Introduction to Information Sciences

Natural Language Processing
Formal Languages

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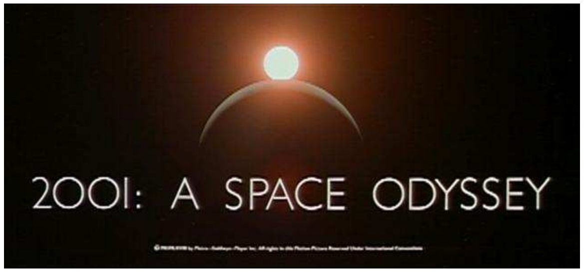
Summary

- Illustrate the difficulties tackled by computational linguistics
  - Define a few of the problems commonly studied
- Introduce formal language theory & Automata
  - formal languages
  - formal grammars
  - Chomsky hierarchy

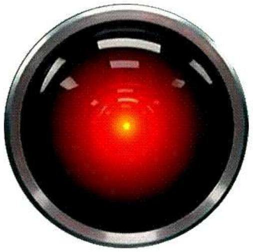
Sources for these slides: A. McCallum's (UMass) online lectures, Wikipedia, Jurafsky/Martin

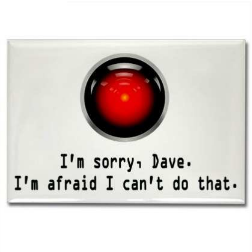
We start with an example: HAL

- An example taken from a famous movie and book:



- Let's check a few scenes:





2001 was shot in 1968

A few years after 2001, what sounds familiar, if not outdated about HAL?

- Graphic capabilities?.. We have much better. The future rather looks like this...

- Chess? 2006, Deep Fritz and before, late 90's, Deep Blue

2001 was shot in 1968

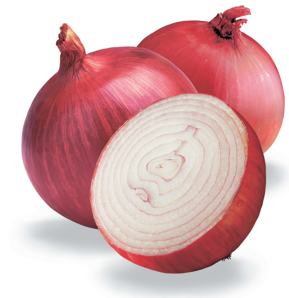
- What still sounds difficult to achieve is HAL's **articulated syntax**...

  David Bowman:
  Open the pod bay doors, Hal.
  HAL:
  I'm sorry, Dave, Im afraid I cant do that.
  David Bowman:
  What are you talking about, Hal?
  ...HAL:
  I know that you and Frank were planning to disconnect me,
  and I'm afraid that's something I cannot allow to happen.

- The machine is also displaying **intelligence**. See Turing's test.
- Yet, **why does language seem more difficult to reach than chess?**

Layers of Computational Linguistics

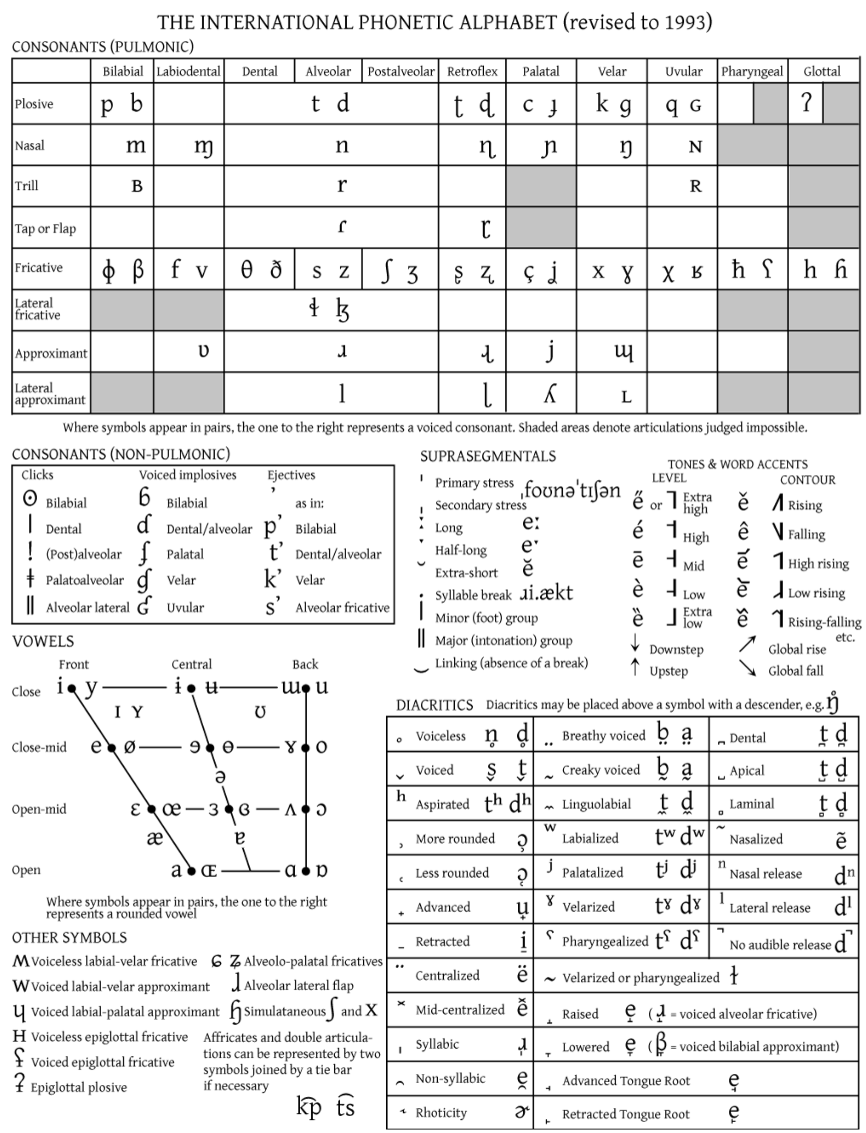
Complex and multilayered system, each layer a different study field



1. Phonetics
2. Phonology
3. Morphology
4. Syntax
5. Semantics
6. Pragmatics
7. Discourse

Phonetics

Study of language sounds, physical aspects.



THE INTERNATIONAL PHONETIC ALPHABET (revised to 1993)

CONSONANTS (PULMONIC)

	Bilabial	Labiodental	Dental	Alveolar	Postalveolar	Retroflex	Palatal	Velar	Uvular	Pharyngeal	Glottal
Plosive	p b			t d		ʈ ɖ	c ɟ	k ɡ	q ɢ		ʔ
Nasal	m	ɱ		n		ɳ	ɲ	ŋ	ɴ		
Trill	ʙ			r					ʀ		
Tap or Flap				ɾ		ɽ					
Fricative	ɸ β	f v	θ ð	s z	ʃ ʒ	ʂ ʐ	ç ʝ	x ɣ	χ ʁ	ħ ʕ	h ɦ
Lateral fricative				ɬ ɮ							
Approximant		ʋ		ɹ		ɻ	j	ɰ			
Lateral approximant				l		ɭ	ʎ	ʟ			

Where symbols appear in pairs, the one to the right represents a voiced consonant. Shaded areas denote articulations judged impossible.

CONSONANTS (NON-PULMONIC)

Clicks		Voiced implosives		Ejectives	
ʘ	Bilabial	ɓ	Bilabial	ʼ	as in:
ǀ	Dental	ɗ	Dental/alveolar	pʼ	Bilabial
ǃ	(Post)alveolar	ʄ	Palatal	tʼ	Dental/alveolar
ǂ	Palatoalveolar	ɠ	Velar	kʼ	Velar
ǁ	Alveolar lateral	ʛ	Uvular	sʼ	Alveolar fricative

VOWELS

Front, Central, Back

Close: i • y — ɨ • ʉ — ɯ • u; ɪ ʏ ʊ

Close-mid: e • ø — ɘ • ɵ — ɤ • o; ə

Open-mid: ɛ • œ — ɜ • ɞ — ʌ • ɔ; æ ɐ

Open: a • ɶ — ɑ • ɒ

Where symbols appear in pairs, the one to the right represents a rounded vowel

OTHER SYMBOLS

ʍ Voiceless labial-velar fricative
w Voiced labial-velar approximant
ɥ Voiced labial-palatal approximant
ʜ Voiceless epiglottal fricative
ʢ Voiced epiglottal fricative
ʡ Epiglottal plosive
ɕ ʑ Alveolo-palatal fricatives
ɺ Alveolar lateral flap
ɧ Simultaneous ʃ and x
Affricates and double articulations can be represented by two symbols joined by a tie bar if necessary k͡p t͡s

SUPRASEGMENTALS

ˈ Primary stress
ˌ Secondary stress ˌfoʊnəˈtɪʃən
ː Long eː
ˑ Half-long eˑ
˘ Extra-short ĕ
. Syllable break ɹi.ækt
| Minor (foot) group
‖ Major (intonation) group
‿ Linking (absence of a break)

TONES & WORD ACCENTS

LEVEL: e̋ or ˥ Extra high; é ˦ High; ē ˧ Mid; è ˨ Low; ȅ ˩ Extra low; ↓ Downstep; ↑ Upstep

CONTOUR: ě Rising; ê Falling; e᷄ High rising; e᷅ Low rising; e᷈ Rising-falling etc.; ↗ Global rise; ↘ Global fall

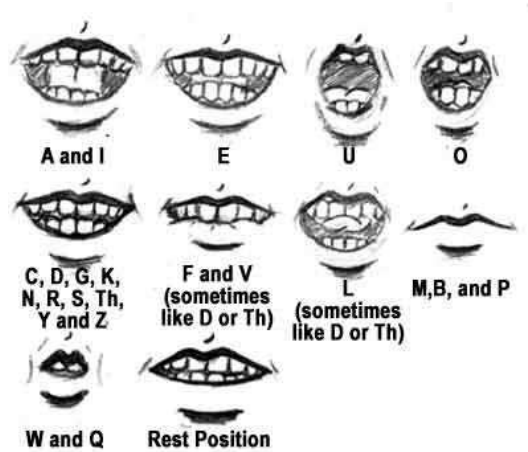
DIACRITICS Diacritics may be placed above a symbol with a descender, e.g. ŋ̊

Voiceless	n̥ d̥	Breathy voiced	b̤ a̤	Dental	t̪ d̪
Voiced	s̬ t̬	Creaky voiced	b̰ a̰	Apical	t̺ d̺
Aspirated	tʰ dʰ	Linguolabial	t̼ d̼	Laminal	t̻ d̻
More rounded	ɔ̹	Labialized	tʷ dʷ	Nasalized	ẽ
Less rounded	ɔ̜	Palatalized	tʲ dʲ	Nasal release	dⁿ
Advanced	u̟	Velarized	tˠ dˠ	Lateral release	dˡ
Retracted	i̠	Pharyngealized	tˤ dˤ	No audible release	d̚
Centralized	ë	Velarized or pharyngealized	ɫ		
Mid-centralized	e̽	Raised	e̝ (ɹ̝ = voiced alveolar fricative)		
Syllabic	ɹ̩	Lowered	e̞ (β̞ = voiced bilabial approximant)		
Non-syllabic	e̯	Advanced Tongue Root	e̘		
Rhoticity	ɚ	Retracted Tongue Root	e̙		

Phonology

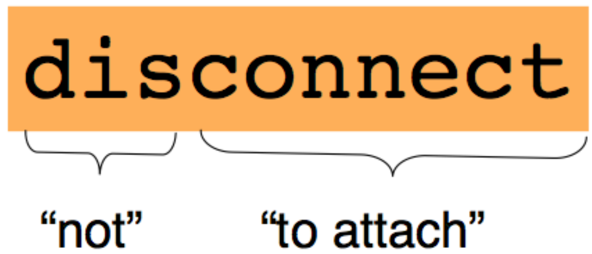
Study of sound **structure** of language.

- Identify units of sounds, in **different** human languages.
  - **phonemes**,
  - **syllables**,
- Phonemes are a major difference between animal language and human language.
- Useful for instance in animations. Phonemes in english:



Morphology

Study of morphemes, the minimal units of linguistic form and meaning



- Important for compounded languages *e.g.* Turkish:

uygarlastiramadiklarimizdanmissinizcasina

uygar las tir ama dik lar imiz dan mis siniz casina

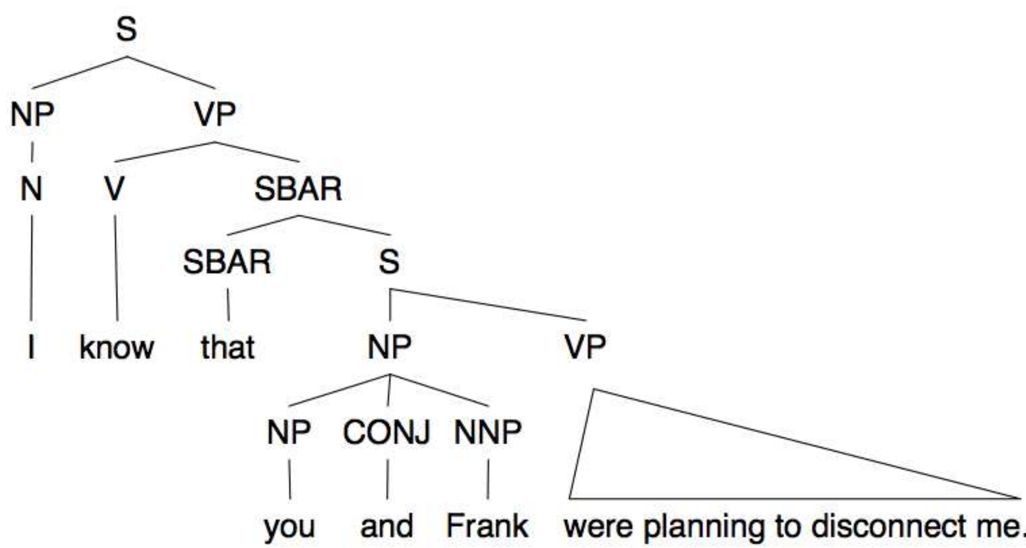
(behaving) as if you are among those whom we could not civilize

- In chinese, chinese characters = morphems = basic semantic unit

Syntax

- From words to sentences:

I know that you and Frank were planning to disconnect me.



- Of course, the structure (the syntax) of the following sentence is also correct

You know me–Frank and I were planning to disconnect that.

Semantics

Study of meaning, the minimal units of linguistic form and meaning

- The meaning of

  I know that you and Frank were planning to disconnect me.

  can be summarized as

  - an *action*, **disconnect**,
  - performed by an *actor*, **you and Franck**,
  - on an *object*, **me**

- In computer science, different syntaxes for the same operation:
  `x += y` (C, Java, Perl, Python, Ruby, etc.)
  `x := x + y` (Pascal)
  `LET X = X + Y` (early BASIC)
  `x = x + y` (MATLAB, most BASIC dialects, Fortran)
  `(incf x y)` (Common Lisp)

Pragmatics

The study of how language is used to accomplish goals within a given **context**

- What is the practical outcome of a sentence as

  Im sorry, Dave, Im afraid I cant do that.

  given the contex?

- The sentence "You have a green light" can have different meanings:
  - It could mean you are holding a green light bulb.
  - Or that you have a green light to drive your car.
  - Or it could be indicating that you can go ahead with the project.
  - Or that your body has a green glow

Discourse

Study of linguistic units which are larger than single **utterances**

- Capture the different turns, threads, changes in the conversation

David Bowman:
Open the pod bay doors, Hal.
HAL:
Im sorry, Dave, Im afraid I cant do that.
David Bowman:
What are you talking about, Hal?
...HAL:
I know that you and Frank were planning to disconnect me,
and I'm afraid that's something I cannot allow to happen.

Languages contain all possible utterances

- Here are sentences in the english language,
  - The man took the book.
  - This sentence is not true.
  - The horse was galloping in the prairie
- Here are sentences which are **not** part of it
  - The true the eat lot looks bird.
  - sense any make not does sentence this
  - dfdlkfh lkjer leREQ ARlkjdf
- A few different kinds of language:
  - Natural languages language that arises in an **unpremeditated** manner as the product of the human innate facility to communicate. Can be spoken, signed, written etc..
  - Constructed languages constructed languages as auxiliary languages such as **esperanto** or artistic languages ($e.g.$ in fiction)
  - Formal languages: languages that computers can parse and understand.
- The latter is the one we will study in this lecture.

Seen from a computer, a language is a set

- We start with the formal idea of alphabets, a set of tokens

$$\Sigma = \{a, b, c, d, e, f, g, \cdots, z, , \cdots\} \text{ or,}$$
$$\Sigma = \{0, 1\} \text{ or,}$$
$$\Sigma = \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9, +, -, *, /, \ln, \exp, \cdots\}.$$

- and use the Kleene operator as a shortcut for

$$\Sigma^\star = \{x \in \Sigma^n, n \in \mathbf{N}\}.$$

- A formal language L is a **subset** of $\Sigma^\star$.

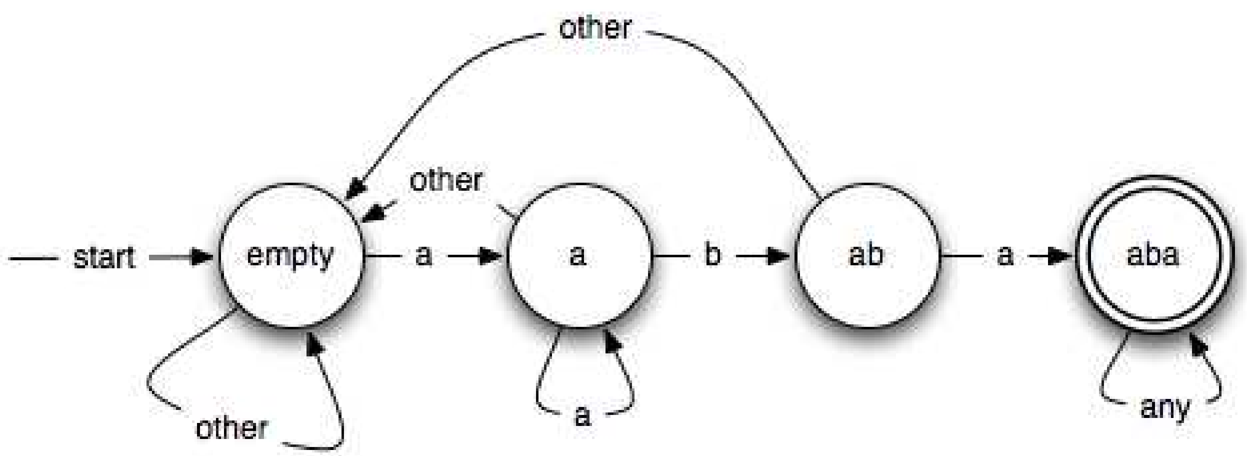
Example of a language

Rules can describe a formal language L

- Consider the language L defined as
  - The alphabet = 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, +, =:
  - Every nonempty string that does not contain + or = and does not start with 0 is in L.
  - The string 0 is in L.
  - A string containing = is in L if and only if there is exactly one =, and it separates two valid strings in L.
  - A string containing + but not = is in L if and only if every + in the string separates two valid strings in L.
  - No string is in L other than those implied by the previous rules.
- With such rules,
  - "23+4=555" is in L,
  - "d433+2e2" is not,
  - "=234=+" is not.
- **no meaning** yet though. Only notion of belonging or not to a language.

Formal languages = typology of such rules

- Other ways to define a language from an alphabet:
- For instance, a language can be given as
  - all strings generated by a **formal grammar**;
  - all strings accepted by some **automaton**, in the example the automaton can generate the language of all words containing at least "*aba*" once



  - all strings described or matched by a particular **regular expression**;
  - all strings for which some decision procedure (an algorithm that asks a sequence of related YES/NO questions) produces the answer YES.

Typical questions asked about such formalisms

- What is their expressive power? (Can formalism X describe every language that formalism Y can describe? Can it describe other languages?)
- What is their recognizability? (How difficult is it to decide whether a given word belongs to a language described by formalism X?)
- What is their comparability? (How difficult is it to decide whether two languages, one described in formalism X and one in formalism Y, or in X again, are actually the same language?).

Formal grammar

A **formal grammar** is a set of rules which generate **formal languages**, defined by:

- a finite set of terminal symbols,
- a finite set of nonterminal symbols,
- a start symbol which is a nonterminal symbol,
- a finite set of production rules:

$$\text{Rule}: \; \cdots \rightarrow \cdots$$

  where the dots are arbitrary symbols.

Formal grammar

- How?
  - Start with the start symbol.
  - Apply any rule by replacing an occurrence of the symbols on the left-hand side of the rule with those that appear on the right-hand side.
- A sequence of rule applications is called a derivation.

> Such a grammar defines the formal language:
> **all words** consisting **solely of terminal symbols**
> which can be reached by **a derivation**
> from the **start symbol**.

- Usually, NONTERMINALS are represented by uppercase letters,
- terminals by lowercase letters,
- the start symbol by S.

Formal grammar Example

- For example, the grammar with
  - terminals $\{a, b\}$,
  - nonterminals $\{S, A, B\}$, starting S,
  - production rules
    - $S \rightarrow ABS$
    - $S \rightarrow \varepsilon$ (where ε is the empty string)
    - $BA \rightarrow AB$
    - $BS \rightarrow b$
    - $Bb \rightarrow bb$
    - $Ab \rightarrow ab$
    - $Aa \rightarrow aa$

  defines the language of all words of the form $a^n b^n$.

- simpler grammar that defines the same language:
  - Terminals $\{a, b\}$,
  - Nonterminals $\{S\}$, Start symbol S, Production rules
    - $S \rightarrow aSb$
    - $S\varepsilon$

Chomsky Hierarchy of Formal Languages

- Type-0 : all grammars.
- Type-1: $\alpha A\beta \rightarrow \alpha\gamma\beta$ where γ cannot be empty. $S \rightarrow \varepsilon$ is allowed iff S does not appear on the right side of a rule.
- Type-2 $A \rightarrow \gamma$ where γ a string of terminals and nonterminals.
- Type-3: Nonterminals can only appear on one side, $S \rightarrow \varepsilon$ is allowed iff S does not appear on the right side of a rule.

Grammar	Languages	Automaton	Production rules (constraints)
Type-0	Recursively enumerable	Turing machine	$\alpha \rightarrow \beta$(no restrictions)
Type-1	Context-sensitive	Linear-bounded non-deterministic Turing machine	$\alpha A\beta \rightarrow \alpha\gamma\beta$
Type-2	**Context-free**	Non-deterministic pushdown automaton	$A \rightarrow \gamma$
Type-3	Regular	Finite state automaton	$A \rightarrow a$ and $A \rightarrow aB$

- Most programming languages are generated by Type-2 rules.
- Trade-off between size of language & capacity to parse it.