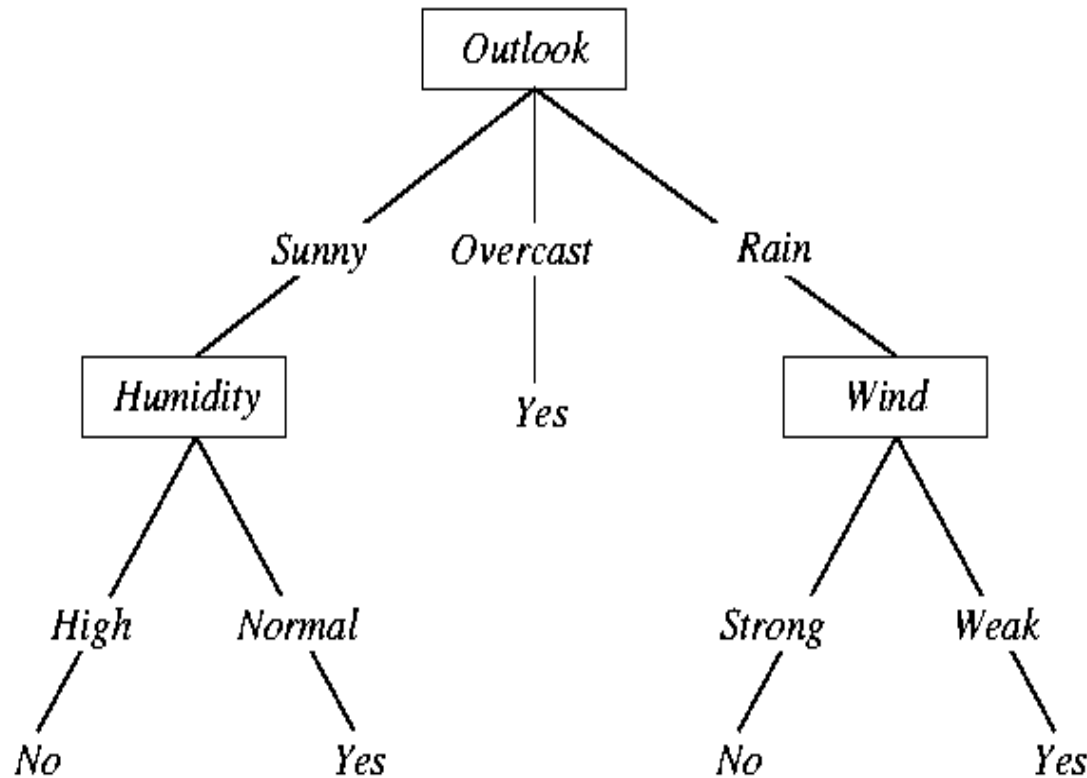
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Basic Machine Learning (Classification)

- I'm going to start by presenting a very brief review of decision trees
 - I'll also briefly discuss overfitting
- Then I'll talk about linear models, which are the workhorse of discriminative classification most used in NLP
- The example I am repeatedly using here is the CMU seminars task, a standard IE task
 - I will explain this task in a few slides

Decision Tree Representation for 'Play Tennis?'



- Internal node
~ test an attribute
- Branch
~ attribute value
- Leaf
~ classification result

When is it useful?

- Medical diagnosis
- Equipment diagnosis
- Credit risk analysis
- etc

Rule Sets as Decision Trees

- Decision trees are quite powerful
- It is easy to see that complex rules can be encoded as decision trees
- For instance, let's look at border detection in CMU seminars...



Example

the seminar at **<time>** 4 pm will

| Condition | Additional Knowledge | | | | Action |
|-----------|----------------------|--------|------|--------|--------------|
| Word | Lemma | LexCat | case | SemCat | Tag |
| | | | | | |
| | at | | | | stime |
| | | Digit | | | |
| | | | | timeid | |
| | | | | | |

A Path in the Decision Tree

- The tree will check if the token to the left of the possible start position has "at" as a lemma
- Then check if the token after the possible start position is a Digit
- Then check the second token after the start position is a timeid ("am", "pm", etc)
- If you follow this path at a particular location in the text, then the decision should be to insert a <stime>

Linear Models

- However, in practice decision trees are not used so often in NLP
- Instead, linear models are used
- Let me first present linear models
- Then I will compare linear models and decision trees

Binary Classification

- I'm going to first discuss linear models for binary classification, using binary features
- We'll take the same scenario as before
- Our classifier is trying to decide whether we have a <stime> tag or not at the current position (between two words in an email)
- The first thing we will do is encode the context at this position into a feature vector

Feature Vector

- Each feature is true or false, and has a position in the feature vector
- The feature vector is typically sparse, meaning it is mostly zeros (i.e., false)
- The feature vector represents the full feature space. For instance, consider...



Example

the seminar at **<time>** 4 pm will

| Condition | Additional Knowledge | | | | Action |
|-----------|----------------------|--------|------|--------|--------------|
| Word | Lemma | LexCat | case | SemCat | Tag |
| the | the | Art | low | | |
| seminar | Seminar | Noun | low | | |
| at | at | Prep | low | | stime |
| 4 | 4 | Digit | low | | |
| pm | pm | Other | low | timeid | |
| will | will | Verb | low | | |



Example

the seminar at **<time>** 4 pm will

| Condition | Additional Knowledge | | | | Action |
|-----------|----------------------|-------|--------|--------|--------------|
| | Word | Lemma | LexCat | case | |
| the | the | Art | low | | |
| seminar | Seminar | Noun | low | | |
| at | at | Prep | low | | stime |
| 4 | 4 | Digit | low | | |
| pm | pm | Other | low | timeid | |
| will | will | Verb | low | | |

- Our features represent this table using binary variables
- For instance, consider the lemma column
- Most features will be false (false = off = 0)
- The lemma features that will be on (true = on = 1) are:
 - 3_lemma_the
 - 2_lemma_Seminar
 - 1_lemma_at
 - +1_lemma_4
 - +2_lemma_pm
 - +3_lemma_will

Classification

- To classify we will take the dot product of the feature vector with a learned weight vector
- We will say that the class is true (i.e., we should insert a `<stime>` here) if the dot product is > 0 , and false otherwise
- Because we might want to shift the decision boundary, we add a feature that is always true
 - This is called the bias
 - By weighting the bias, we can shift where we make the decision (see next slide)

Feature Vector

- We might use a feature vector like this:
(this example is simplified – really we'd have all features for all positions)

| | |
|---|-----------------------------|
| 1 | Bias term |
| 0 | ... (say, -3_lemma_giraffe) |
| 1 | -3_lemma_the |
| 0 | ... |
| 1 | -2_lemma_Seminar |
| 0 | ... |
| 0 | ... |
| 1 | -1_lemma_at |
| 1 | +1_lemma_4 |
| 0 | ... |
| 1 | +1_Digit |
| 1 | +2_timeid |

Weight Vector

- Now we'd like the dot product to be > 0 if we should insert a `<stime>` tag
- To encode the rule we looked at before we have three features that we want to have a positive weight
 - `-1_lemma_at`
 - `+1_Digit`
 - `+2_timeid`
- We can give them weights of 1
- Their sum will be three
- To make sure that we only classify if all three weights are on, let's set the weight on the bias term to `-2`

Dot Product - I

| | |
|---|------------------|
| 1 | Bias term |
| 0 | |
| 1 | -3_lemma_the |
| 0 | |
| 1 | -2_lemma_Seminar |
| 0 | |
| 0 | |
| 1 | -1_lemma_at |
| 1 | +1_lemma_4 |
| 0 | |
| 1 | +1_Digit |
| 1 | +2_timeid |

| | |
|----|----------------|
| -2 | To compute |
| 0 | the dot |
| 0 | product first |
| 0 | take the |
| 0 | product of |
| 0 | each row, and |
| 0 | then sum these |
| 1 | |
| 0 | |
| 0 | |
| 1 | |
| 1 | |

Dot Product - II

| | | | | |
|---|------------------|----|----------|----------|
| 1 | Bias term | -2 | $1 * -2$ | $1 * -2$ |
| 0 | | 0 | $0 * 0$ | |
| 1 | -3_lemma_the | 0 | $0 * 0$ | |
| 0 | | 0 | $0 * 0$ | |
| 1 | -2_lemma_Seminar | 0 | $1 * 0$ | |
| 0 | | 0 | $0 * 0$ | |
| 0 | | 0 | $0 * 0$ | |
| 1 | -1_lemma_at | 1 | $1 * 1$ | $1 * 1$ |
| 1 | +1_lemma_4 | 0 | $1 * 0$ | |
| 0 | | 0 | $0 * 0$ | |
| 1 | +1_Digit | 1 | $1 * 1$ | $1 * 1$ |
| 1 | +2_timeid | 1 | $1 * 1$ | $1 * 1$ |
| | | | | ----- |
| | | | | 1 |

Learning the Weight Vector

- The general learning task is simply to find a good weight vector!
 - This is sometimes also called "training"
- Basic intuition: you can check weight vector candidates to see how well they classify the training data
 - Better weights vectors get more of the training data right
- So we need some way to make (smart) changes to the weight vector
 - The goal is to make better decisions on the training data
- I will talk more about this later

Feature Extraction

- We run **feature extraction** to get the feature vectors for each position in the text
- We typically use a text representation to represent true values (which are sparse)
- Often we define **feature templates** which describe the feature to be extracted and give the name of the feature (i.e., -1_lemma_XXX)

-3_lemma_the -2_lemma_Seminar -1_lemma_at +1_lemma_4 +1_Digit +2_timeid STIME

-3_lemma_Seminar -2_lemma_at -1_lemma_4 -1_Digit +1_timeid +2_lemma_will NONE

...

Training vs. Testing

- When training the system, we have gold standard labels (see previous slide)
- When testing the system on new data, we have no gold standard
 - We run the same feature extraction first
 - Then we take the dot product with the weight vector to get a classification decision
- Finally, we have to go back to the original text to write the `<stime>` tags into the correct positions

Summary so far

- So we've seen training and testing
- We have an idea about train error and test error (key concepts!)
- We are aware of the problem of overfitting
 - And we know what overfitting means in terms of train error and test error!
- Now let's compare decision trees and linear models

Linear models are weaker

- Linear models are weaker than decision trees
 - This means they can't express the same richness of decisions as decision trees can (if both have access to the same features)
- It is easy to see this by extending our example
- Recall that we have a weight vector encoding our rule (see next slide)
- Let's take another reasonable rule



Example

the seminar at **<time>** 4 pm will

| Condition | Additional Knowledge | | | | Action |
|-----------|----------------------|--------|------|--------|--------------|
| Word | Lemma | LexCat | case | SemCat | Tag |
| | | | | | |
| | at | | | | stime |
| | | Digit | | | |
| | | | | timeid | |
| | | | | | |



Example


the seminar at **<time>** 4 pm will

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| Word | Lemma | LexCat | case | SemCat | Tag |
| the | the | Art | low | | |
| seminar | Seminar | Noun | low | | |
| at | at | Prep | low | | stime |
| 4 | 4 | Digit | low | | |
| pm | pm | Other | low | timeid | |
| will | will | Verb | low | | |

- The rule we'd like to learn is that if we have the features:
 - 2_lemma_Seminar
 - 1_lemma_at
 - +1_Digit
- We should insert a <stime>
- This is quite a reasonable rule, it lets us correctly cover the new sentence:
"The Seminar at 3 will be given by ..."
(there is no timeid like "pm" here!)
- Let's modify the weight vector

Adding the second rule

| | | |
|---|------------------|----|
| 1 | Bias term | -2 |
| 0 | | 0 |
| 1 | -3_lemma_the | 0 |
| 0 | | 0 |
| 1 | -2_lemma_Seminar | 1 |
| 0 | | 0 |
| 0 | | 0 |
| 1 | -1_lemma_at | 1 |
| 1 | +1_lemma_4 | 0 |
| 0 | | 0 |
| 1 | +1_Digit | 1 |
| 1 | +2_timeid | 1 |



- Let's first verify that both rules work with this weight vector
- But does anyone see any issues here?

How many rules?

- If we look back at the vector, we see that we have actually encoded quite a number of rules
 - Any combination of three features with ones will be sufficient so that we have a `<stime>`
 - This might be good (i.e., it might generalize well to other examples). Or it might not.
- But what is definitely true is that it would be easy to create a decision tree that only encodes exactly our two rules!
- This should give you an intuition as to how linear models are weaker than decision trees

How can we get this power in linear models?

- Change the features!
- For instance, we can create combinations of our old features as new features
- For instance, clearly if we have:
 - One feature to encode our first rule
 - Another feature to encode our second rule
 - And we set the bias to 0
- We get the same as the decision tree
- Sometimes these new compound features would be referred to as trigrams (they each combine three basic features)

Feature Selection

- A task which includes automatically finding such new compound features is called **feature selection**
 - This is built into some machine learning toolkits
 - Or you can implement it yourself by trying out feature combinations and checking the training error
 - Use human intuition to check a small number of combinations
 - Or do it automatically, using a script

Training I

Training is **automatically adjusting** the feature vector so as to better fit the training corpus! **Intuition: make small adjustments** to get a better score on the training data (these all fit our example!)

$$\begin{bmatrix} -2 \\ 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 1 \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} -2.01 \\ 0.04 \\ 0.0004 \\ 0 \\ 1.1 \\ 0 \\ 0 \\ 0.9001 \\ 0 \\ 0 \\ 0.89 \\ 0.91 \end{bmatrix}$$

$$\begin{bmatrix} -1.99 \\ 0.04 \\ 0.002 \\ 0 \\ 1.101 \\ 0 \\ 0 \\ 0.9111 \\ 0 \\ 0 \\ 0.892 \\ 0.91 \end{bmatrix}$$

$$\begin{bmatrix} -2.01 \\ 0.043 \\ 0.0003 \\ 0 \\ 1.1 \\ 0 \\ 0 \\ 0.9144 \\ 0 \\ 0 \\ 0.93 \\ 1.01 \end{bmatrix}$$

Perceptron Update I

- One way to do this is using a so-called **perceptron**
- Algorithm:
 - Read the training examples one at a time
 - For each training example, decide how to update the weight vector
 - The perceptron update rule says:
 - If a training example is classified correctly:
 - Do nothing (because the current weight vector is fine)
 - If a training example is classified incorrectly:
 - Adjust the weight of every active feature by a small amount towards the desired decision
 - So that the example will score a bit better next time it is observed
 - Intuition: we hope that by making many small changes
 - The weights on important features increase consistently to the desired values which work well on the entire training set
 - The changes to unimportant feature weights will be random (sometimes up, sometimes down), and the weights will tend towards zero (meaning: no effect on the classification)

Perceptron Update II

Say we have $-2\ 0\ 0\ 0 \dots 0\ 0\ 0\ 0.5$, and see this training example. Clearly we will get it wrong...

| | | | | |
|---|------------------|-----|---------------|------------|
| 1 | Bias term | -2 | $1 \cdot -2$ | -2 |
| 0 | | 0 | | |
| 1 | -3_lemma_the | 0 | | |
| 0 | | 0 | | |
| 1 | -2_lemma_Seminar | 0 | | |
| 0 | | 0 | | |
| 0 | | 0 | | |
| 1 | -1_lemma_at | 0 | | |
| 1 | +1_lemma_4 | 0 | | |
| 0 | | 0 | | |
| 1 | +1_Digit | 0 | | |
| 1 | +2_timeid | 0.5 | $1 \cdot 0.5$ | <u>0.5</u> |
| | | | | -1.5 |

Perceptron Update III

So change the weight vector, by adding 0.1 to all active features. Score is now better (but still wrong)

| | | | | |
|---|------------------|-----|------------|-------|
| 1 | Bias term | -2 | $1 * -1.9$ | -1.9 |
| 0 | | 0 | | |
| 1 | -3_lemma_the | 0 | $1 * 0.1$ | 0.1 |
| 0 | | 0 | | |
| 1 | -2_lemma_Seminar | 0 | $1 * 0.1$ | 0.1 |
| 0 | | 0 | | |
| 0 | | 0 | | |
| 1 | -1_lemma_at | 0 | $1 * 0.1$ | 0.1 |
| 1 | +1_lemma_4 | 0 | $1 * 0.1$ | 0.1 |
| 0 | | 0 | | |
| 1 | +1_Digit | 0 | $1 * 0.1$ | 0.1 |
| 1 | +2_timeid | 0.5 | $1 * 0.6$ | 0.6 |
| | | | | ----- |
| | | | | -0.8 |

Perceptron Update IV

After looking at many other examples, irrelevant features (like "-3_lemma_the") are pushed back towards zero, and important features have stronger weights.

We have learned a good weight vector for this example, no further update is needed

| | | | | |
|---|------------------|------|--------|-------|
| 1 | Bias term | -2.1 | 1*-2.1 | -2.1 |
| 0 | | 0 | | |
| 1 | -3_lemma_the | -0.1 | 1*-0.1 | -0.1 |
| 0 | | 0 | | |
| 1 | -2_lemma_Seminar | 0.1 | 1*0.1 | 0.1 |
| 0 | | 0 | | |
| 0 | | 0 | | |
| 1 | -1_lemma_at | 0.7 | 1*0.7 | 0.7 |
| 1 | +1_lemma_4 | 0 | | |
| 0 | | 0 | | |
| 1 | +1_Digit | 1.1 | 1*1.1 | 1.1 |
| 1 | +2_timeid | 1.2 | 1*1.2 | 1.2 |
| | | | | <hr/> |
| | | | | 0.9 |

Two classes

- So far we discussed how to deal with a single label
 - At each position between two words we are asking whether there is a `<stime>` tag
- However, we are interested in `<stime>` and `</stime>` tags
- How can we deal with this?
- We can simply train one classifier on the `<stime>` prediction task
 - Here we are treating `</stime>` positions like every other non `<stime>` position
- And train another classifier on the `</stime>` prediction task
 - Likewise, treating `<stime>` positions like every other non `</stime>` position
- If both classifiers predict "true" for a single position, take the one that has the highest dot product

More than two labels

- What we have had up until now is called **binary classification**
- But we can generalize this idea to many possible labels
- This is called **multiclass classification**
 - We are picking one label (class) from a set of classes
- For instance, maybe we are also interested in the `<etime>` and `</etime>` labels
 - These labels indicate seminar end times, which are also often in the announcement emails (see next slide)

CMU Seminars - Example

<0.24.4.93.20.59.10.jgc+@NL.CS.CMU.EDU (Jaime Carbonell).0>

Type: cmu.cs.proj.mt

Topic: <speaker>Nagao</speaker> Talk

Dates: 26-Apr-93

Time: <stime>10:00</stime> - <etime>11:00 AM</etime>

PostedBy: jgc+ on 24-Apr-93 at 20:59 from NL.CS.CMU.EDU (Jaime Carbonell)

Abstract:

<paragraph><sentence>This Monday, 4/26, <speaker>Prof. Makoto Nagao</speaker> will give a seminar in the <location>CMT red conference room</location> <stime>10</stime>-<etime>11 am</etime> on recent MT research results</sentence>.</paragraph>

One against all

- We can generalize the way we handled two binary classification decisions to many labels
- Let's add the `<etime>` and `</etime>` labels
- We can train a classifier for each tag
 - Just as before, every position that is not an `<etime>` is a negative example for the `<etime>` classifier, and likewise for `</etime>`
- If multiple classifiers say "true", take the classifier with the highest dot product
- This is called **one-against-all**
- It is a quite reasonable way to use binary classification to predict one of multiple classes
 - It is not the only option, but it is easy to understand (and to implement too!)

Optional: "notag" classifier

- Actually, not inserting a tag is also a decision
- When working with multiple classifiers, we could train a classifier for "no tag here" too
- This is trained using all positions that do not have a tag as positive examples
 - And all positions that have tags as negative examples
- And again, we take the highest activation as the winning class
 - What happens if all of the classifications are negative?
 - We still take the highest activation!
- This is usually not done in domains with a heavy imbalance of "notag" like decisions, but it is an interesting possibility
- Question: what would happen to the weight vector if we did this in the binary classification (<stime> or no <stime>) case?

Summary: Multiclass classification

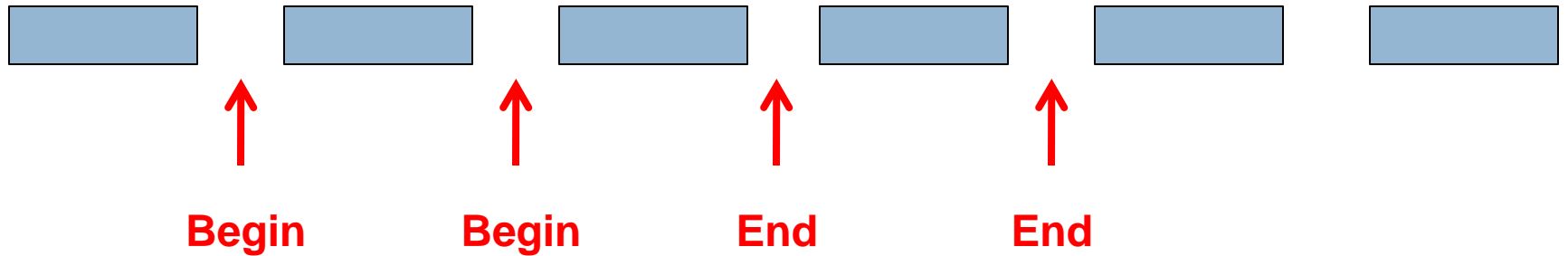
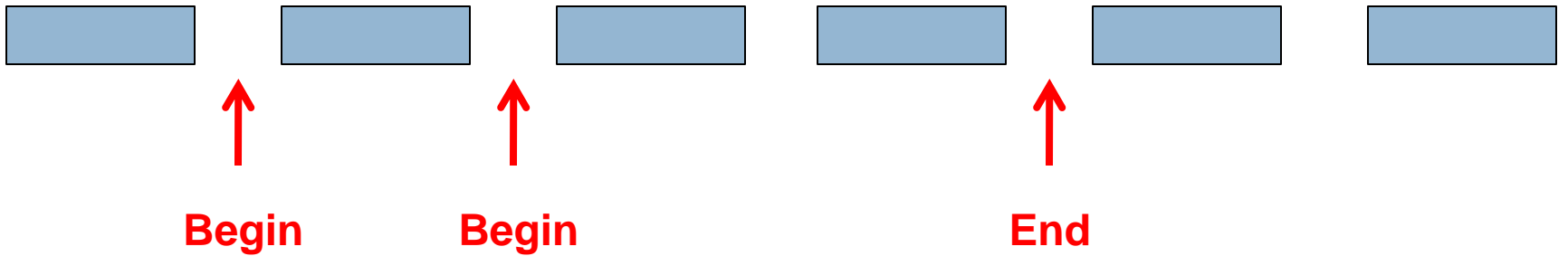
- We discussed **one-against-all**, a framework for combining binary classifiers
- It is not the only way to do this, but it often works pretty well
 - There are also techniques involving building classifiers on different subsets of the data and voting for classes
 - And other techniques can involve, e.g., a sequence of classification decisions (for instance, a tree-like structure of classifications)

Binary classifiers and sequences

- We can detect seminar start times by using two binary classifiers:
 - One for `<stime>`
 - One for `</stime>`
- And recall that if they both say "true" to the same position, take the highest dot product

- Then we need to actually annotate the document
- But this is problematic...

Some concerns



A basic approach

- One way to deal with this is to use a greedy algorithm
- Loop:
 - Scan the document until the `<stime>` classifier says true
 - Then scan the document until the `</stime>` classifier says true
- If the last tag inserted was `<stime>` then insert a `</stime>` at the end of the document
- Naturally, there are smarter algorithms than this that will do a little better
- But relying on these two independent classifiers is not optimal

How can we deal better with sequences?

- We can make our classification decisions dependent on previous classification decisions
- For instance, think of the Hidden Markov Model as used in POS-tagging
- The probability of a verb increases after a noun

Basic Sequence Classification

- We will do the following
 - We will add a feature template into each classification decision representing the **previous classification decision**
 - And we will change the labels we are predicting, so that in the span between a start and end boundary we are predicting a different label than outside

Basic idea

Seminar at 4 pm
 <stime> in-stime </stime>

- The basic idea is that we want to use the previous classification decision
- We add a special feature template `-1_label_XXX`
- For instance, between 4 and pm, we have:
`-1_label_<stime>`
- Suppose we have learned reasonable classifiers
- How often should we get a `<stime>` classification here? (Think about the training data in this sort of position)

-1_label_<stime>

- This should be an extremely strong indicator not to annotate a <stime>
- What else should it indicate?
 - It should indicate that there must be either a in-stime or a </stime> here!

Changing the problem slightly

- We'll now change the problem to a problem of annotating tokens (rather than annotating boundaries)
- This is traditional in IE, and you'll see that it is slightly more powerful than the boundary style of annotation
- We also make less decisions (see next slide)

IOB markup

| | | | | | | | |
|---------|----|---------|---------|------|----|----|-----|
| Seminar | at | 4 | pm | will | be | on | ... |
| O | O | B-stime | I-stime | O | O | O | |

- This is called IOB markup (or BIO = begin-in-out)
- This is a standardly used markup when modeling IE problems as sequence classification problems
- We can use a variety of models to solve this problem
- One popular model is the Hidden Markov Model, which you have seen in Statistical Methods
 - There, the label is the state
- However, in this course we will (mostly) stay more general and talk about binary classifiers and one-against-all

(Greedy) classification with IOB

| | | | | | | | |
|---------|----|---------|---------|------|----|----|-----|
| Seminar | at | 4 | pm | will | be | on | ... |
| O | O | B-stime | I-stime | O | O | O | |

- To perform greedy classification, first run your classifier on "Seminar"
- You can use a label feature here like -1_Label_StartOfSentence
- Suppose you correctly choose "O"
- Then when classifying "at", use the feature: -1_Label_O
- Suppose you correctly choose "O"
- Then when classifying "4", use the feature: -1_Label_O
- Suppose you correctly choose "B-stime"
- Then when classifying "pm", use the feature: -1_Label_B-stime
- Etc...

Training

- How to create the training data (do feature extraction) should be obvious
 - We can just use the gold standard label of the previous position as our feature

BIEWO Markup

- A popular alternative to IOB markup is BIEWO markup
- E stands for "end"
- W stands for "whole", meaning we have a one-word entity (i.e., this position is both the begin and end)

| | | | | | | | |
|---------|----|---------|---------|------|----|----|-----|
| Seminar | at | 4 | pm | will | be | on | ... |
| ○ | ○ | B-stime | E-stime | ○ | ○ | ○ | |

| | | | | | | |
|---------|----|---------|------|----|----|-----|
| Seminar | at | 4 | will | be | on | ... |
| ○ | ○ | W-stime | ○ | ○ | ○ | |

BIEWO vs IOB

- BIEWO fragments the training data
 - Recall that we are learning a binary classifier for each label
 - In our two examples on the previous slide, this means we are not using the same classifiers!
- Use BIEWO when single-word mentions require different features to be active than the first word of a multi-word mention

Conclusion

- I've taught you the basics of:
 - Binary classification using features
 - Multiclass classification (using one-against-all)
 - Sequence classification (using a feature that uses the previous decision)
 - And IOB or BIEWO labels
- I've skipped a lot of details
 - I haven't told you how to actually learn the weight vector in the binary classifier
 - I also haven't talked about non-greedy ways to do sequence classification
 - And I didn't talk about probabilities, which are used directly, or at least approximated, in many kinds of commonly used linear models!
- Hopefully what I did tell you is fairly intuitive and helps you understand classification, that is the goal

- Further reading (optional):
 - Tom Mitchell “Machine Learning” (text book)

- Thank you for your attention!