Classification Systems:

Combining taxonomical and perceptual meaning

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Aspects of lexical semantic competence (Marconi, 1997)

- **Inferential competence** – knowledge of true sentences in which a word is used
  - specifies logical relations between lexical items: *There is a book on the table* $\Rightarrow$ *There is an object on a piece of furniture.*
  - expressible in terms of meaning postulates: $\forall x.\ \mathit{Table}(x) \rightarrow \mathit{Furnature}(x)$
- **Referential competence** – application of a word to the real world
  - to be referentially competent with *table*, a speaker must be able to recognise tables in the real world (e.g., as part of a visual scene)

Marconi argues that referential competence is not reducible to inferential competence and *vice versa*.

How are these different aspects of meaning combined in the lexicon?

Classification and perceptual meaning

Part of what it means to understand a (perceptual) word is to have the ability to identify instances of it based on perceptual input. I.e., to classify

- A *classifier* is a function from perceptual data to a (possibly fuzzy) truth-value.
- Classifiers can be incorporated in formal semantics (Larsson, 2013) and are compatible with compositional meaning (Larsson, 2017).
- Representations learned through classification have been used to ground meaning in neural machine learning systems (Schlangen et al., 2016).

Folk taxonomies

Taxonomies are defined by a genus-species relation between concept:

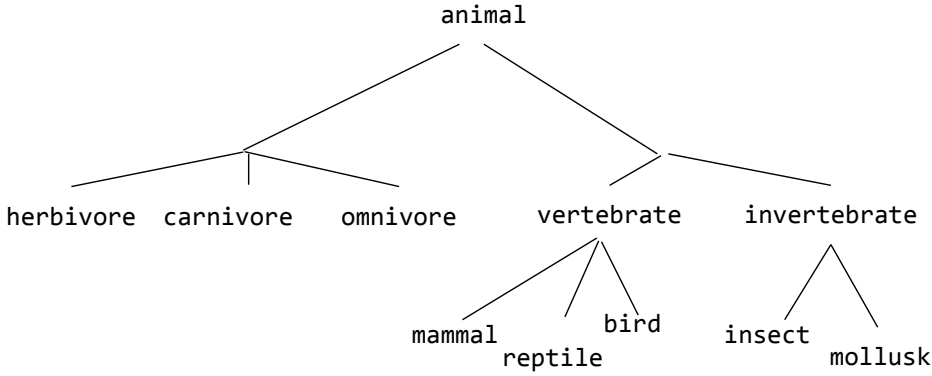
*A **tiger** is a type of **cat**.*

Genus-species relations entail a hyper/hyponymy (*X is a Y*) relation between lexical items

- Each species is a subclass (later, subtype) of the genus
- Each species of a given genus is mutually exclusive
- Together, all the species cover the genus

Key concept: Distinction

A genus-species relation entails a *distinction* among the species of a particular genus:



Classification systems

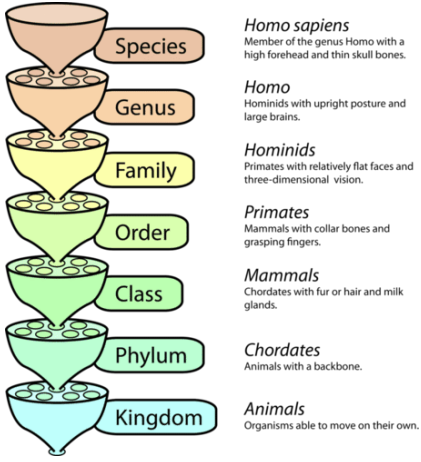
Classification systems are a natural phenomenon like folk taxonomies, but enriched with additional (perceptual/observational/non-logical) content.

They encode

1. perceptual meanings of words and
2. inferential relationships between words,

with respect to a particular *community of practice* (Gumperz, 1972) in which the taxonomy is taken as semantic *common ground* (Clark, 1996).

- Linnean classification (biologists)
- Peterson bird identification system (amateur birders, ornithologists)
- Fujita tornato damage scale (metrologists)
- Swedish vowels (L2 learners of Swedish)
- Desserts (pastry chefs; dessert-enjoyers)



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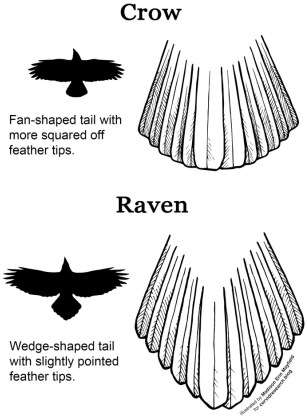

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EF Rating	Wind Speeds	Expected Damage	
EF-0	65-85 mph	'Minor' damage: shingles blown off or parts of a roof peeled off, damage to gutters/siding, branches broken off trees, shallow rooted trees toppled.	 
EF-1	86-110 mph	'Moderate' damage: more significant roof damage, windows broken, exterior doors damaged or lost, mobile homes overturned or badly damaged.	 
EF-2	111-135 mph	'Considerable' damage: roofs torn off well constructed homes, homes shifted off their foundation, mobile homes completely destroyed, large trees snapped or uprooted, cars can be tossed.	 
EF-3	136-165 mph	'Severe' damage: entire stories of well constructed homes destroyed, significant damage done to large buildings, homes with weak foundations can be blown away, trees begin to lose their bark.	 
EF-4	166-200 mph	'Extreme' damage: Well constructed homes are leveled, cars are thrown significant distances, top story exterior walls of masonry buildings would likely collapse.	 
EF-5	> 200 mph	'Massive/incredible' damage: Well constructed homes are swept away, steel-reinforced concrete structures are critically damaged, high-rise buildings sustain severe structural damage, trees are usually completely debarked, stripped of branches and snapped.	 

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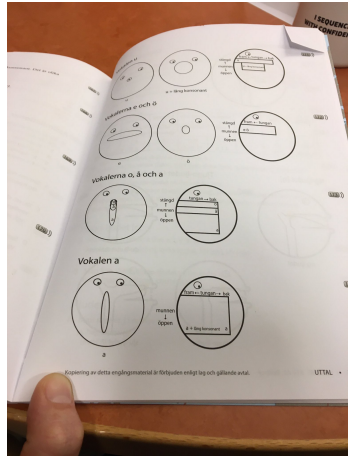

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Classification systems: Desiderata

1. An instance of a species is an instance of its corresponding genus.

2. An instance of a genus is an instance of exactly one species in each of its distinctions.

Classification systems: Desiderata

given a distinction $\langle g, \{s_1, ..., s_n\} \rangle$

1. An instance of a species is an instance of its corresponding genus.
   $T_{s_i} \sqsubseteq T_g$ (i.e., for any entity a, $a : T_{s_i} \Rightarrow a : T_g$)

2. An instance of a genus is an instance of exactly one species in each of its distinctions.
   $a : T_g \Rightarrow \exists! s_i \,.\, a : T_{s_i}$

Classification systems: Type system formalization

A classification system is a type system that we will define from from components:

1. a taxonomy (set theoretic description)
2. classifiers (set indexed by *distinctions* in the taxonomy)

Classifiers will provide the *witness conditions* for basic types.

Taxonomies (set-theoretic)

A taxonomy takes the form:

$$\mathrm{Tax} := \langle \mathrm{Taxon}, \mathrm{Set}(\mathrm{Set}(\mathrm{Tax})) \rangle,$$

And a distinction is a pair:

$$\mathrm{Dist} : \langle \mathrm{Taxon}, \mathrm{Set}(\mathrm{Taxon}) \rangle.$$

We'll need a function from a taxonomy to its distinctions:

$$\mathit{dists} : \mathrm{Tax} \to \mathrm{Set}(\mathrm{Dist})$$

Probabilistic type judgments (Cooper et al., 2015)

$$p(a : T) = r$$

where $r \in [0, 1]$.

We can think of p as a function, $p : \mathit{Ind} \times \mathit{Type} \rightarrow [0, 1]$.

- for basic types, p is defined by the type's *witness conditions*
- for logical types, p is determined by the semantics of the type constructor

e.g.,

$$p(a : T_1 \wedge T_2) = p(a : T_1) \cdot p(a : T_2 \mid a : T_1)$$

Classifiers as witness conditions

A classifier $C : \mathit{PerceptualData} \to [0, 1]$ can be used to give witness conditions for a basic type:

$$p(a : T) = C(a)$$

Classification systems: Type system formalization

Let...

- $\mathbf{T} = \langle t^*, D^* \rangle$ be a taxonomy
- $\{C_d\}_{d \in dist(\mathbf{T})}$ be a set of multiclass classifiers

Define basic types:

- T_{t^*} such that for any object a, $p(a : T_{t^*}) = 1$
- For each distinction $d = \langle g, \{s_1, ..., s_n\} \rangle \in dists(\mathbf{T})$ define $A_{s_1} ... A_{s_n}$ with the following witness condition:

$$p(a : A_{s_i}) = C_d(a)(s_i)$$

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$$p(a : A_{s_i}) = C_d(a)(s_i)$$

We define T_{s_i} as a *logical type* as follows:

$$p(a : T_{s_i}) = p(a : A_{s_i}) \cdot p(a : T_g)$$

Desiderata (reprise)

given a distinction $\langle g, \{s_1, ..., s_n\} \rangle$

1. An instance of a species is an instance of its corresponding genus.

$$T_{s_i} \sqsubseteq T_g$$
$$p(a : T_{s_i}) \leq p(a : T_g)$$

2. An instance of a genus is an instance of exactly one species in each of its distinctions.

$$a : T_g \Rightarrow \exists! s_i \,.\, a : T_{s_i}$$
$$p(a : T_{s_i} \mid T_g) = 1 - \sum_{j \neq i} p(a : T_{s_j} \mid a : T_g)$$

Toy implementation

https://github.com/GU-CLASP/classification-systems/blob/master/classification-systems.ipynb

Other ways...

Other ways of classifying in a taxonomical hierarchy:

- **hierarchy agnostic** – Each label is considered by a single *multi-label* classifier, without respect to taxonomical hierarchy.
- **marginalization** – A single categorical classifier is trained on the leaf nodes. Labels at higher levels are predicted by marginalizing the leaf node probabilities

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	Precision	Recall	F1
per-distribution	**0.93**	**0.90**	**0.90**
marginalization	0.90	0.86	0.82
hierarchy-agnostic	0.80	0.84	0.81

In conclusion...

- On a lexical level, NLU involves both inferential competence and referential competence.
- Classification systems are a common ground resource that can ground lexical meaning.
- Probabilistic type theory with external witness conditions can be used to formalize classification systems.
- From a ML point of view, taking taxonomical *distinctions* as the cite of classification is (tentatively) at least as performant as other options.

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