Natural Language Processing

Coreference and Anaphora Resolution

Alessandro Moschitti, Olga Uryupina
Department of information and communication technology
University of Trento
Email: moschitti@disi.unitn.it uryupina@gmail.com

Anaphora Resolution

Example

Sophia Loren says she will always be grateful to Bono. The actress revealed that the U2 singer helped her calm down when she became scared by a thunderstorm while travelling on a plane.

Coreference Chains:

- {Sophia Loren, she, the actress, her, she}
- {Bono, the U2 singer }
- {a thunderstorm}
- {a plane}

Anaphora Resolution

The interpretation of most expressions depends on the context in which they are used

- Studying the semantics & pragmatics of context dependence a crucial aspect of linguistics

Developing methods for interpreting anaphoric expressions useful in many applications

- Information extraction: recognize which expressions are mentions of the same object
- Summarization / segmentation: use entity coherence
- Multimodal interfaces: recognize which objects in the visual scene are being referred to

Outline

- Terminology
- A brief history of anaphora resolution
  - First algorithms: Charniak, Winograd, Wilks
  - Pronouns: Hobbs
  - Salience: S-List, LRC
- The MUC initiative
- Early statistical approaches
  - The mention-pair model
- Modern ML approaches
  - ILP
  - Entity-mention model
  - Work on features
- Evaluation

Anaphora resolution: a specification of the problem

Example

Sophia Loren says she will always be grateful to Bono. The actress revealed that the U2 singer helped her calm down when she became scared by a thunderstorm while travelling on a plane.

- *she* $\Rightarrow$ *Sophia Loren*
- *the actress* $\Rightarrow$ *Sophia Loren*
- *the U2 singer* $\Rightarrow$ *Bono*
- *her* $\Rightarrow$ *Sophia Loren*
- *she* $\Rightarrow$ *Sophia Loren*

Interpreting anaphoric expressions

Interpreting ('resolving') an anaphoric expressions involves at least three tasks:

- Deciding whether the expression is in fact anaphoric
- Identifying its antecedent (possibly not introduced by a nominal)
- Determining its meaning (cfr. identity of sense vs. identity of reference)

(not necessarily in this order!)

Anaphoric expressions: nominals

- PRONOUNS:

Definite pronouns: Ross bought {a radiometer | three kilograms of after-dinner mints} and gave {it | them} to Nadia for her birthday. (Hirst, 1981)

Indefinite pronouns: Sally admired Sue's jacket, so she got one for Christmas. (Garnham, 2001)

Reflexives: John bought himself an hamburger

- DEFINITE DESCRIPTIONS:

A man and a woman came into the room. The man sat down.

Epiteths: A man ran into my car. The idiot wasn't looking where he was going.

- DEMONSTRATIVES:

Tom has been caught shoplifting. That boy will turn out badly.

- PROPER NAMES:

Factors that affect the interpretation of anaphoric expressions

- Factors:
  - Surface similarity
  - Morphological features (agreement)
  - Syntactic information
  - Salience
  - Lexical and commonsense knowledge

Coreference vs. Anaphora

Example

Sophia Loren says she will always be grateful to Bono. The actress revealed that the U2 singer helped her calm down when she became scared by a thunderstorm while travelling on a plane.

Coreference Chains:

- {Sophia Loren, she, the actress, her, she}
- {Bono, the U2 singer }
- {a thunderstorm}
- {a plane}

Coreference vs. Anaphora

COREFERENT, not ANAPHORIC

- two mentions of same object in different documents

ANAPHORIC, not COREFERENT

- identity of sense: John bought a shirt, and Bill got ONE, too
- Dependence on non-referring expressions: EVERY CAR had been stripped of ITS paint
- Non-identity relations (bridging, “other” etc)
- Reference to events

A brief history of early work on anaphora resolution

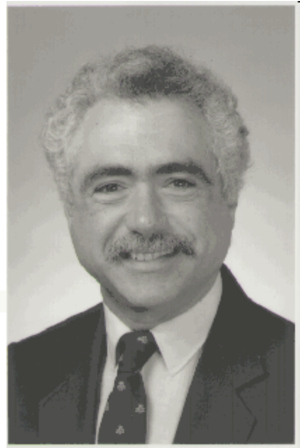
- Algorithms heavily based on (hand-coded) commonsense knowledge: Charniak 72, Winograd 74, Hobbs 1974, Wilks 1975
- Syntax-based algorithms: Hobbs 1974
- Salience-based algorithms: Brennan et al, Strube & Hahn, Tetreault

First approaches to anaphora resolution: Charniak, Winograd, Wilks

- Heavy emphasis on inference
- Hand-coded
- No formal evaluation

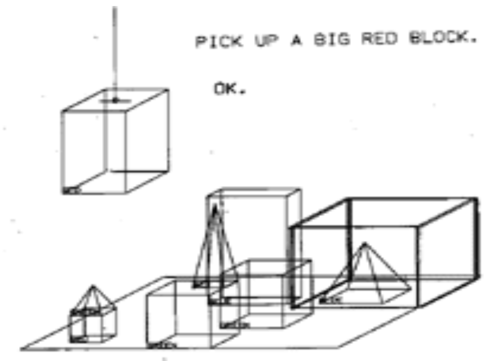
1970s Example: SHRDLU

http://hci.stanford.edu/~winograd/shrdlu/



Terry Winograd

Terry Winograd. 1971.
MIT Ph.D. Thesis.



Person: PICK UP A BIG RED BLOCK.
Computer: OK. (does it)
Person: GRASP THE PYRAMID.
Computer: I DON'T UNDERSTAND WHICH PYRAMID YOU MEAN.
Person: FIND A BLOCK WHICH IS TALLER THAN THE ONE YOU ARE HOLDING AND PUT IT INTO THE BOX.
Computer: BY "IT", I ASSUME YOU MEAN THE BLOCK WHICH IS TALLER THAN THE ONE I AM HOLDING.
Computer: OK. (does it)
Person: WHAT DOES THE BOX CONTAIN?
Computer: THE BLUE PYRAMID AND THE BLUE BLOCK.
Person: WHAT IS THE PYRAMID SUPPORTED BY?
Computer: THE BOX.
Person: HOW MANY BLOCKS ARE NOT IN THE BOX?
Computer: FOUR OF THEM.
Person: IS AT LEAST ONE OF THEM NARROWER THAN THE ONE WHICH I TOLD YOU TO PICK UP?
Computer: YES, THE RED CUBE.

- This is one of the only dialogs it knows.
- SHRDLU is too stupid to make mistakes.
- Beautiful “Demo-ware”

Anaphora in SHRDLU

- First example of HISTORY LIST algorithm
- Uses a combination of agreement features and semantic constraints
- Check all possibilities and assign a global score rather than simply find the first match
- Score incorporates syn component: entities in subj position higher score than entities in object position, in turn ranked more highly than entities in adjunct position
- Performance made more impressive by including solutions to a number of complex cases, such as reference to events (Why did you do it?) – often ad hoc

Hobbs' `Naïve Algorithm' (Hobbs, 1974)

- The reference algorithm for PRONOUN resolution (until Soon et al it was the standard baseline)
  - Interesting since Hobbs himself in the 1974 paper suggests that this algorithm is very limited (and proposes one based on semantics)
- The first anaphora resolution algorithm to have an (informal) evaluation
- Purely syntax based

Hobbs: example

- **Mr. Smith** saw a driver of **his** truck.

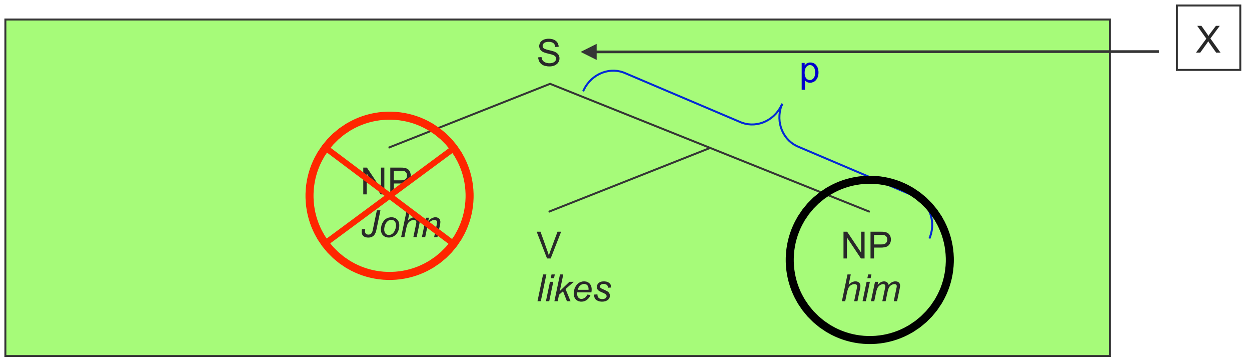
- Mr. Smith saw **a driver** in **his** truck.

Hobbs' `Naïve Algorithm' (Hobbs, 1974)

- Works off 'surface parse tree'
- Starting from the position of the pronoun in the surface tree,
  - first go up the tree looking for an antecedent in the current sentence (left-to-right, breadth-first);
  - then go to the previous sentence, again traversing left-to-right, breadth-first.
  - And keep going back

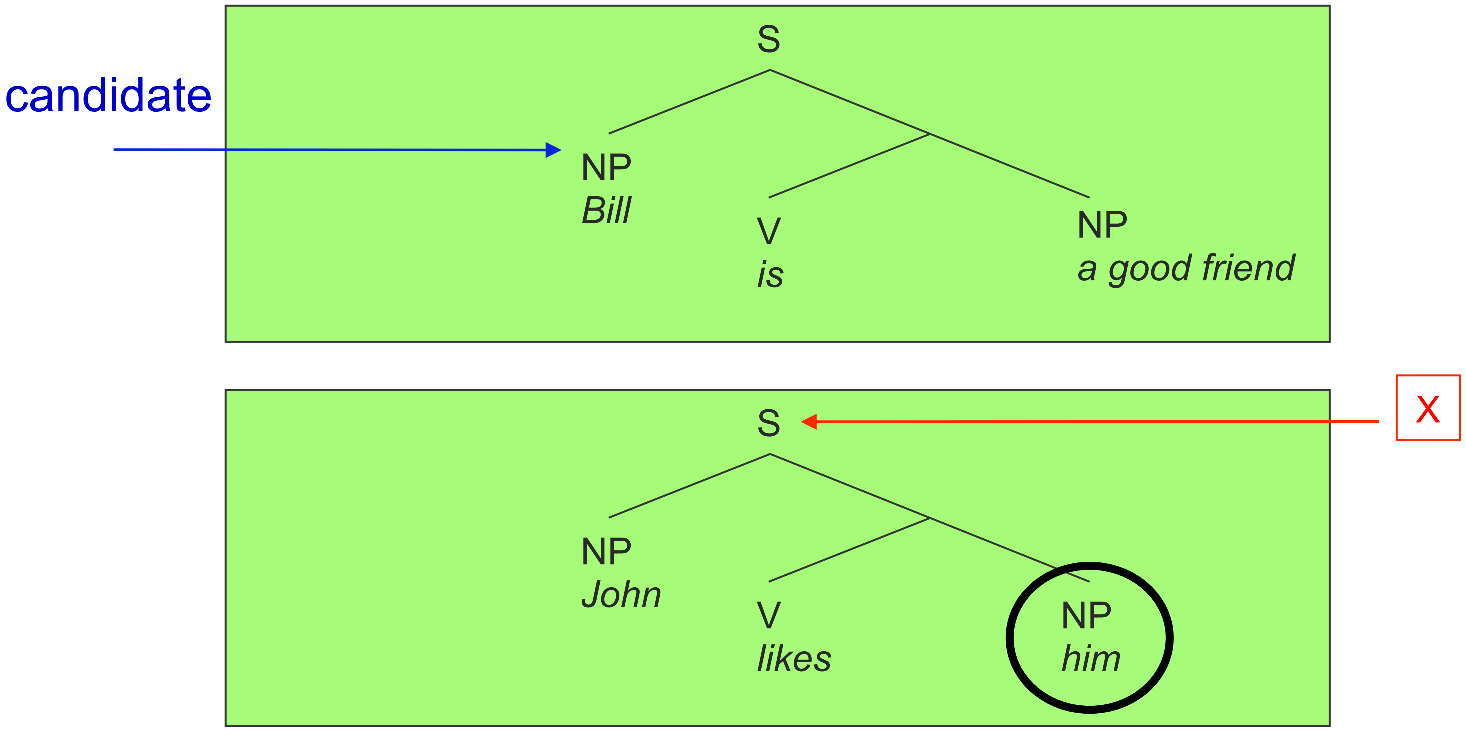
Hobbs' algorithm: Intrasentential anaphora

- Steps 2 and 3 deal with intrasentential anaphora and incorporate basic syntactic constraints:



- Also: *John's portrait of him*

Hobbs' Algorithm: intersentential anaphora



Evaluation

- The first anaphora resolution algorithm to be evaluated in a systematic manner, and still often used as baseline (hard to beat!)
- Hobbs, 1974:
  - 300 pronouns from texts in three different styles (a fiction book, a non-fiction book, a magazine)
  - Results: 88.3% correct without selectional constraints, 91.7% with SR
  - 132 ambiguous pronouns; 98 correctly resolved.
- Tetreault 2001 (no selectional restrictions; all pronouns)
  - 1298 out of 1500 pronouns from 195 NYT articles (76.8% correct)
  - 74.2% correct intra, 82% inter
- Main limitations
  - Reference to propositions excluded
  - Plurals
  - Reference to events

Salience-based algorithms

- Common hypotheses:
  - Entities in discourse model are RANKED by salience
  - Salience gets continuously updated
  - Most highly ranked entities are preferred antecedents
- Variants:
  - DISCRETE theories (Sidner, Brennan et al, Strube & Hahn): 1-2 entities singled out
  - CONTINUOUS theories (Alshawi, Lappin & Leass, Strube 1998, LRC): only ranking

Factors that affect prominence

- Distance
- Order of mention in the sentence

Entities mentioned earlier in the sentence more prominent

- Type of NP (proper names > other types of NPs)
- Number of mentions
- Syntactic position (subj > other GF, matrix > embedded)
- Semantic role (‘implicit causality’ theories)
- Discourse structure

Salience-based algorithms

- Sidner 1979:
  - Most extensive theory of the influence of salience on several types of anaphors
  - Two FOCI: discourse focus, agent focus
  - never properly evaluated
- Brennan et al 1987 (see Walker 1989)
  - Ranking based on grammatical function
  - One focus (CB)
- Strube & Hahn 1999
  - Ranking based on information status (NP type)
- S-List (Strube 1998): drop CB
  - LRC (Tetreault): incremental

Results

Algorithm	PTB-News (1694)	PTB-Fic (511)
LRC	74.9%	72.1%
S-List	71.7%	66.1%
BFP	59.4%	46.4%

Comparison with ML techniques of the time

Algorithm	All 3
LRC	76.7%
Ge et al. (1998)	87.5% (*)
Morton (2000)	79.1%

MUC

- ARPA’s Message Understanding Conference (1992-1997)
- First big initiative in Information Extraction
- Changed NLP by producing the first sizeable annotated data for semantic tasks including
  - named entity extraction
  - `coreference’
- Developed first methods for evaluating anaphora resolution systems

MUC terminology:

- MENTION: any markable
- COREFERENCE CHAIN: a set of mentions referring to an entity
- KEY: the (annotated) solution (a partition of the mentions into coreference chains)
- RESPONSE: the coreference chains produced by a system

Since MUC

- ACE
  - Much more data
  - Subset of mentions
  - IE perspective
- SemEval-2010
  - More languages
  - CL perspective
- Evalita
  - Italian (ACE-style)
- **CoNLL-OntoNotes**
  - English (2011), Arabic, Chinese (2012)

MODERN WORK IN ANAPHORA RESOLUTION

- Availability of the first anaphorically annotated corpora from MUC6 onwards made it possible
  - To evaluate anaphora resolution on a large scale
  - To train statistical models

PROBLEMS TO BE ADDRESSED BY LARGE-SCALE ANAPHORIC RESOLVERS

- Robust mention identification
  - Requires high-quality parsing
- Robust extraction of morphological information
- Classification of the mention as referring / predicative / expletive
- Large scale use of lexical knowledge
- Global inference

Problems to be resolved by a large-scale AR system: mention identification

- Typical problems:
  - Nested NPs (possessives)
    - [a city] 's [computer system] →

    [[a city]'s computer system]
  - Appositions:
    - [Madras], [India] → [Madras, [India]]
  - Attachments

Computing agreement: some problems

- Gender:
  - [India] withdrew HER ambassador from the Commonwealth
  - "…to get a customer's 1100 parcel-a-week load to *its* doorstep"
    - [actual error from LRC algorithm]
- Number:
  - The Union said that THEY would withdraw from negotations until further notice.

Problems to be solved: anaphoricity determination

- Expletives:
  - IT’s not easy to find a solution
  - Is THERE any reason to be optimistic at all?
- Non-anaphoric definites

PROBLEMS: LEXICAL KNOWLEDGE

- Still the weakest point
- The first breaktrough: WordNet
- Then methods for extracting lexical knowledge from corpora
- A more recent breakthrough: Wikipedia

MACHINE LEARNING APPROACHES TO ANAPHORA RESOLUTION

- First efforts: MUC-2 / MUC-3 (Aone and Bennet 1995, McCarthy & Lehnert 1995)
- Most of these: SUPERVISED approaches
  - Early (NP type specific): Aone and Bennet, Vieira & Poesio
  - McCarthy & Lehnert: all NPs
  - Soon et al: standard model
- UNSUPERVISED approaches
  - Eg Cardie & Wagstaff 1999, Ng 2008

ANAPHORA RESOLUTION AS A CLASSIFICATION PROBLEM

1. Classify NP1 and NP2 as coreferential or not
2. Build a complete coreferential chain

SUPERVISED LEARNING FOR ANAPHORA RESOLUTION

- Learn a model of coreference from training labeled data
- need to specify
  - learning algorithm
  - feature set
  - clustering algorithm

SOME KEY DECISIONS

- ENCODING
  - I.e., what positive and negative instances to generate from the annotated corpus
  - Eg treat all elements of the coref chain as positive instances, everything else as negative:
- DECODING
  - How to use the classifier to choose an antecedent
  - Some options: ‘sequential’ (stop at the first positive), ‘parallel’ (compare several options)

Early machine-learning approaches

- Main distinguishing feature: concentrate on a single NP type
- Both hand-coded and ML:
  - Aone & Bennett (pronouns)
  - Vieira & Poesio (definite descriptions)
- Ge and Charniak (pronouns)

Mention-pair model

- Soon et al. (2001)
- First ‘modern’ ML approach to anaphora resolution
- Resolves ALL anaphors
- Fully automatic mention identification
- Developed instance generation & decoding methods used in a lot of work since

Soon et al. (2001)

Wee Meng Soon, Hwee Tou Ng, Daniel Chung Yong Lim, *A Machine Learning Approach to Coreference Resolution of Noun Phrases*, Computational Linguistics 27(4):521–544

MENTION PAIRS

<ANAPHOR (j), ANTECEDENT (i)>

Mention-pair: encoding

- Sophia Loren says she will always be grateful to Bono. The actress revealed that the U2 singer helped her calm down when she became scared by a thunderstorm while travelling on a plane.

Mention-pair: encoding

- Sophia Loren says she will always be grateful to Bono. The actress revealed that the U2 singer helped her calm down when she became scared by a thunderstorm while travelling on a plane.

Mention-pair: encoding

- Sophia Loren
- she
- Bono
- The actress
- the U2 singer
- U2
- her
- she
- a thunderstorm
- a plane

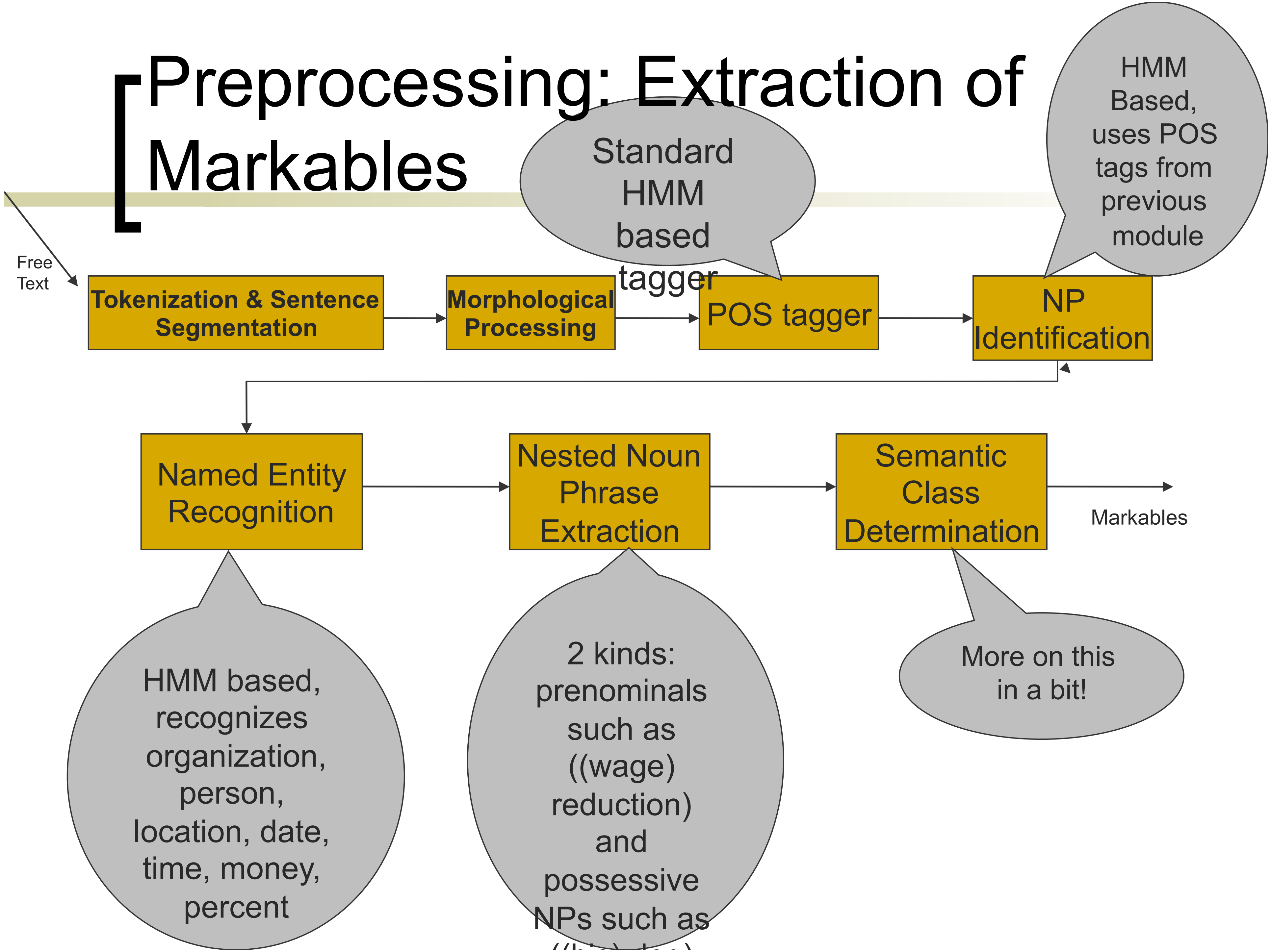
Mention-pair: encoding

- Sophia Loren → none
- she → (she,S.L,+)
- Bono → none
- The actress → (the actress, Bono,-),(the actress,she,+)
- the U2 singer → (the U2 s., the actress,-), (the U2 s.,Bono,+)
- U2 → none
- her → (her,U2,-),(her,the U2 singer,-),(her,the actress,+)
- she → (she, her,+)
- a thunderstorm → none
- a plane → none

Mention-pair: decoding

- Right to left, consider each antecedent until classifier returns true

Preprocessing: Extraction of Markables



Soon et al: preprocessing

- POS tagger: HMM-based
  - 96% accuracy
- Noun phrase identification module
  - HMM-based
  - Can identify correctly around 85% of mentions
- NER: reimplementation of Bikel Schwartz and Weischedel 1999
  - HMM based
  - 88.9% accuracy

Soon et al 2001: Features of mention - pairs

- NP type
- Distance
- Agreement
- Semantic class

Soon et al: NP type and distance

NP type of anaphor j (3)

`j-pronoun, def-np, dem-np (bool)`

NP type of antecedent i

`i-pronoun (bool)`

Types of both

`both-proper-name (bool)`

DIST

`0, 1, ….`

Soon et al features: string match, agreement, syntactic position

STR_MATCH
ALIAS

```
dates   (1/8 - January 8)
person   (Bent Simpson / Mr. Simpson)
organizations: acronym match
            (Hewlett Packard / HP)
```

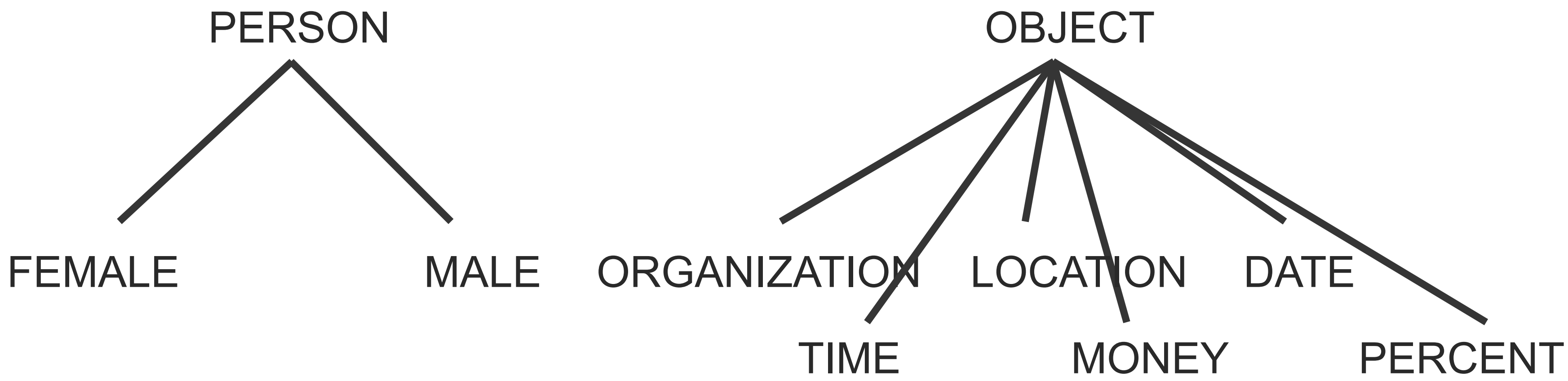
AGREEMENT FEATURES

```
number agreement
gender agreement
```

SYNTACTIC PROPERTIES OF ANAPHOR

```
occurs in appositive contruction
```

Soon et al: semantic class agreement



SEMCLASS = true iff semclass(i) <= semclass(j) or viceversa

Soon et al: evaluation

- MUC-6:
  - P=67.3, R=58.6, F=62.6
- MUC-7:
  - P=65.5, R=56.1, F=60.4
- Results about 3rd or 4th amongst the best MUC-6 and MUC-7 systems

Basic errors: synonyms & hyponyms

Toni Johnson pulls a tape measure across the front of what was once [a stately Victorian home].

…..

The remainder of [THE HOUSE] leans precariously against a sturdy oak tree.

Most of the 10 analysts polled last week by Dow Jones International News Service in Frankfurt .. .. expect [the US dollar] to ease only mildly in November

…..

Half of those polled see [THE CURRENCY] …

Basic errors: NE

- [Bach]'s air followed. Mr. Stolzman tied [the composer] in by proclaiming him the great improviser of the 18^{th} century ….
- [The FCC] …. [the agency]

Modifiers

FALSE NEGATIVE:

A new incentive plan for advertisers …

…. **The new ad plan** ….

FALSE NEGATIVE:

The 80-year-old house

….

The Victorian house …

Soon et al. (2001): Error Analysis (on 5 random documents from MUC-6)

Types of Errors Causing Spurious Links (→ affect precision)	**Frequency**	**%**
Prenominal modifier string match	16	42.1%
Strings match but noun phrases refer to different entities	11	28.9%
Errors in noun phrase identification	4	10.5%
Errors in apposition determination	5	13.2%
Errors in alias determination	2	5.3%

Types of Errors Causing Missing Links (→ affect recall)	**Frequency**	**%**
Inadequacy of current surface features	38	63.3%
Errors in noun phrase identification	7	11.7%
Errors in semantic class determination	7	11.7%
Errors in part-of-speech assignment	5	8.3%
Errors in apposition determination	2	3.3%
Errors in tokenization	1	1.7%

Mention-pair: locality

- Bill Clinton .. Clinton .. Hillary Clinton
- Bono .. He .. They

Subsequent developments

- Improved versions of the mention-pair model: Ng and Cardie 2002, Hoste 2003
- Improved mention detection techniques (better parsing, joint inference)
- Anaphoricity detection
- Using lexical / commonsense knowledge (particularly semantic role labelling)
- Different models of the task: ENTITY MENTION model, graph-based models
- Salience
- Extensive feature engineering
- Development of AR toolkits (GATE, LingPipe, GUITAR, BART)

Modern ML approaches

- ILP: start from pairs, impose global constraints
- Entity-mention models: global encoding/ decoding
- Feature engineering

Integer Linear Programming

- Optimization framework for global inference
- NP-hard
- But often fast in practice
- Commercial and publicly available solvers

ILP: general formulation

- Maximize objective function
- $\sum \lambda i * Xi$
- Subject to constraints
- $\sum \alpha i * Xi >= \beta i$
- Xi – integers

ILP for coreference

- Klenner (2007)
- Denis & Baldridge
- Finkel & Manning (2008)

ILP for coreference

- Step 1: Use Soon et al. (2001) for encoding. Learn a classifier.
- Step 2: Define objective function:
- $\sum \lambda_{ij} * X_{ij}$
- $X_{ij}=-1$ – not coreferent
- 1 – coreferent
- λ_{ij} – the classifier's confidence value

ILP for coreference: example

- Bill Clinton .. Clinton .. Hillary Clinton
- (Clinton, Bill Clinton) $\rightarrow$ +1
- (Hillary Clinton, Clinton) $\rightarrow$ +0.75
- (Hillary Clinton, Bill Clinton) $\rightarrow$ -0.5 /-2

- $\max(1*X_{21}+0.75*X_{32} -0.5*X_{31})$
- Solution: $X_{21}=1$, $X_{32}=1$, $X_{31}=-1$
- This solution gives the same chain..

ILP for coreference

- Step 3: define constraints
- transitivity constraints:
  - $i<j<k$
  - $Xik>=Xij+Xjk-1$

Back to our example

- Bill Clinton .. Clinton .. Hillary Clinton
- (Clinton, Bill Clinton) $\rightarrow$ +1
- (Hillary Clinton, Clinton) $\rightarrow$ +0.75
- (Hillary Clinton, Bill Clinton) $\rightarrow$ -0.5 /-2

- $\max(1*X_{21}+0.75*X_{32} -0.5*X_{31})$
- $X_{31}>=X_{21}+X_{32}-1$

Solutions

- $\max(1*X_{21}+0.75*X_{32} + \lambda_{31}*X_{31})$
- $X_{31} >= X_{21}+X_{32}-1$
- X_{21}, X_{32}, X_{31} $\lambda_{31}=-0.5$ $\lambda_{31}=-2$
- 1,1,1 obj=1.25 obj=-0.25
- 1,-1,-1 obj=0.75 obj=2.25
- -1,1,-1 obj=0.25 obj=1.75
- $\lambda_{31}=-0.5$: same solution
- $\lambda_{31}=-2$: {Bill Clinton, Clinton}, {Hillary Clinton}

ILP constraints

- Transitivity
- Best-link
- Agreement etc as hard constraints
- Discourse-new detection
- Joint preprocessing

Entity-mention model

- Bell trees (Luo et al, 2004)
- Ng
- Latest Berkeley model (2015)
- And many others..

Entity-mention model

- Mention-pair model: resolve mentions to mentions, fix the conflicts afterwards

- Entity-mention model: grow entities by resolving each mention to already created entities

Example

- Sophia Loren says she will always be grateful to Bono. The actress revealed that the U2 singer helped her calm down when she became scared by a thunderstorm while travelling on a plane.

Example

- Sophia Loren
- she
- Bono
- The actress
- the U2 singer
- U2
- her
- she
- a thunderstorm
- a plane

Mention-pair vs. Entity-mention

- Resolve “her” with a perfect system
- Mention-pair – build a list of candidate mentions:
- Sophia Loren, she, Bono, The actress, the U2 singer, U2
- process backwards.. {her, the U2 singer}
- Entity-mention – build a list of candidate entities:
- {Sophia Loren, she, The actress}, {Bono, the U2 singer}, {U2}

First-order features

- Using pairwise boolean features and quantifiers
  - Ng
  - Recasens
  - Unsupervised
- Semantic Trees

History features in mention-pair modelling

- Yang et al (pronominal anaphora)
- Salience

Entity update

- Incremental
- Beam (Luo)
- Markov logic – joint inference across mentions (Poon & Domingos)

Tree-based models of entities

- An entity is represented as a tree of its mentions, with pairwise links being edges
- Structural learning (perceptron, SVMstruct)
- Winner of CoNLL-2012 (Fernandes et al.)

Ranking

- Coreference resolution with a classifier:
  - Test candidates
  - Pick the best one
- Coreference resolution with a ranker
  - Pick the best one directly

Features

- Soon et al (2001): 12 features
- Ng & Cardie (2003): 50+ features
- Uryupina (2007): 300+ features
- Bengston & Roth (2008): feature analysis
- BART: around 50 feature templates
- State of the art (2015, 2016) – gigabytes of automatically generated features (cf. Berkeley's success, CoNLL-2012 win by Fernandes et al.)

New features

- More semantic knowledge, extracted from text (Garera & Yarowsky), Wordnet (Harabagiu) or Wikipedia (Ponzetto & Strube)
- Better NE processing (Bergsma)
- Syntactic constraints (back to the basics)
- Approximate matching (Strube)
- Combinations

Evaluation of coreference resolution systems

- Lots of different measures proposed
- ACCURACY:
  - Consider a mention correctly resolved if
    - Correctly classified as anaphoric or not anaphoric
    - ‘Right’ antecedent picked up
- Measures developed for the competitions:
  - Automatic way of doing the evaluation
- More realistic measures (Byron, Mitkov)
  - Accuracy on ‘hard’ cases (e.g., ambiguous pronouns)

Vilain et al. (1995)

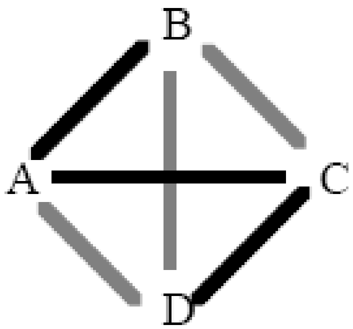
- The official MUC scorer
- Based on precision and recall of links
- Views coreference scoring from a model-theoretical perspective
  - Sequences of coreference links (= coreference chains) make up entities as SETS of mentions
  - → Takes into account the transitivity of the IDENT relation

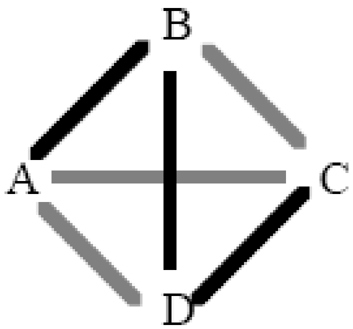
MUC-6 Coreference Scoring Metric (Vilain, et al., 1995)

- Identify the minimum number of **link** modifications required to make the set of mentions identified by the system as coreferring **perfectly align** to the gold-standard set
  - Units counted are link edits

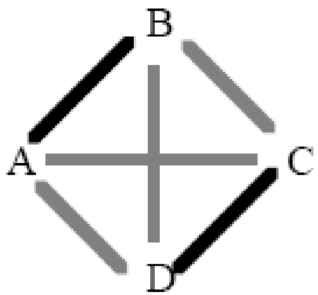
Vilain et al. (1995): a model-theoretic evaluation

Given that A,B,C and D are part of a coreference chain in the KEY, treat as equivalent the two responses:





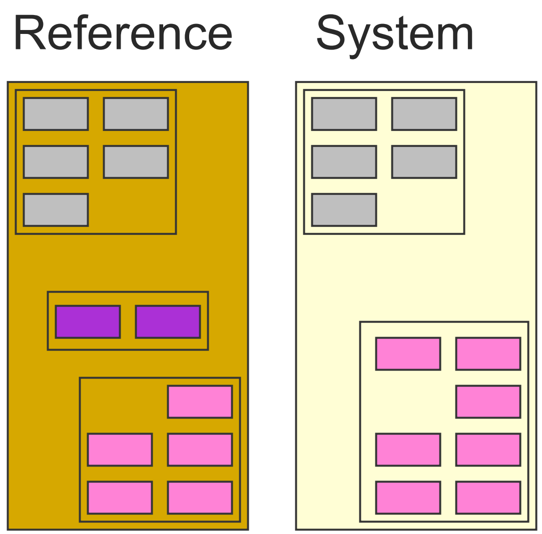
And as superior to:



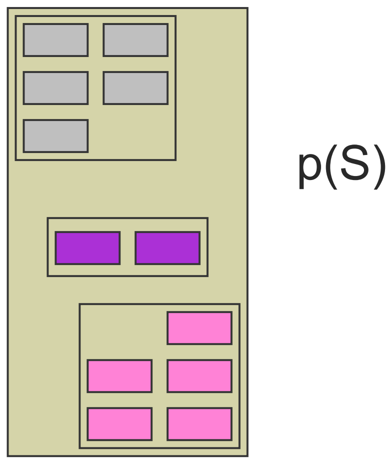
MUC-6 Coreference Scoring Metric: Computing Recall

- To measure RECALL, look at how each coreference chain S_i in the KEY is partitioned in the RESPONSE, and count how many links would be required to recreate the original
- Average across all coreference chains

MUC-6 Coreference Scoring Metric: Computing Recall



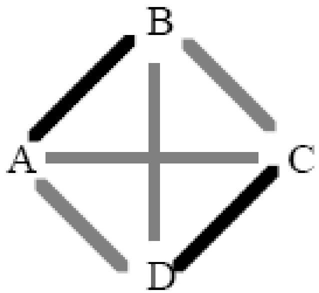
- S => set of key mentions
- p(S) => Partition of S formed by intersecting all system response sets R_i
  - Correct links: $c(S) = |S| - 1$
  - Missing links: $m(S) = |p(S)| - 1$



- **Recall**: $\dfrac{c(S) - m(S)}{c(S)} = \dfrac{|S| - |p(S)|}{|S| - 1}$
- **Recall$_T$** $= \dfrac{\sum |S| - |p(S)|}{\sum |S| - 1}$

MUC-6 Coreference Scoring Metric: Computing Recall

- Considering our initial example



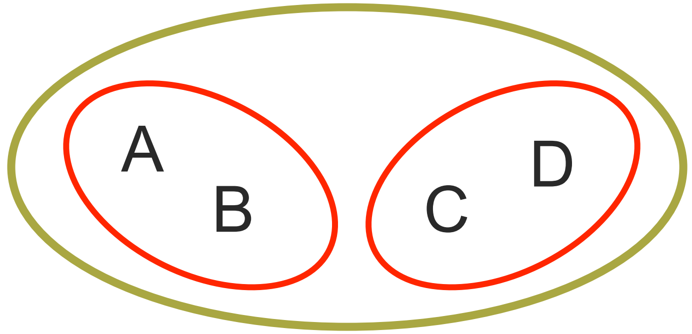
- KEY: 1 coreference chain of size 4 (|S| = 4)
- (INCORRECT) RESPONSE: partitions the coref chain in two sets (|p(S)| = 2)
- R = 4-2 / 4-1 = 2/3

MUC-6 Coreference Scoring Metric: Computing Precision

- To measure PRECISION, look at how each coreference chain S_i in the RESPONSE is partitioned in the KEY, and count how many links would be required to recreate the original
  - Count links that would have to be (incorrectly) added to the key to produce the response
  - I.e., ‘switch around’ key and response in the previous equation

MUC-6 Scoring in Action

- KEY = [A, B, C, D]
- RESPONSE = [A, B], [C, D]



Recall $\frac{4 - 2}{3} = 0.66$

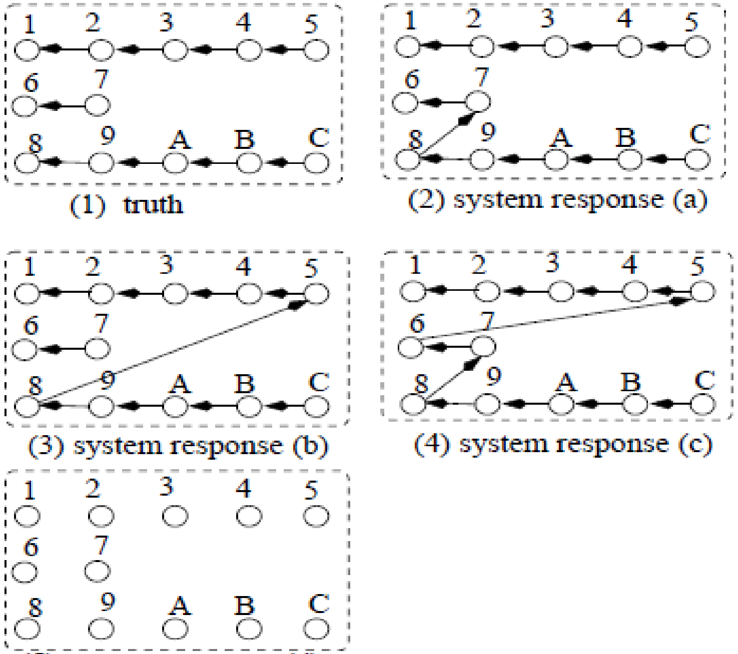
Precision $\frac{(2 - 1) + (2 - 1)}{(2 - 1) + (2 - 1)} = 1.0$

F-measure $\frac{2 * 2/3 * 1}{2/3 + 1} = 0.79$

Beyond MUC Scoring

- Problems:
  - Only gain points for links. No points gained for correctly recognizing that a particular mention is not anaphoric
  - All errors are equal

Not all links are equal



(1) truth (2) system response (a) (3) system response (b) (4) system response (c) (5) system response (d)

System response	MUC
(a)	0.947
(b)	0.947
(c)	0.900
(d)	–

Beyond MUC Scoring

- Alternative proposals:
  - Bagga & Baldwin's B-CUBED algorithm (1998)
  - Luo's CEAF (2005)

B-CUBED (BAGGA AND BALDWIN, 1998)

- MENTION-BASED
  - Defined for singleton clusters
  - Gives credit for identifying non-anaphoric expressions
- Incorporates weighting factor
  - Trade-off between recall and precision normally set to equal

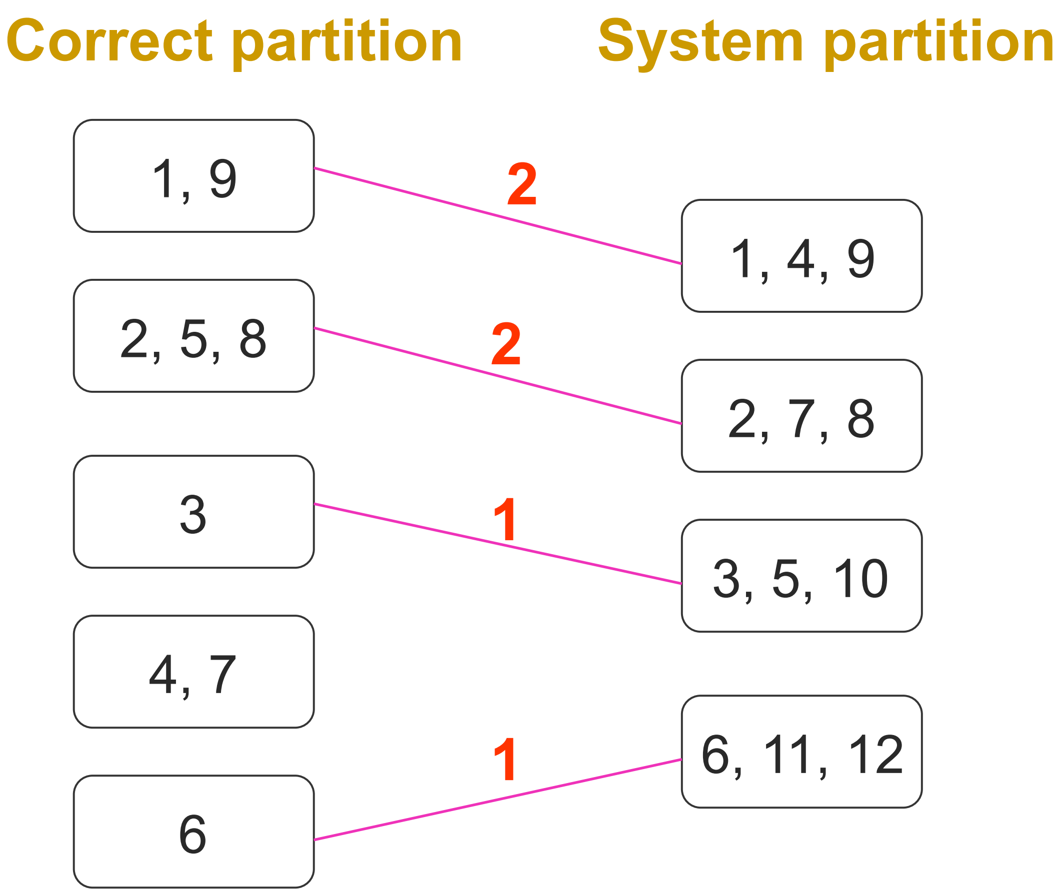
Entity-based score metrics

- ACE metric
  - Computes a score based on a mapping between the entities in the key and the ones output by the system
  - Different (mis-)alignments costs for different mention types (pronouns, common nouns, proper names)
- CEAF (Luo, 1995)
  - Computes also an alignment score score between the key and response entities but uses no mention-type cost matrix

CEAF

- Precision and recall measured on the basis of the SIMILARITY Φ between ENTITIES (= coreference chains)
  - Difference similarity measures can be imagined
- Look for OPTIMAL MATCH g* between entities
  - Using Kuhn-Munkres graph matching algorithm

CEAF



Recast the scoring problem as bipartite matching

Find the best match using the Kuhn-Munkres Algorithm

Matching score = 6

Recall = 6 / 9 = 0.66

Prec = 6 / 12 = 0.5

F-measure = 0.57

Set vs. entity-based score metrics

- **MUC** underestimates precision errors
  - → More credit to larger coreference sets
- **B-Cubed** underestimates recall errors
  - → More credit to smaller coreference sets
- **ACE** reasons at the entity-level
  - → Results often more difficult to interpret

Practical experience with these metrics

- BART computes these three metrics
- Hard to tell which metric is better at identifying better performance
- CEAF metrics depend on mention detection, hard to compare systems directly
- Multimetric (Pareto) optimization
- Reference implementation: CoNLL scorer

BEYOND QUANTITATIVE METRICS

- Byron 2001:
  - Many researchers remove from the reported evaluation cases which are 'out of the scope of the algorithm'
  - E.g. for pronouns: expletives, discourse deixis, cataphora
  - Need to make sure that systems being compared are considering the same cases
- Mitkov:
  - Distinguish between hard (= highly ambiguous) and easy cases

GOLD MENTIONS vs. SYSTEM MENTIONS

- Apparent split in performance on same datasets:
  - ACE 2004:
    - Luo & Zitouni 2005: ACE score of 80.8
    - Yang et al 2008: ACE score of 67
- Reason:
    - Luo & Zitouni report results on GOLD MENTIONs
    - Yang et al results on SYSTEM mentions

Coreference Resolvers

- BART
  - In-house
  - Models and specific tools for several languages (incl. Italian)
  - Several models for coreference and mention detection
  - Easy to integrate linguistic work
  - Uses its own format
- Stanford
  - Rule-based
  - Very fast and easy
  - Only works for English
- Berkeley
  - SOTA performance
  - High computing requirements
- Older toolkits
  - Caution: CoNLL breakthrough, older tools not on par

SUMMARY-1

Anaphora:
- Difficult task
- Needed for NLP applications
- Requires substantial preprocessing

First algorithms:
- Charniak, Winograd, Wilks
- Pronouns: Hobbs
- Salience: S-List, LRC

MUC, ACE, SemEval

Mention-pair model:
- Based on (anaphor, antecedent) pairs
- Widely(?) accepted as a baseline
- Very local

SUMMARY-2

- Modern Coreference Resolution:
  - ILP
  - Entity-mention models
  - Features
- Evaluation metrics
  - MUC
  - BCUBED, ACE
  - CEAF