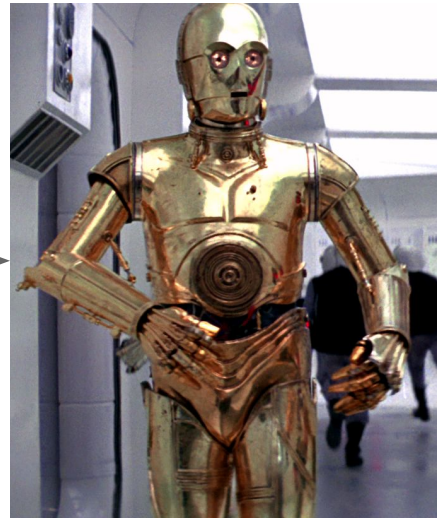
Natural Language Processing

Tom Williams

Goal: design algorithms to allow human-computer interaction through everyday language

Wide variety of use cases



Associated Press:
Auto-generates textual summaries of news stories.

Not embodied, and **not** part of an “intelligent agent”

C3PO: General conversational capabilities.

Is embodied, and **is** part of an “intelligent agent”

Breaking Down C-3PO

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Understanding

Recognition

Speech recognition,
Optical Character Recognition

Generation

Synthesis

Speech synthesis,
Handwriting synthesis

Breaking Down C-3PO

Understanding

Recognition
Speech recognition,
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Analysis
Syntactic Analysis
Semantic Analysis
Pragmatic Analysis

Generation

Synthesis
Speech synthesis,
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Tactical Generation
Sentence Realization
Lexical Choice
Referring Expression Generation

Breaking Down C-3PO

Understanding

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Incorporation
Trust Modelling

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Strategic Generation
Content Determination
Document Structuring

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Natural Language Understanding

- The dog bit the boy.
- The boy bit the dog.
- * Bit boy dog the the.

Natural Language Understanding

Syntax

Semantics

Pragmatics

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- Colorless green ideas sleep furiously.
- ? More people have been to Germany than I have.

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Semantics

- Plant (n: organism)
- Plant (n: factory)
- Plant (v: sowing)

Pragmatics

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Pragmatics

- Could you X ⇒ Do X
- This ⇒ Recently mentioned or pointed at

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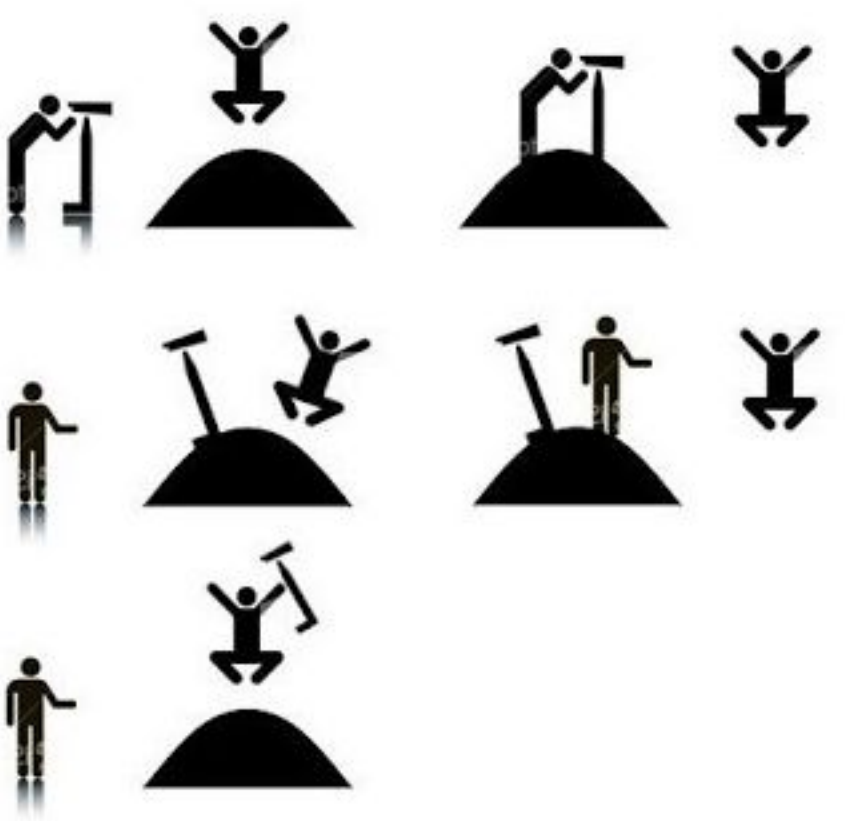
So why is this hard?

Natural language is
highly ambiguous

Count: how many syntactically plausible ways are there to interpret:

“I saw the man on the hill with the telescope”



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An English sentence ending with *n* prepositional phrases has *at least* 2^n possible syntactic interpretations!

- "I saw the man with the telescope" -- 2
- "I saw the man on the hill with the telescope" -- 5
- "I saw the man on the hill in Golden with the telescope" -- 14
- "I saw the man on the hill in Golden with the telescope at noon" -- 132
- "I saw the man on the hill in Golden with the telescope at noon on Monday" -- 429

(The sequence continues... 1430, 4862, 16796...)

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- **Syntactic Analysis**

So why is this hard?

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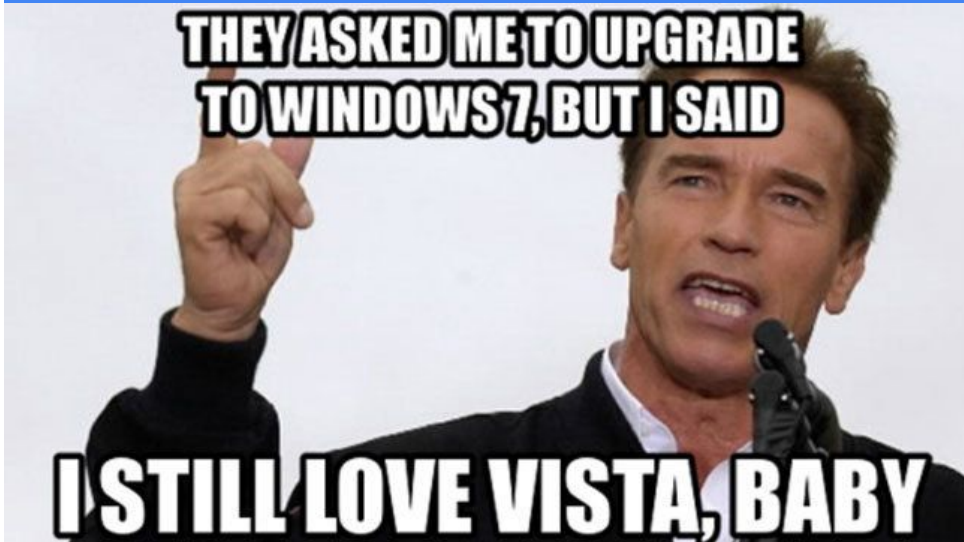
- **Syntactic Analysis**
- **Speech Recognition**
  (i.e., the source of all the greatest puns)



So why is this hard?

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- **Syntactic Analysis**
- **Speech Recognition**
- **Semantic Analysis**

*The pig **is in the pen** vs.*
*The ink **is in the pen** vs.*
*The convict **is in the pen***

So why is this hard?

Natural language is
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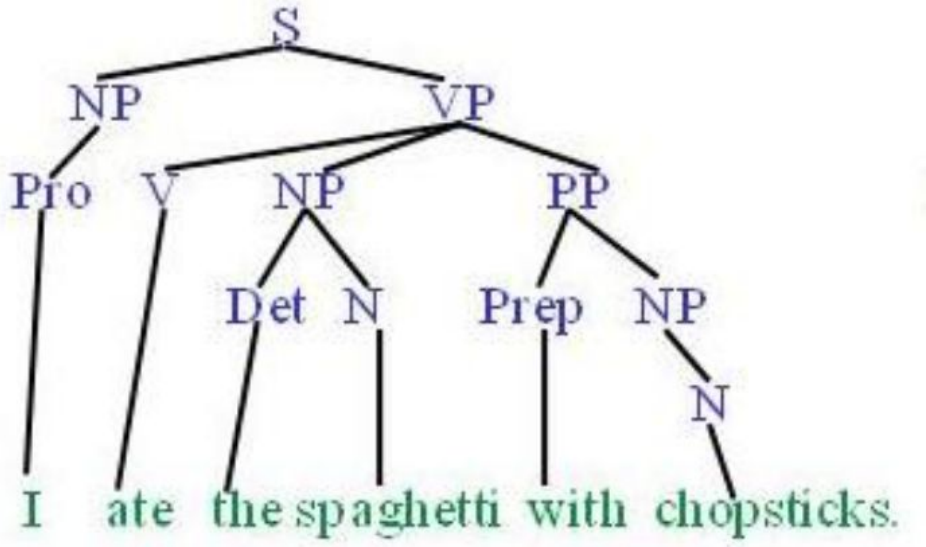
- Syntactic Analysis
- Speech Recognition
- Semantic Analysis
- Pragmatic Analysis

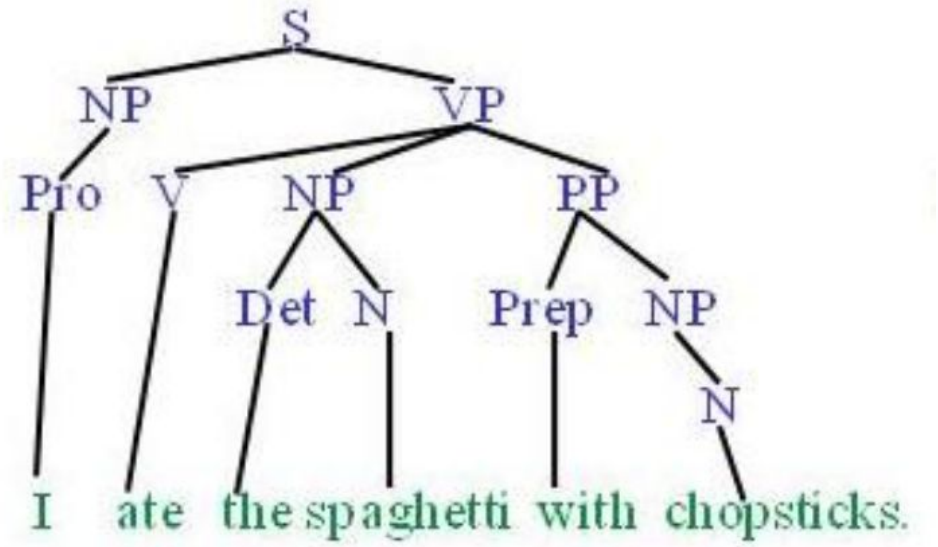
This is in contrast to *programming languages* which are *unambiguous* by design

Syntactic Structures: The Goal



Syntactic Structures: Wait but how?
Context Free Grammars

- X_t: a set of *terminal* symbols (i.e., our "words")
- X_{nt}: a separate set of *non-terminal* symbols (i.e., our parts of speech) including a special "start symbol" S.
- *R*: a set of "productions" or "rules" of the form
  $x_{nt} \rightarrow x^*$
  where x_{nt} is a non-terminal symbol in X_{nt} and x^* is a sequence of either terminal or non-terminal symbols



Syntactic Structures:
Wait but how?
Context Free Grammars

- X_t = {the, a, that, this, book, train, meal, money, include, prefer, I, he, she, me, south-station, north-station, does, from, to, on, near, through}
- X_{nt} = {S, Det, NP, Pronoun, Proper-Noun, Nominal, Noun, VP, Aux, Verb, PP, Prep}
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Lexicon

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Verb → book | include | prefer

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S → Aux NP VP

S → VP

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NP → Proper-Noun

NP → Det Nominal

Nominal → Noun

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Parsing - Top Down vs Bottom Up

Top Down Parsing

Start with the start symbol, recursively expand tree until it fits target string.

Bottom-Up Parsing

Start with the target string, and work backwards towards the goal of the start symbol.

Top-Down Parsing

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“Book that train!”

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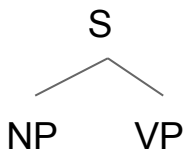

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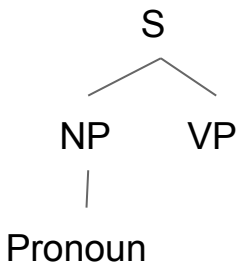

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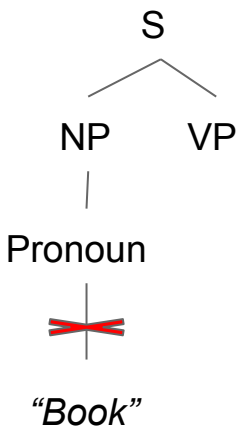

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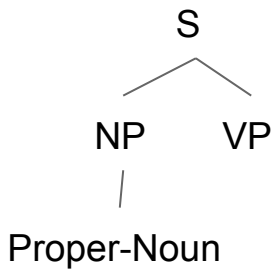

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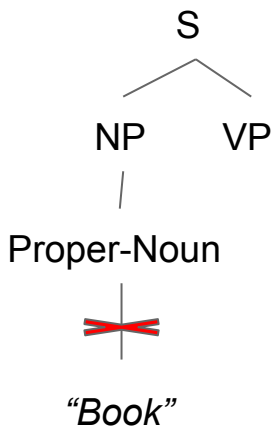

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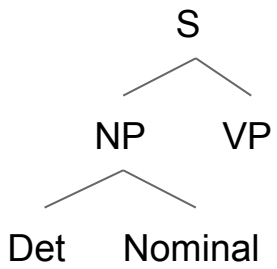

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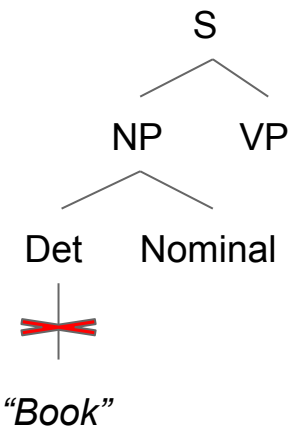

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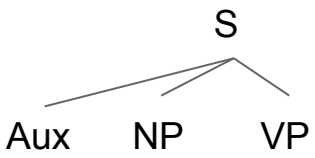

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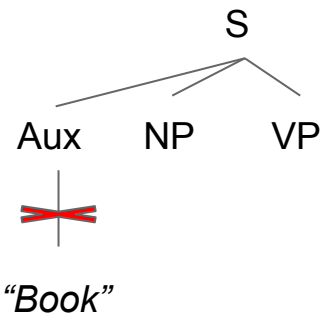

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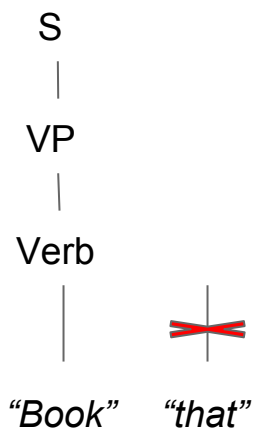

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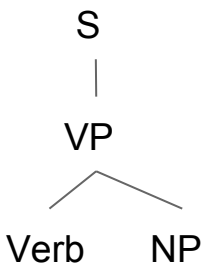

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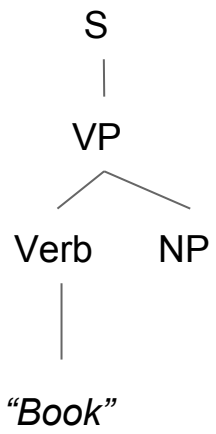

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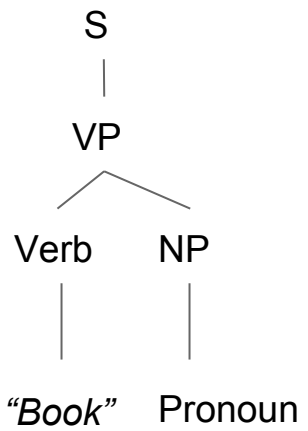

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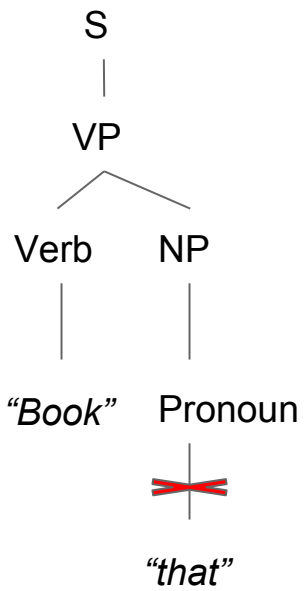

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Aux → does
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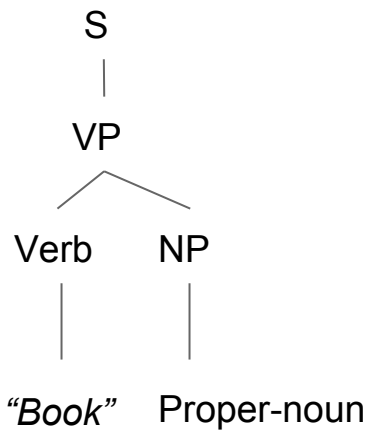

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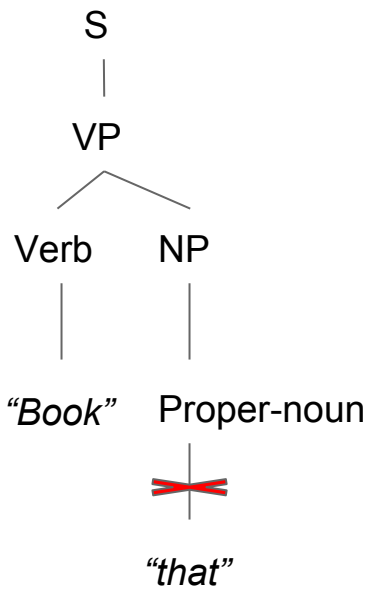

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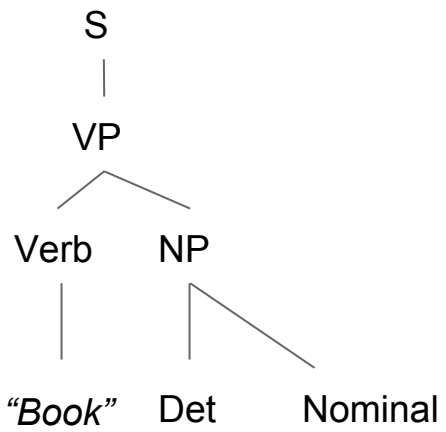

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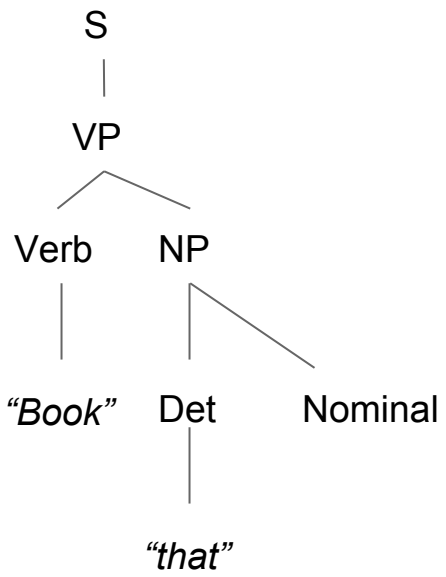

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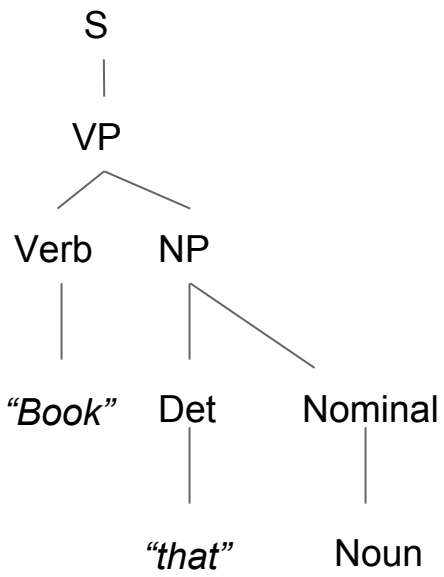

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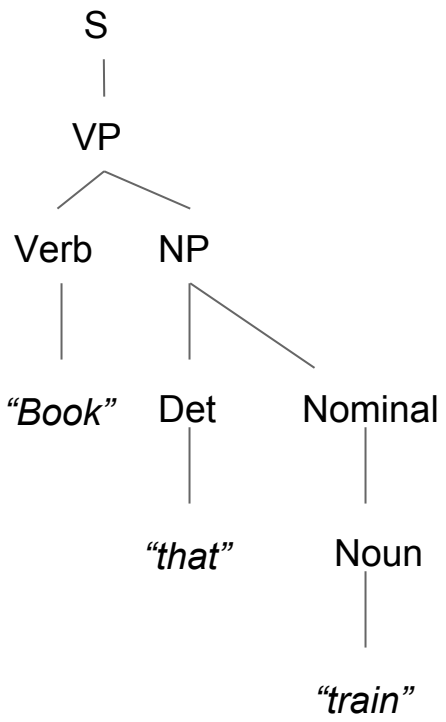

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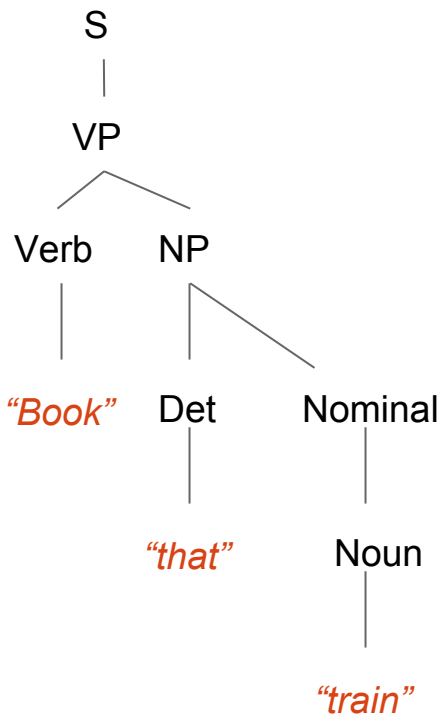

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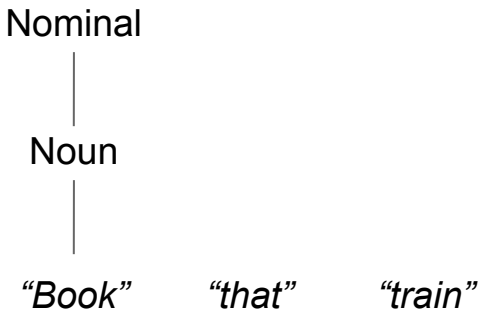

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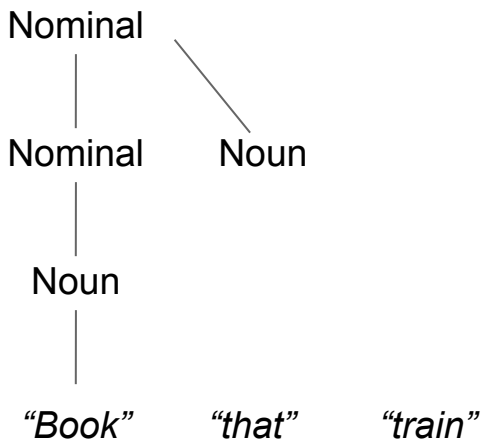

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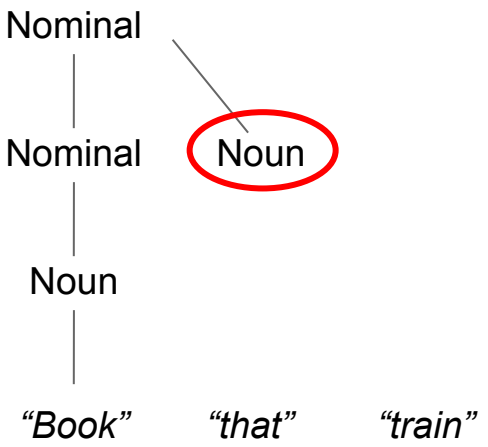

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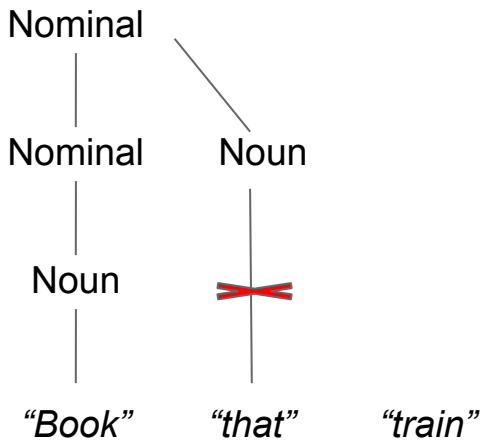

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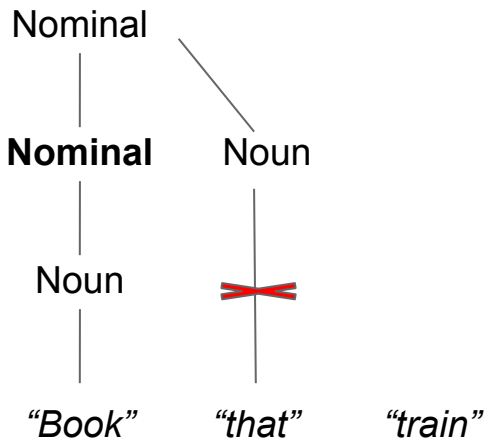

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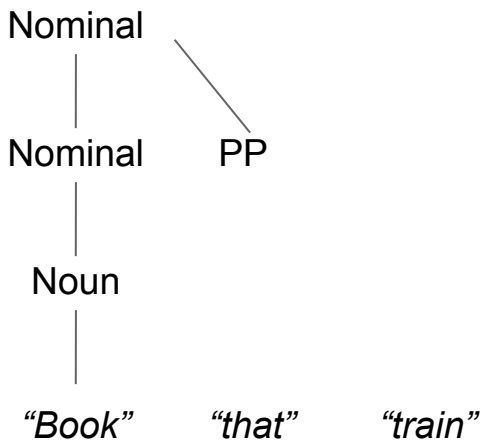

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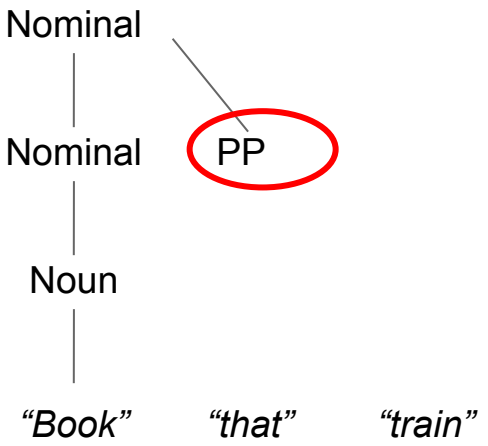

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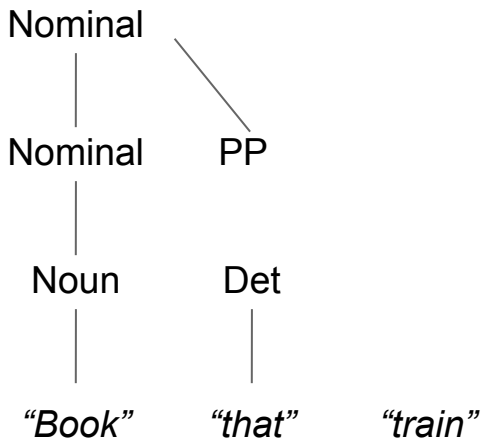

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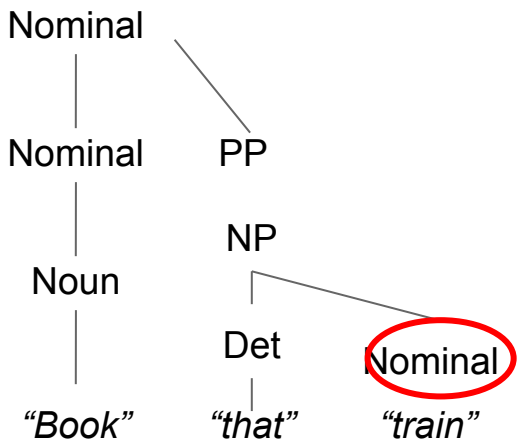

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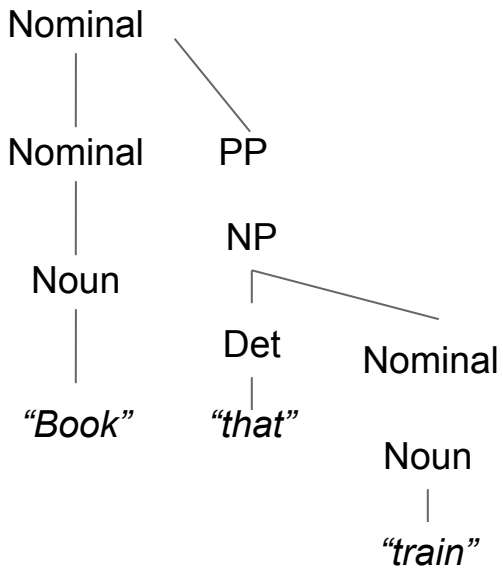

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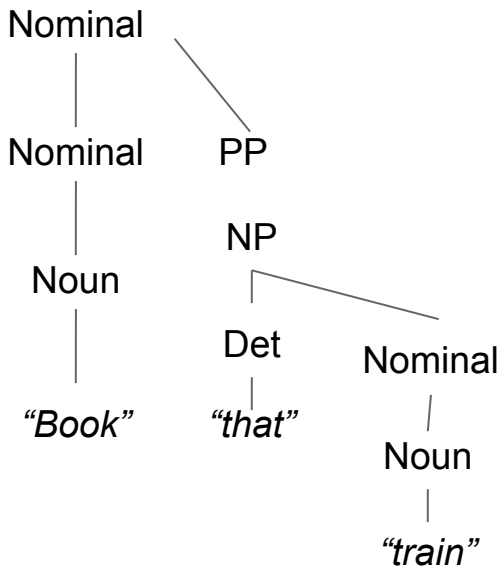

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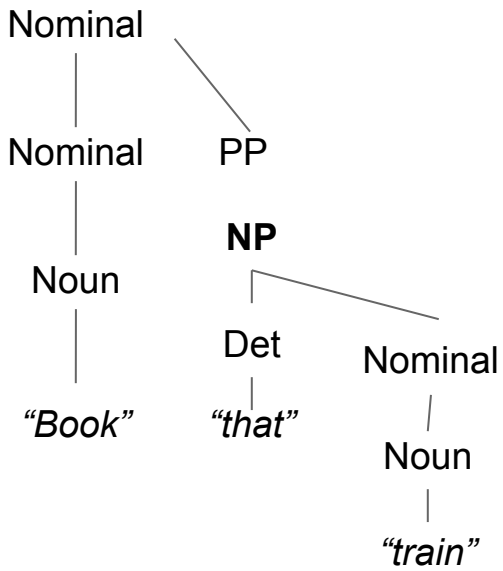

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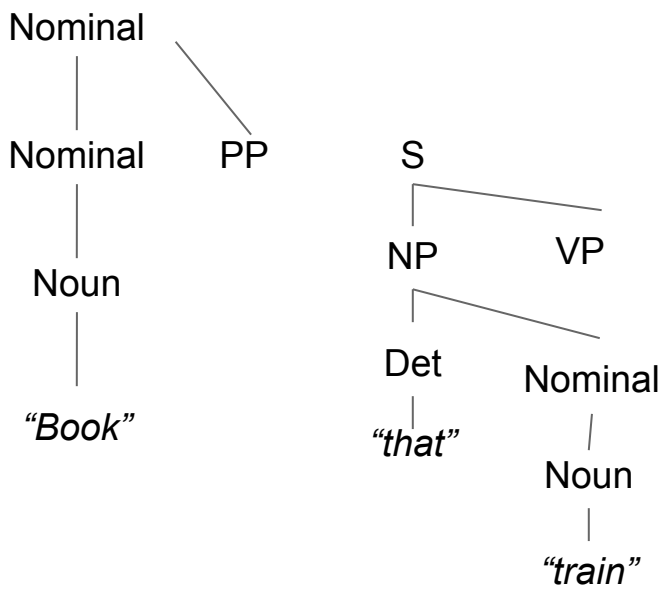

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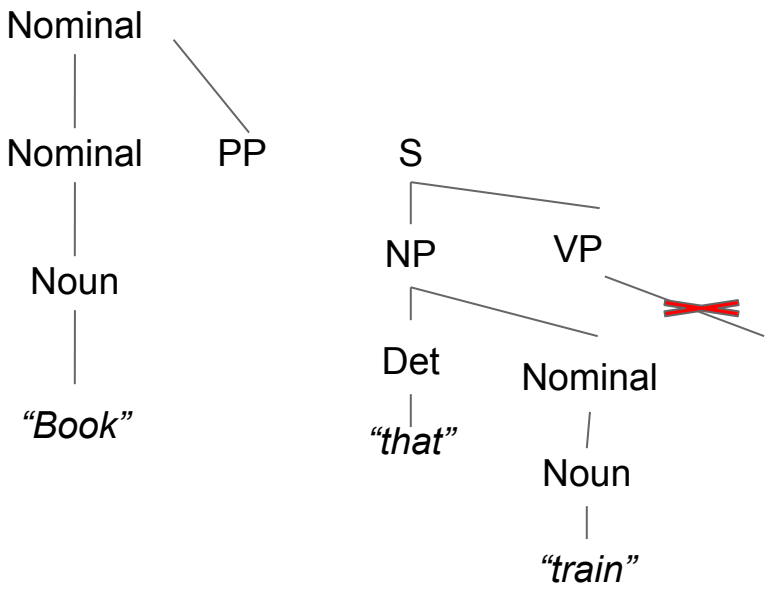

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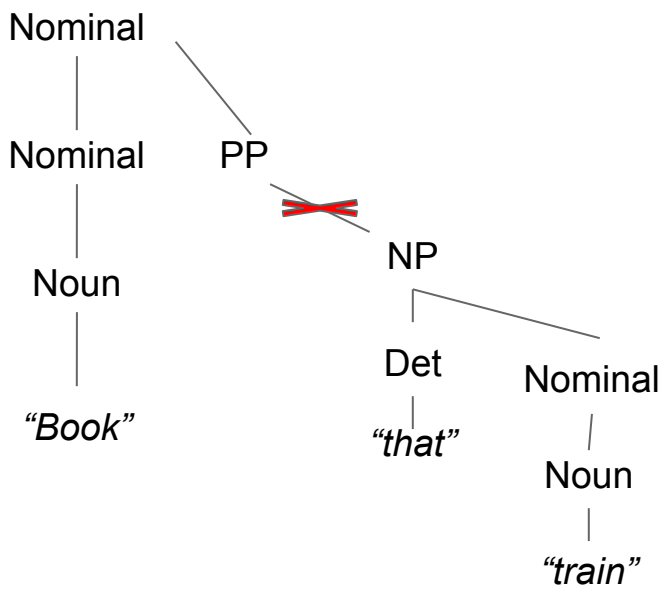

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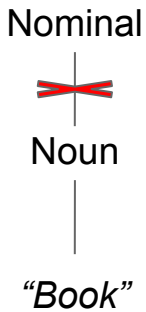

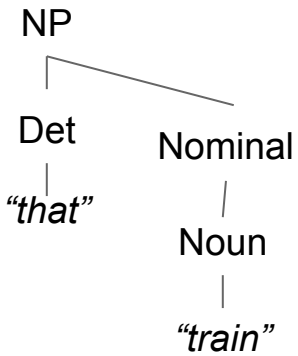

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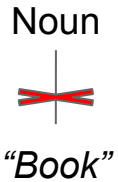

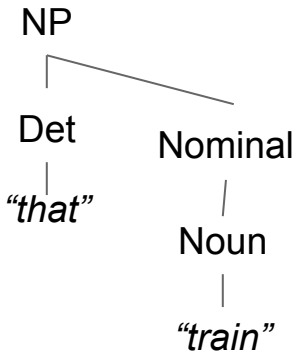

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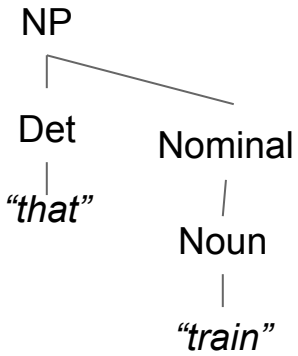

Bottom-Up Parsing

Lexicon

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Aux → does
Prep → from | to | on | near | through

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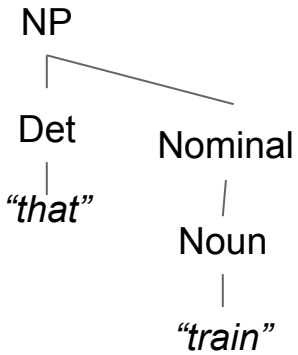

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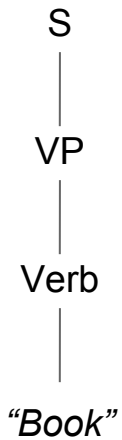

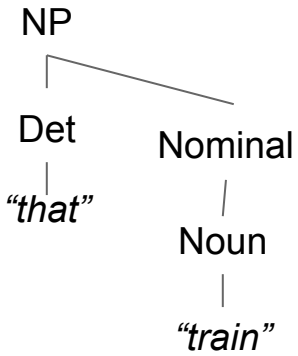

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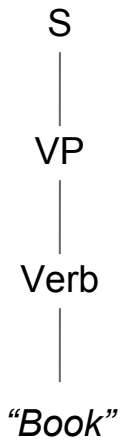

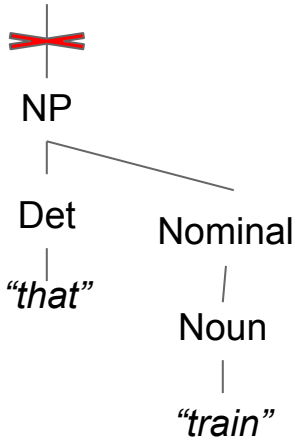

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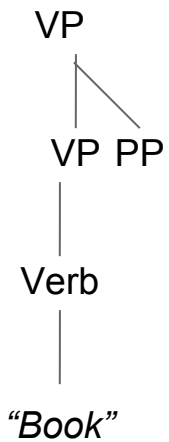

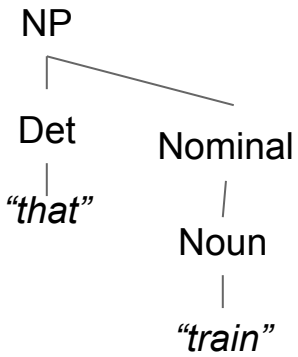

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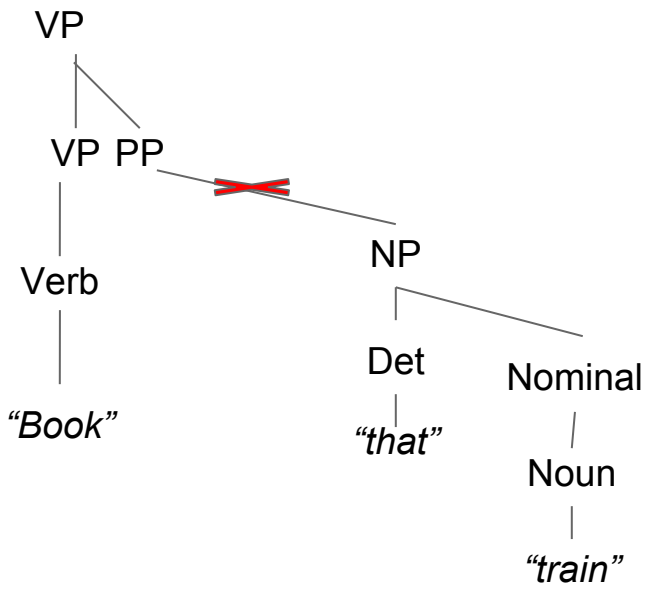

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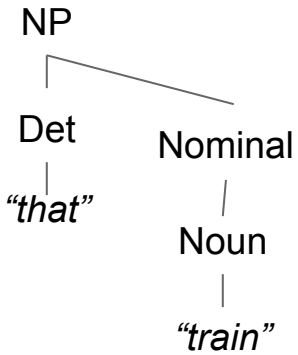

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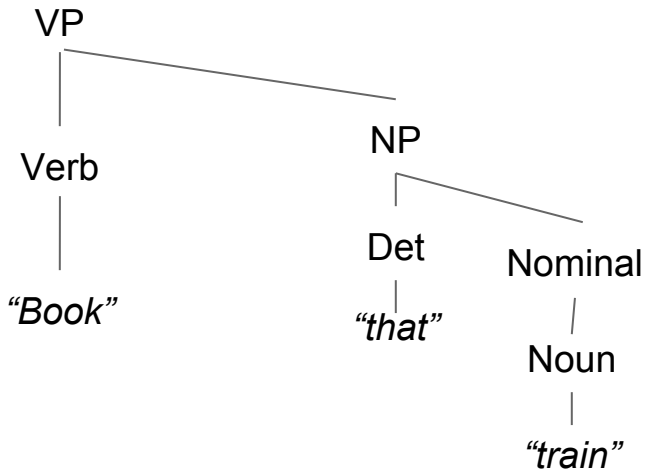

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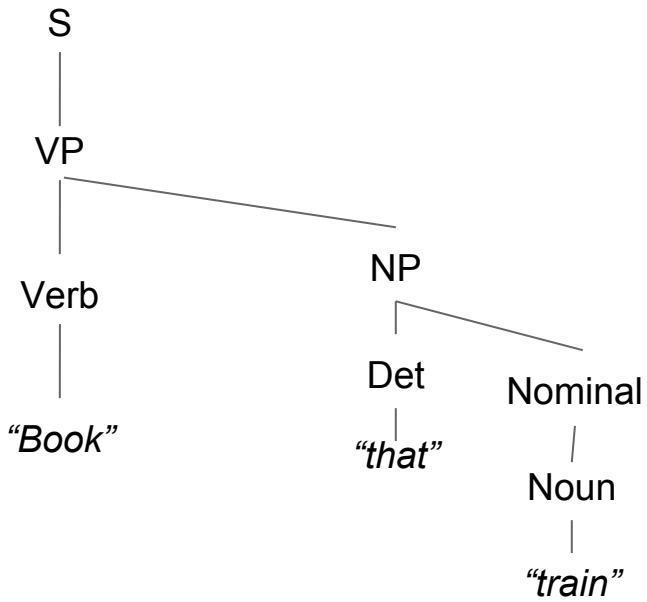

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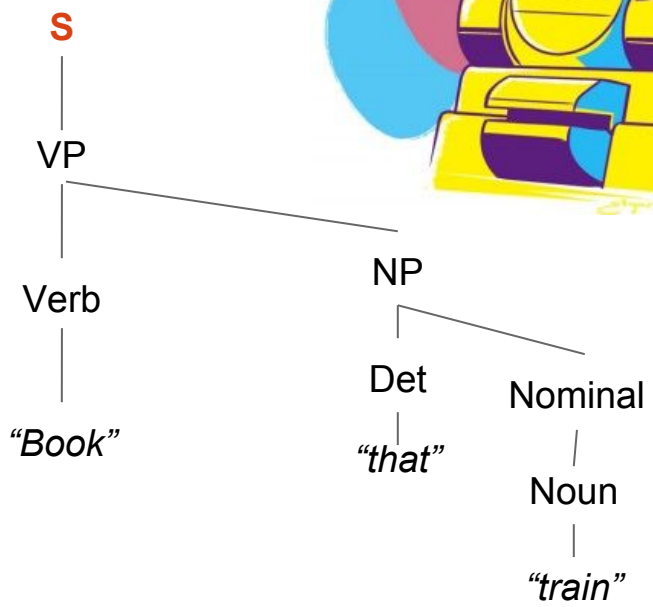

Top-Down vs. Bottom-Up Parsing

Top-Down Parsing

- Never explores options that won't lead to a full parse.

Bottom-Up Parsing

- Never explores options that won't connect to the actual words.

If there's more than one, *How do we decide which parse is most likely?*

Statistical Parsing

Statistical Parsing

- Idea: Use a **probabilistic model** of syntax that specifies **how likely** each rule expansion is.
- This allows us to calculate the **probability** of a particular parse tree.
- This allows us to easily resolve ambiguity, by choosing the **most probable** parse tree.
- Allows us to **learn** our grammars from provided parse tree corpuses.

Reminder:
Context Free Grammars

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Really Freaking Simple Extension: Probabilistic Context Free Grammars

Lexicon

Det → the | a | that | this

0.6 0.2 0.1 0.1

Noun → book | train| meal | money

0.1 0.5 0.2 0.2

Verb → book | include | prefer

0.5 0.2 0.3

Pronoun → I | he | she | me

0.5 0.1 0.1 0.3

Proper-Noun → North-Station | South-Station

0.8 0.2

Aux → does

1.0

Prep → from | to | on | near | through

0.25 0.25 0.1 0.2 0.2

Grammar

0.8 S → NP VP

0.1 S → Aux NP VP

0.1 S → VP

0.2 NP → Pronoun

0.2 NP → Proper-Noun

0.6 NP → Det Nominal

0.3 Nominal → Noun

0.2 Nominal → Nominal Noun

0.5 Nominal → Nominal PP

0.2 VP → Verb

0.5 VP → Verb NP

0.3 VP → VP PP

1.0 PP → Prep NP

Really Freaking Simple Extension: Probabilistic Context Free Grammars

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Det → the | a | that | this

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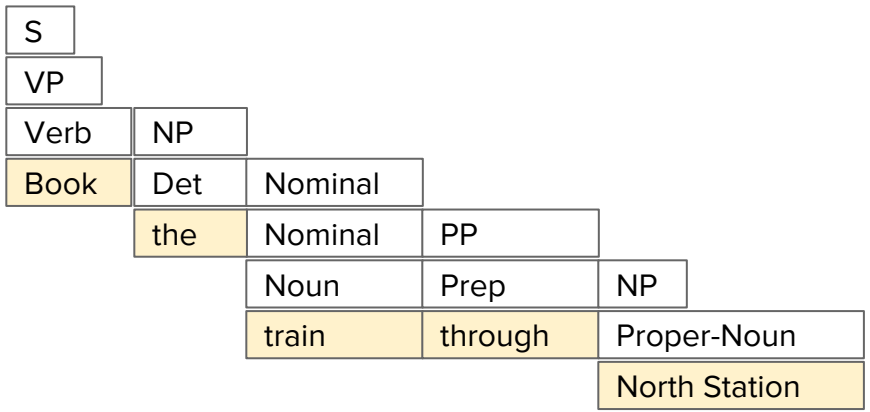


Two useful tasks for PCFGs

1. Most likely derivation -- which parse is most likely for a given sentence?
2. Observation likelihood -- How likely is a given sentence?

Other important NLP Tasks

1. Syntax

Word Segmentation

Given a sequence of letters, what is the most likely sequence of words?

worldswithoutend.com ➜
worlds without end .com

facebook.com/fivehundreddaysofsummer/ ➜
facebook .com five hundred days of summer

Morphological Analysis

Given a word, how does it segment into (prefixes) root (suffixes)?

carried ➜ carry + ed

independently ➜ in + (depend + ent) + ly

Googlers ➜ (Google + er) +s

unlockable ➜ un + (lock + able) ... or ... (un + lock) + able

Part of Speech (POS) Tagging

Given a sentence, annotate each word with its part of speech

I	ate	the	spaghetti	with	meatballs
Pro	V	Det	N	Prep	N

John	saw	the	saw	and	decided	to	take	it	to	the	table
PN	V	Det	N	Con	V	Part	V	Pro	Prep	Det	N

Phrase Chunking

Given a sentence, find all non-recursive noun and verb phrases

- [NP I] [VP ate] [NP the spaghetti] [PP with] [NP meatballs].
- [NP He] [VP reckons] [NP the current account deficit] [VP will narrow] [PP to] [NP only # 1.8 billion] [PP in] [NP September]

2. Semantics

(Shallow) Semantic Parsing i.e., Semantic Role Labeling

Given a sentence, determine the semantic role played by each noun phrase that is an argument to a verb. This is also known as “shallow semantic parsing”

agent patient source destination instrument

John drove Mary from Austin to Dallas in his Toyota Prius.

The hammer broke the window.

(Deep) Semantic Parsing

Given a sentence, derive a semantic representation such as a **logical form**

How many cities are there in the US?

```
answer(A,
       count(B,
                 (city(B), loc(B, C), const(C,
                                            countryid(USA))),
                  A))
```

Textual Entailment

Given two sentences, decide whether the first *logically entails* the second.

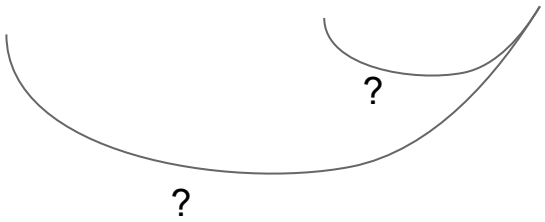
Eyeing the huge market potential, currently led by Google, Yahoo took over search company Overture Services Inc last year	Yahoo bought Overture.	TRUE
Microsoft's rival Sun Microsystems Inc. bought Star Office last month and plans to boost its development as a Web-based device running over the Net on personal computers and Internet appliances.	Microsoft bought Star Office.	FALSE
The National Institute for Psychobiology in Israel was established in May 1971 as the Israel Center for Psychobiology by Prof. Joel.	Israel was established in May 1971.	FALSE
Since its formation in 1948, Israel fought many wars with neighboring Arab countries	Israel was established in 1948.	TRUE

3. Pragmatics

Co-reference resolution

Given a document, find clusters of phrases that refer to the same entity.

John put the carrot on the plate and ate it



Ellipsis Resolution

Given a sentence, determine if there are any missing words or phrases, and if so, what they are.

Fred took a picture of you, and Susan ... of me.

^ took a picture

Sally is working on Monday, ... not ... on Tuesday

^ she is ^ working

What is the capital of New York? Albany

^The capital of new york is

Dialogue Act Classification

Given an utterance, decide what type of dialogue act is being made

“Keep going straight” -- INSTRUCTION
“Even past the tree?” -- QUESTION-YN
“Mmhmm” -- REPLY-Y

4. Other Tasks

Other Tasks

- **Information Extraction:** Infer new FOL knowledge from a document
- **Question Answering**: Answer a question given a collection of documents or webpages
- **Text Summarization:** Given a document, write a short summary
- **Machine Translation:** Given a sentence, translate it to a different language

NLP Summary

Natural Language is difficult to process because of **ambiguity**

The three basic levels of linguistic analysis are syntax, semantics, and pragmatics

Language can be parsed using (possibly probabilistic) context-free grammars

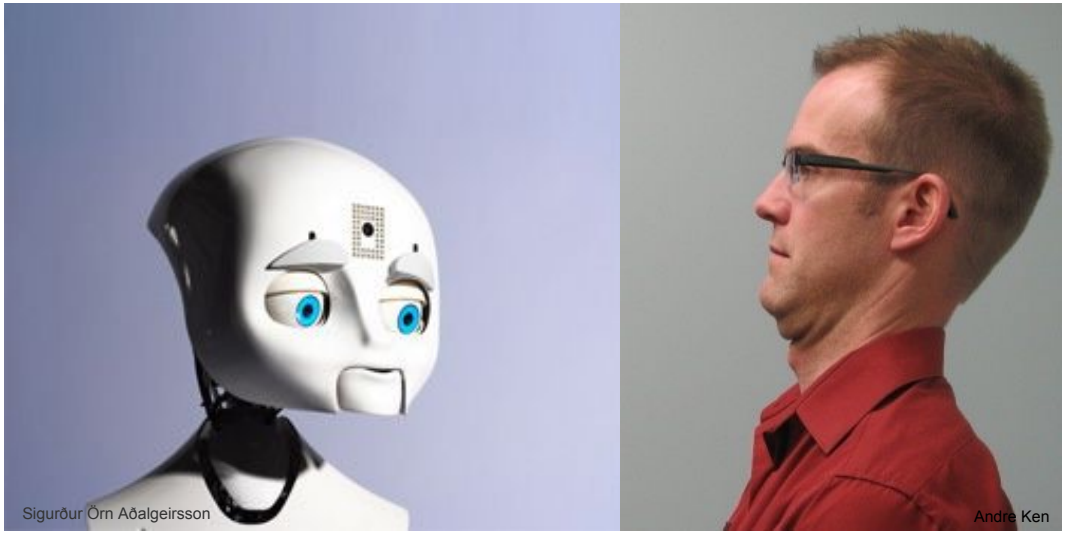
There are a **ton of really super-interesting problems** associated with processing different aspects natural language, many of which could be the topic of an entire course

Research in the MIRORLab

Mines Interactive Robotics Research

REFERENCE RESOLUTION

ERIN **JIM**



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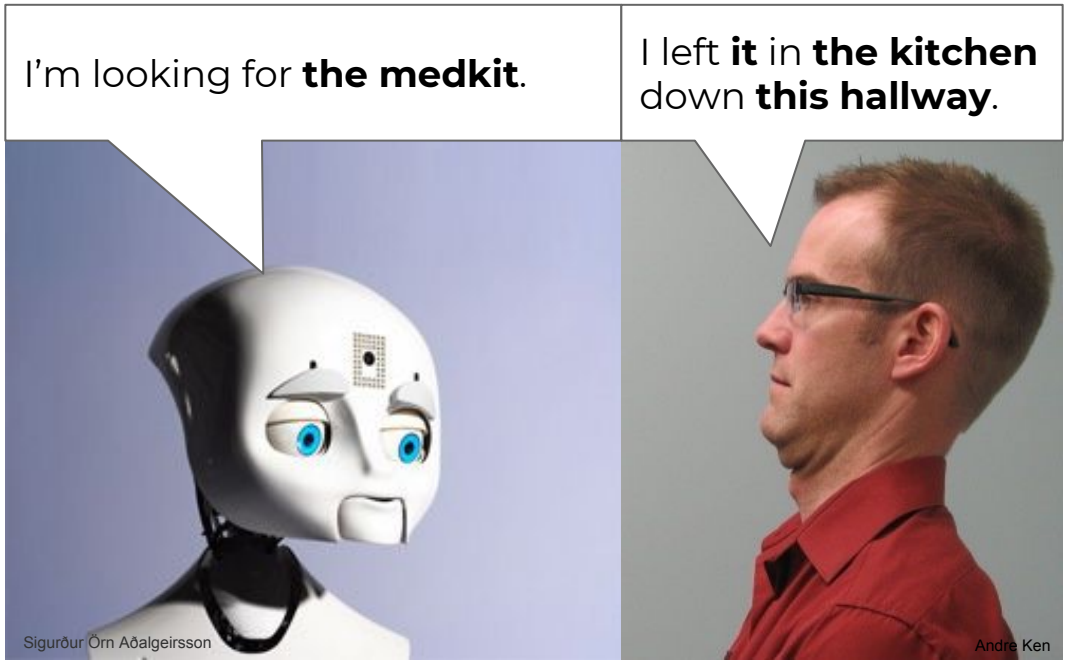
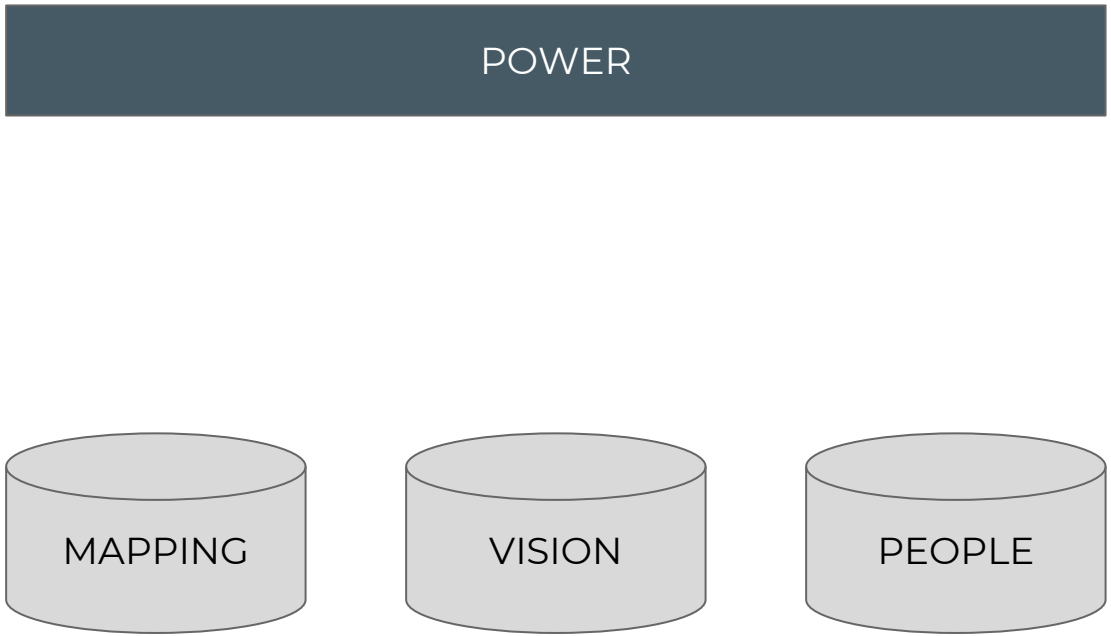
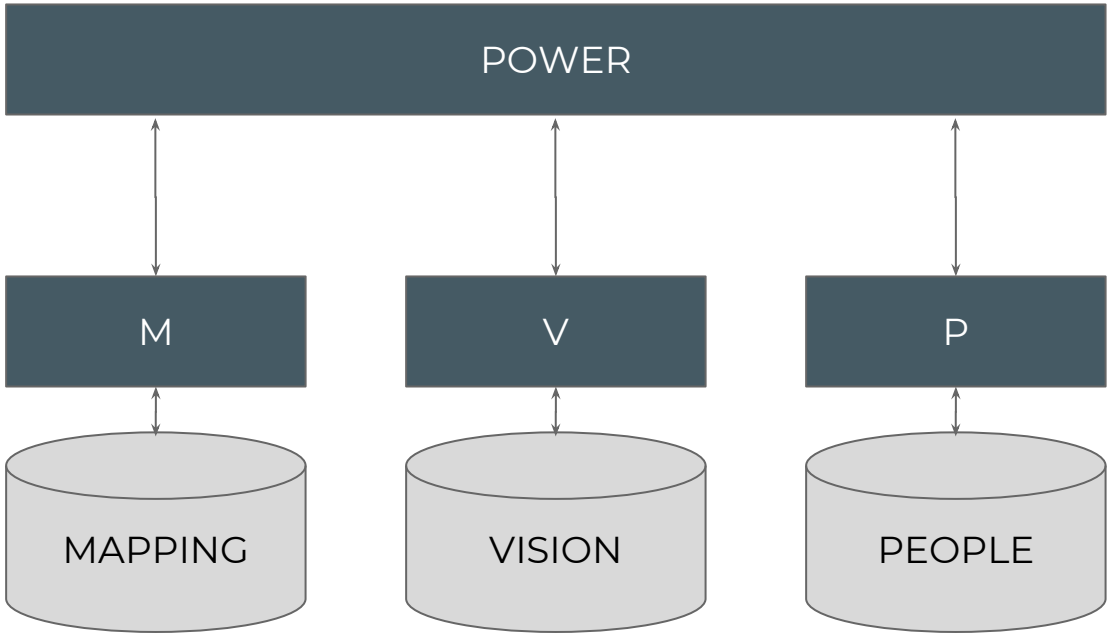



POWER
MAPPING
VISION
PEOPLE

Consultants



(Williams and Scheutz, AAAI 2016)

Consultant Capabilities

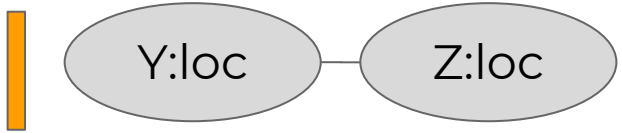
1. Advertise the constraints it can handle
2. Provide a list of candidate atomic entities
3. Provide the probability that a given constraint holds for a given set of atomic entities
4. Modify its world model based on new information

(Williams and Scheutz, IROS 2015)
(Williams and Scheutz, COGSCI 2015)

POWER : Resolves *Definite Noun Phrases*

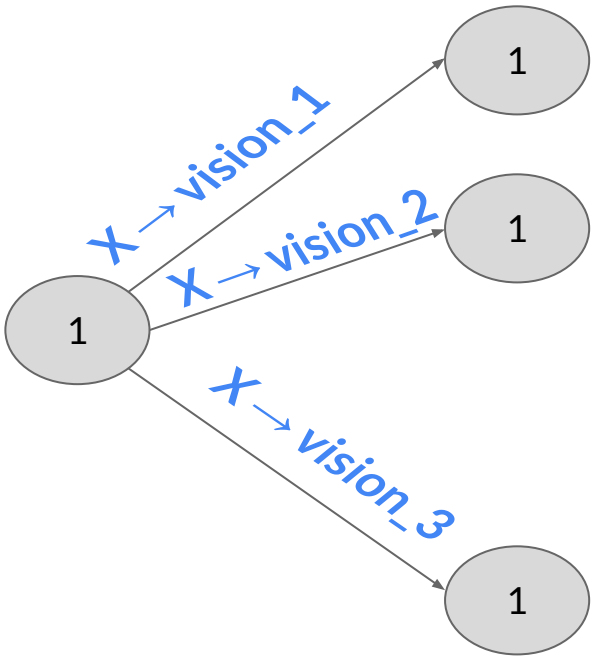
“the kitchen down the hallway”

kitchen(Y), hallway(Z), down(Y,Z)



Strategy: Find most probable mapping subject to constraints
{Y → (Some location), Z→ (Some location)}

ball(X), in(X,Y), kitchen(Y)



Williams and Scheutz, IROS 2015, Williams and Scheutz, AAAI 2016

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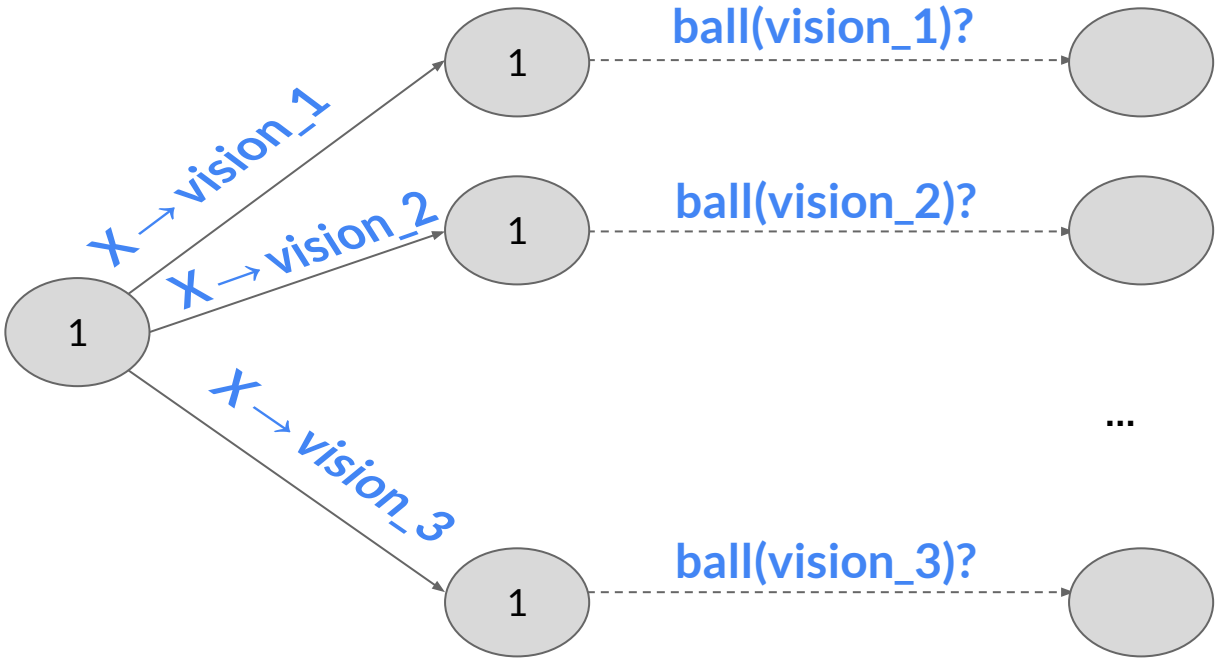

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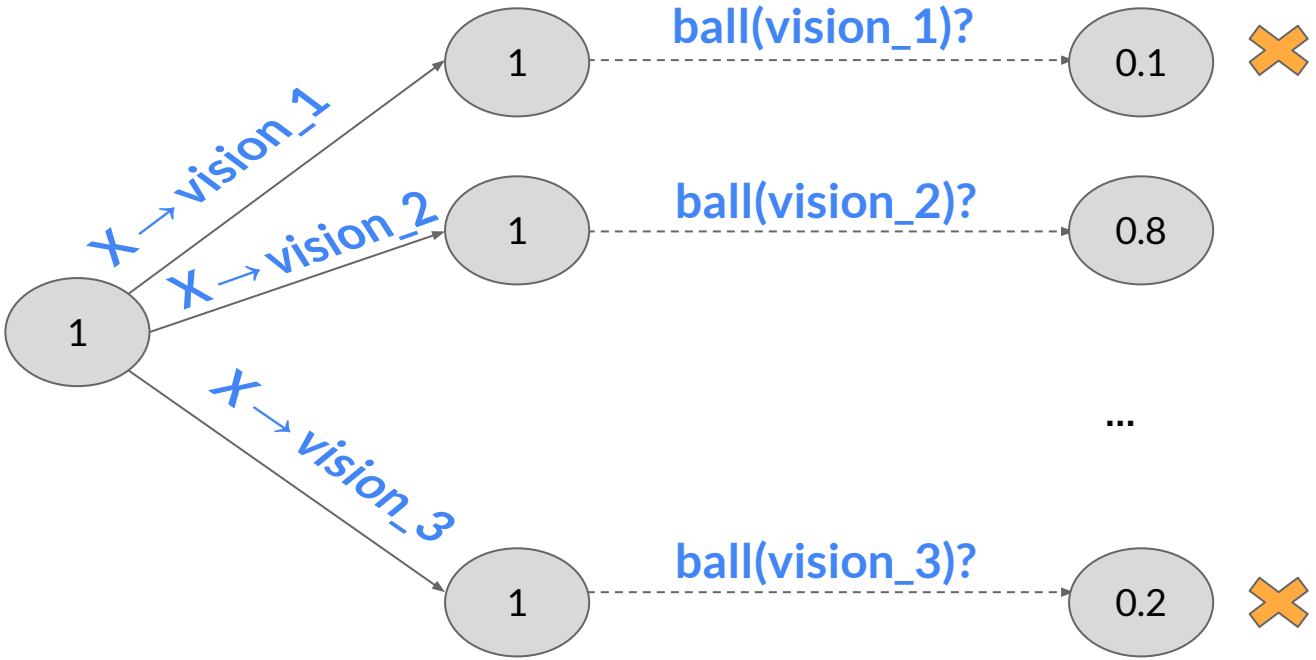

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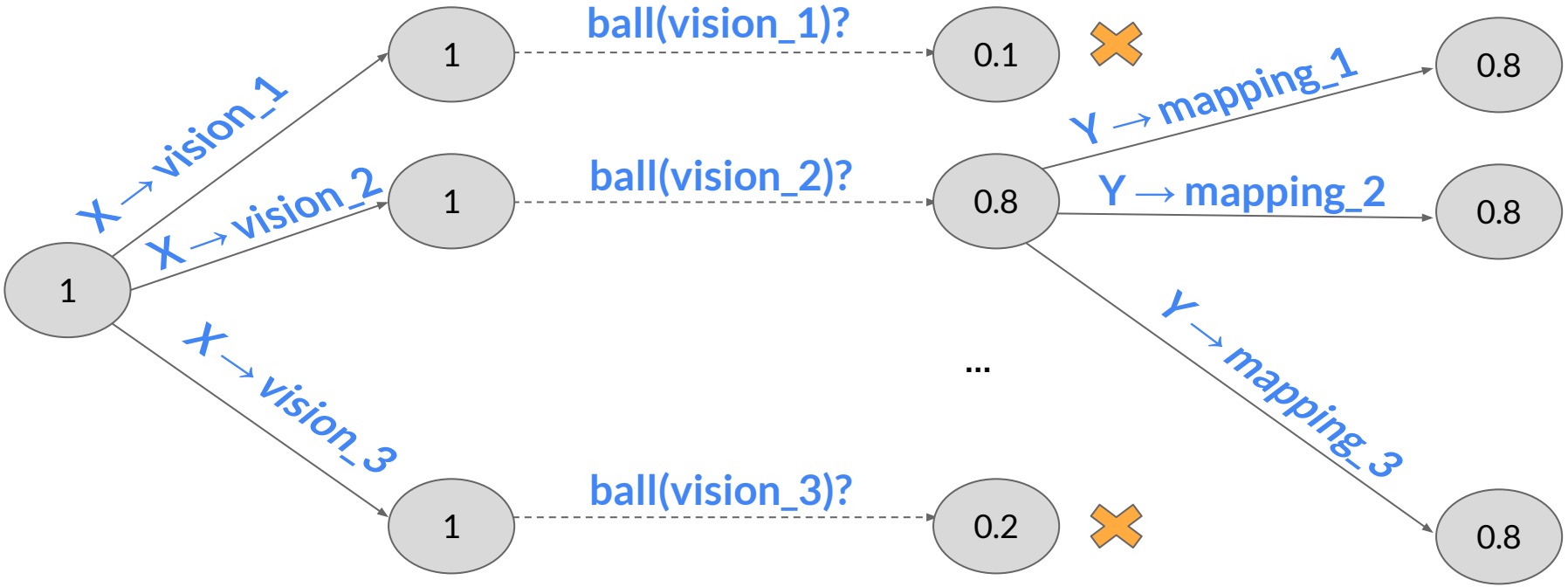
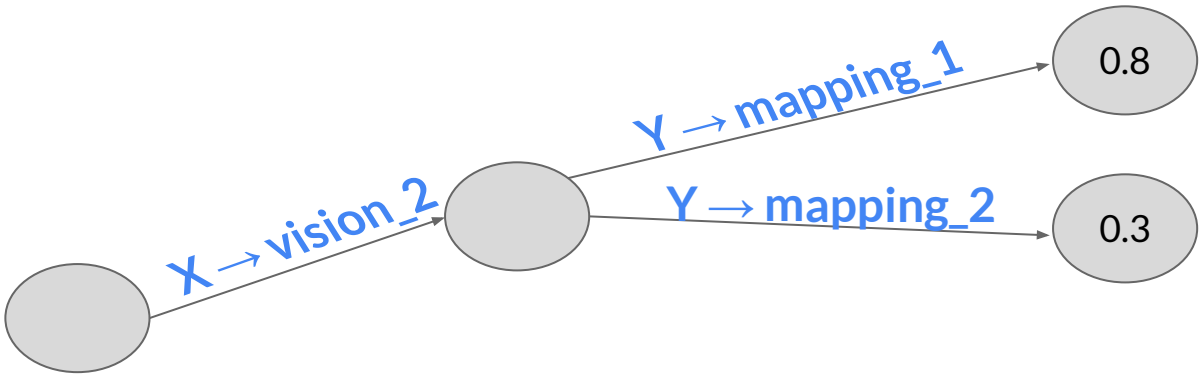


Williams and Scheutz, IROS 2015, Williams and Scheutz, AAAI 2016

Final Result….

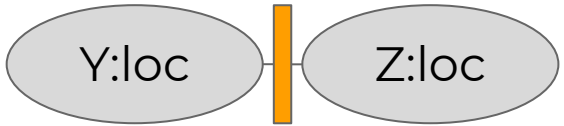
ball(X), in(X,Y), kitchen(Y)



{X → vision_2, Y→ mapping_1}: 0.8
{X → vision_1, Y→ mapping_2}: 0.3

Williams and Scheutz, IROS 2015, Williams and Scheutz, AAAI 2016

kitchen(Y), hallway(Z), down(Y,Z)



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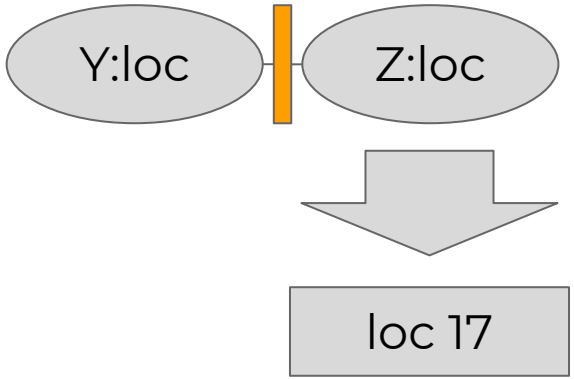
kitchen(Y), hallway(Z), down(Y,Z)



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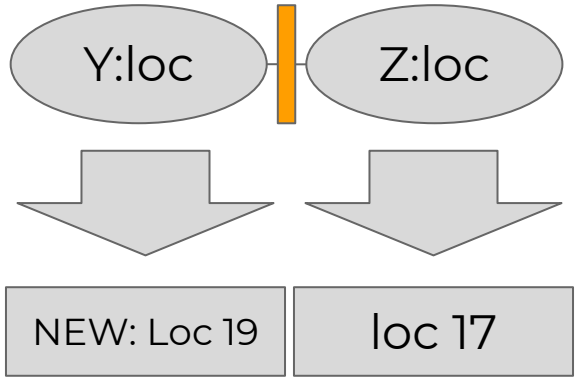

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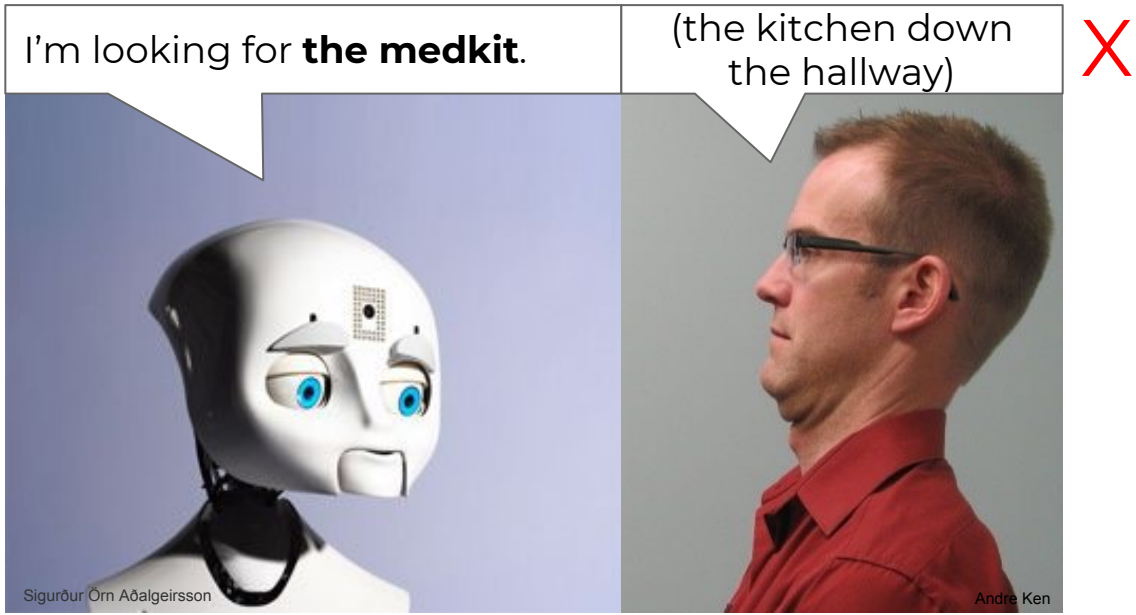
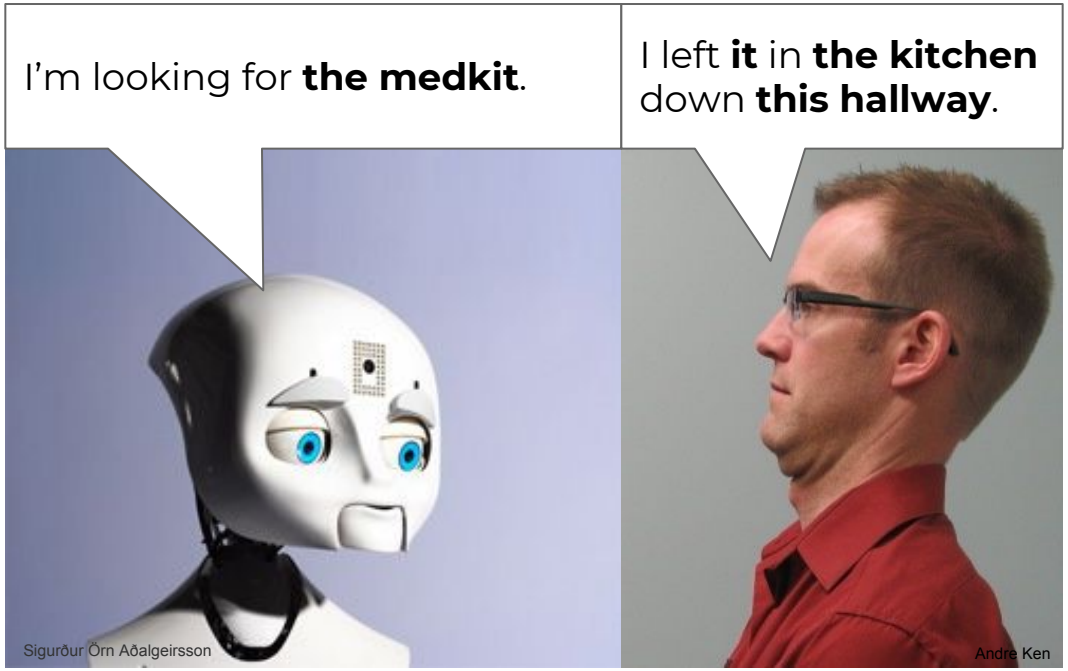
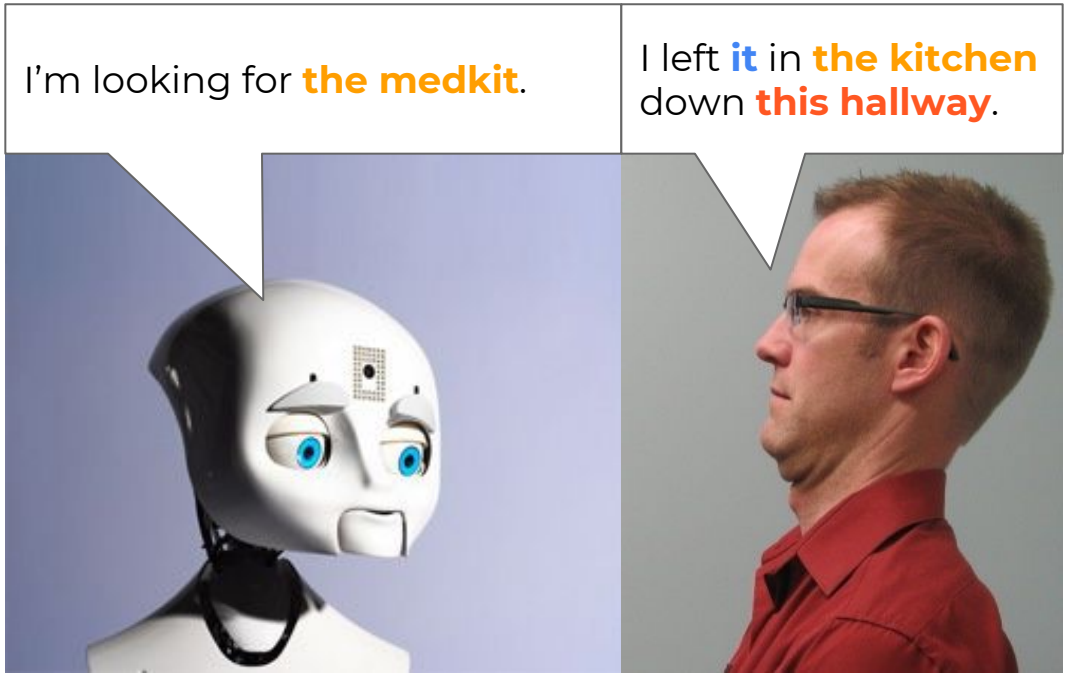
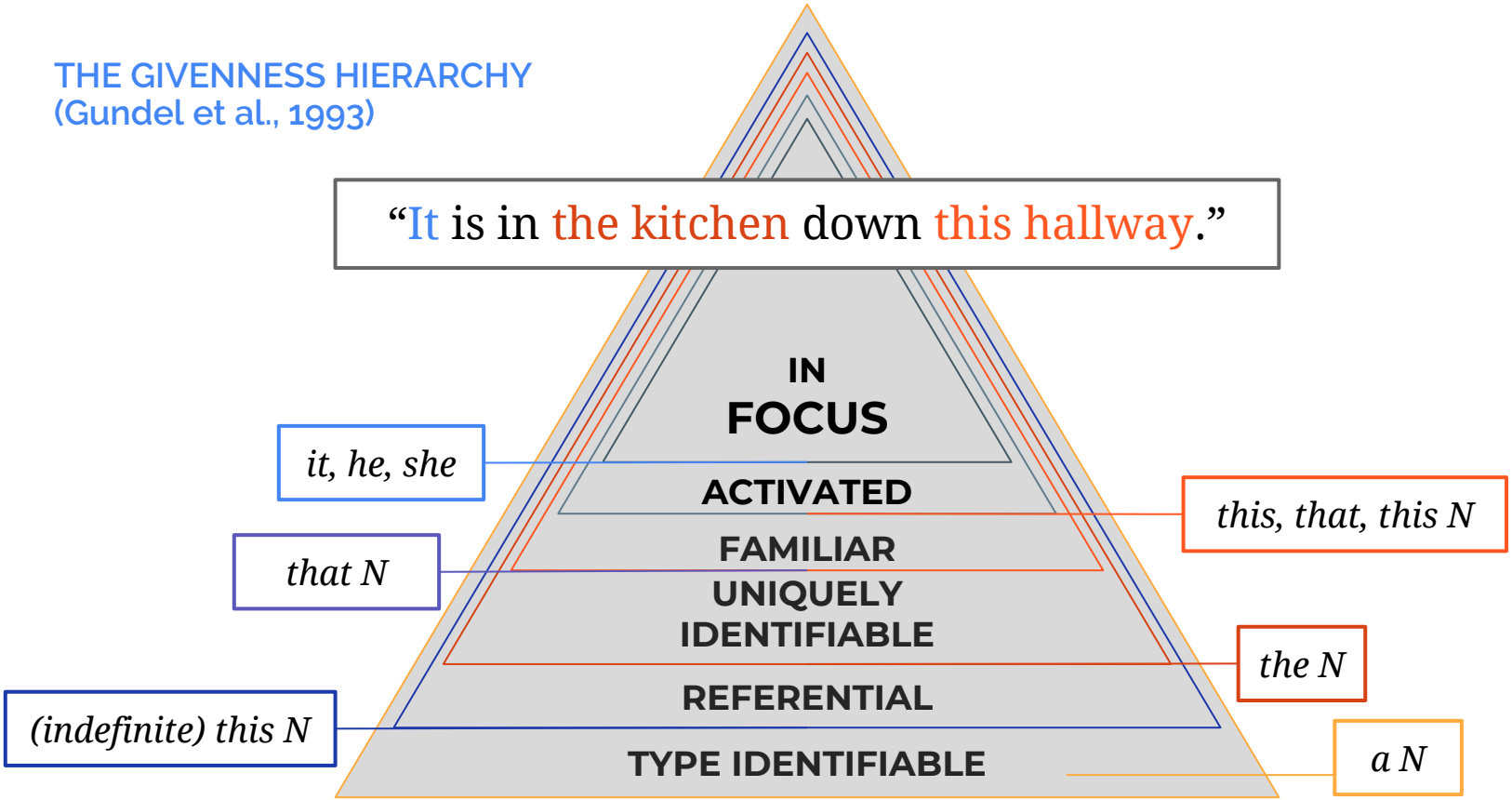

I’m looking for **the medkit**.
(the kitchen down the hallway)
X
Sigurður Örn Aðalgeirsson
Andre Ken


I'm looking for **the medkit**.
I left **it** in **the kitchen** down **this hallway**.
Sigurður Örn Aðalgeirsson
Andre Ken

Definite noun phrases
Other Anaphoric or Deictic expressions



THE GIVENNESS HIERARCHY
(Gundel et al., 1993)



GUIDELINES FOR THE GIVENNESS HIERARCHY

Level	Search Plan
In Focus	FOCUS
Activated	ACTIVATED => FOCUS
Familiar	ACTIVATED => FOCUS => DISCOURSE => MEMORY
Uniquely ID'able	ACTIVATED => FOCUS => DISCOURSE => MEMORY => HYPOTHESIZE
Referential	ACTIVATED => FOCUS => HYPOTHESIZE
Type ID'able	HYPOTHESIZE

(Williams, Acharya, Schreitter and Scheutz, HRI 2016)

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Type ID'able	HYPOTHESIZE

(Williams, Acharya, Schreitter and Scheutz, HRI 2016)

“I left it in the kitchen down this hallway”

Statement(Jim,Self, left(Jim,in(obj13,loc19)))

“The Commander needs the medkit!”

Statement(Jim,Self, needs(person10,obj15))

Statement(Jim,Self, needs(person10,obj15))

$$R_0: \quad \frac{U_0\text{:Statement(X,Y,needs(Z,W))} \quad C_0\text{:bel(X,subordinate(Y,X))}}{I_0\text{: want(X,goal(Y,get(Y,Z,W)))}}$$

$$R_1: \quad \frac{U_1\text{:Statement(X,Y,needs(Z,W))} \quad C_1\text{:bel(X,subordinate(X,Y))}}{I_1\text{:itk(X,location(W))}}$$

Statement(Jim,Self, needs(person10,obj15))

R_0: $\dfrac{\mathbf{U_0}\mathbf{:Statement(X,Y,needs(Z,W))} \quad C_0\text{:bel(X,subordinate(Y,X))}}{I_0\text{: want(X,goal(Y,get(Y,Z,W)))}}$

R_1: $\dfrac{\mathbf{U_1}\mathbf{:Statement(X,Y,needs(Z,W))} \quad C_1\text{:bel(X,subordinate(X,Y))}}{I_1\text{:itk(X,location(W))}}$

Statement(Jim,Self, needs(person10,obj15))

R_0: U_0:Statement(X,Y,needs(Z,W)), **C_0:bel(X,subordinate(Y,X))** ⊢ I_0: want(X,goal(Y,get(Y,Z,W)))

R_1: U_1:Statement(X,Y,needs(Z,W)), **C_1:bel(X,subordinate(X,Y))** ⊢ I_1:itk(X,location(W))

Statement(Jim,Self, needs(person10,obj15))

R_0: U_0:Statement(X,Y,needs(Z,W)) C_0:bel(X,subordinate(Y,X)) / **I_0: want(X,goal(Y,get(Y,Z,W)))**

R_1: U_1:Statement(X,Y,needs(Z,W)) C_1:bel(X,subordinate(X,Y)) / **I_1:itk(X,location(W))**

(“intention to know”)


seattletimes.com

Barista, Customer, Manager

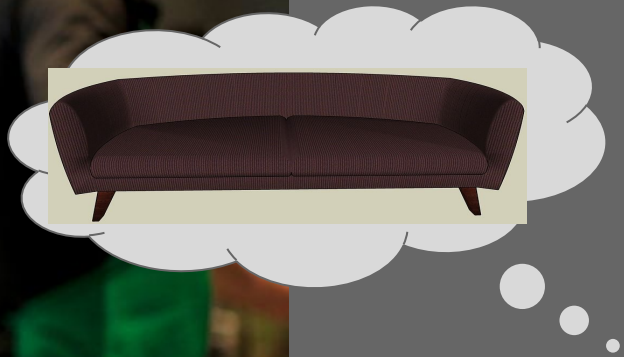
Θ={Barista, Customer, Manager}

Θ={Barista, Customer, Manager}

m({Barista})=0.3

Θ={Barista, Customer, Manager}

m({Customer})=0.1



m({Barista})=0.3

Θ={Barista, Customer, Manager}

m({Customer})=0.1

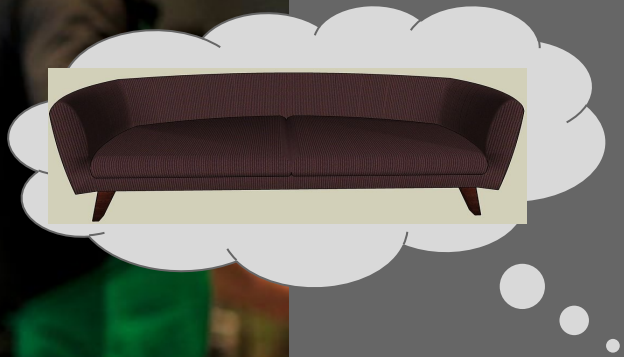
m({Barista})=0.3

m({...})=???

seattletimes.com

Θ={Barista, Customer, Manager}

m({Customer})=0.1



m({Barista})=0.3

m({Barista,Manager})=0.4

seattletimes.com

Body of Evidence

Hypothesis:	Mass:
{Barista}	0.3
{Customer}	0.1
{Manager}	0
{Barista ,Customer}	0
{Barista,Manager}	0.4
{Customer,Manager}	0
{Barista,Customer,Manager}	0.2

Hypothesis:	Mass:
{Barista}	0.3
{Customer}	0.1
{Manager}	0
{Barista ,Customer}	0
{Barista,Manager}	0.4
{Customer,Manager}	0
{Barista,Customer,Manager}	0.2

Hypothesis:	Mass:
{Barista}	0.3
{Customer}	0.1
{Manager}	0
{Barista ,Customer}	0
{Barista,Manager}	0.4
{Customer,Manager}	0
{Barista,Customer,Manager}	0.2

Belief

Hypothesis:	Mass:
{Barista}	0.3
{Customer}	0.1
{Manager}	0
{Barista ,Customer}	0
{Barista,Manager}	0.4
{Customer,Manager}	0
{Barista,Customer,Manager}	0.2

$$Bel(A) = \sum_{B \subseteq A} m(B)$$

Bel({Barista,Manager})

= 0.4 + 0 + 0.3

= 0.7

Hypothesis:	Mass:
{Barista}	0.3
{Customer}	0.1
{Manager}	0
{Barista ,Customer}	0
{Barista,Manager}	0.4
{Customer,Manager}	0
{Barista,Customer,Manager}	0.2

Plausibility

Hypothesis:	Mass:
{Barista}	0.3
{Customer}	0.1
{Manager}	0
{Barista ,Customer}	0
{Barista,Manager}	0.4
{Customer,Manager}	0
{Barista,Customer,Manager}	0.2

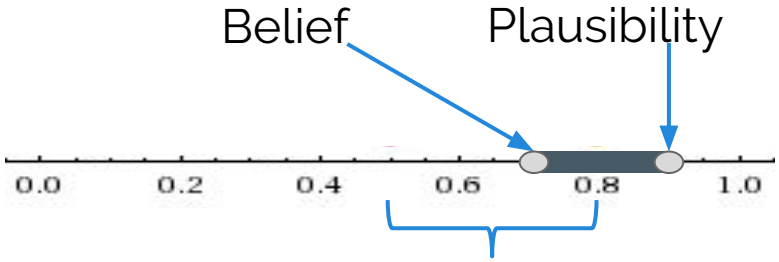
$Pl(A) = 1 - Bl(\neg A)$

$Pl(\{Barista,Manager\})$
$= 1 - (0.1)$
$= 0.9$

Hypothesis:	Mass:	Bel:	Pl:
{Barista}	0.3	0.3	0.9
{Customer}	0.1	0.1	0.3
{Manager}	0	0	0.6
{Barista ,Customer}	0	0.4	1.0
{Barista,Manager}	0.4	0.7	0.9
{Customer,Manager}	0	0.1	0.7
{Barista,Customer,Manager}	0.2	1.0	1.0

Uncertainty Intervals

Hypothesis:	Mass:	Bel:	Pl:
{Barista}	0.3	0.3	0.9
{Customer}	0.1	0.1	0.3
{Manager}	0	0	0.6
{Barista ,Customer}	0	0.4	1.0
{Barista,Manager}	0.4	0.7	0.9
{Customer,Manager}	0	0.1	0.7
{Barista,Customer,Manager}	0.2	1.0	1.0



"Uncertainty Interval"
[Bel(X),Pl(X)]

Statement(Jim,Self, needs(person10,obj15))

$R_0[0.7,0.9]$: $U_0[0.8,0.9]$:Statement(X,Y,needs(Z,W)) $C_0[0.6,0.7]$:bel(X,subordinate(Y,X)) / $I_0[0.336,0.9]$: want(X,goal(Y,get(Y,Z,W)))

$R_1[0.7,0.9]$: $U_1[0.8,0.9]$:Statement(X,Y,needs(Z,W)) $C_1[0.3,0.4]$:bel(X,subordinate(X,Y)) / $I_1[0.168,0.9]$:itk(X,location(W))

(Williams, Nunez, Briggs, Scheutz, Premaratne and Murthi, AAAI 2015)

“The Commander needs the medkit!”

Statement(Jim,Self, needs(person10,obj15))

itk(Self,or(

want(Jim,goal(Self,get(Self,person10,obj15))),

itk(Jim,location(obj15))))

“The Commander needs the medkit!”

Statement(Jim,Self, needs(person10,obj15))

Question(Self,Jim,or(

want(Jim,goal(Self,get(Self,person10,obj15))),

itk(Jim,location(obj15))))

“The Commander needs the medkit!”

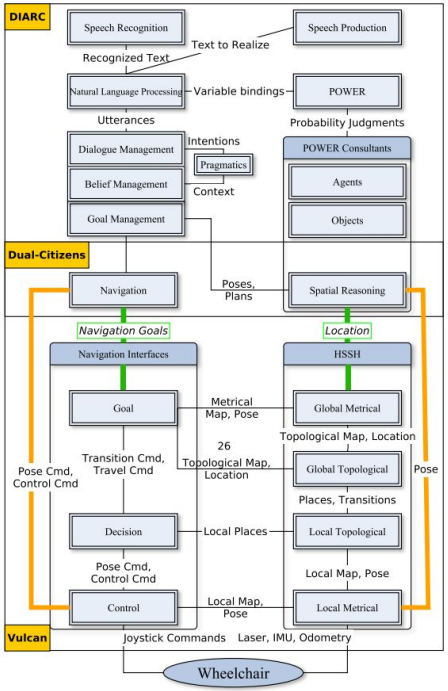
Statement(Jim,Self, needs(person10,obj15))

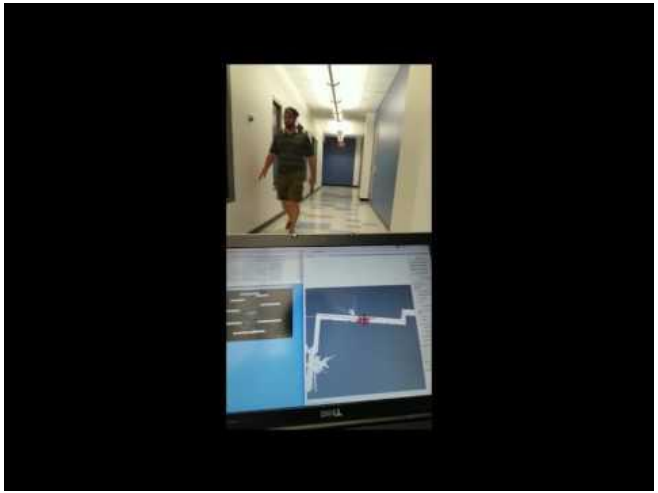
Question(Self,Jim,or(want(Jim,goal(Self,get(Self,person10,obj15))),itk(Jim,location(obj15))))

“Do you want me to bring him the medkit,
or do you want to know where to find the medkit?”

(Williams, Nunez, Briggs, Scheutz, Premaratne and Murthi, AAAI 2015)

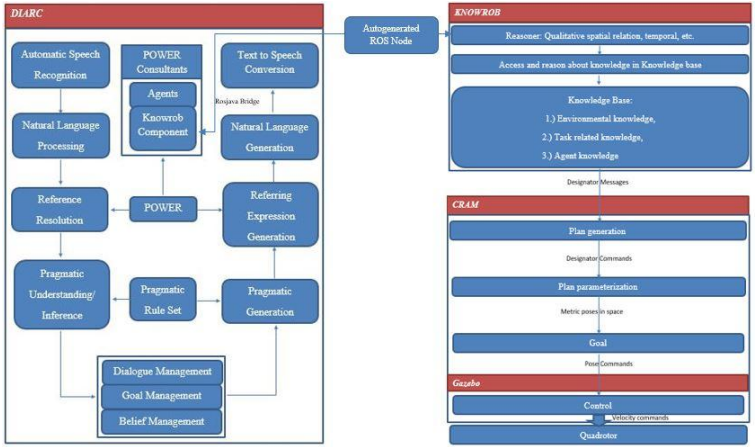
Applications: (1) Assistive Robotics (Collaboration with University of Michigan)

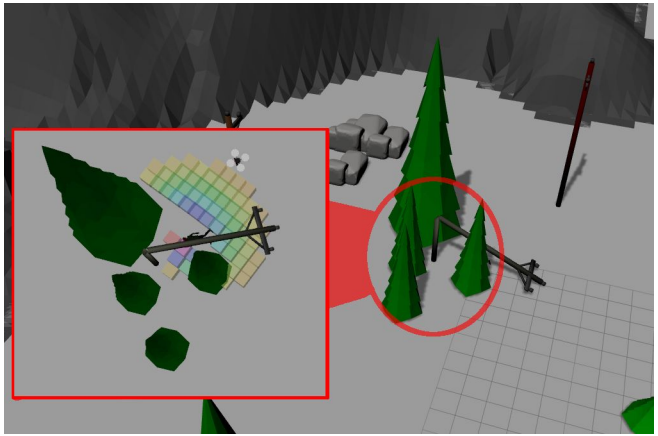




Williams, Johnson, Scheutz & Kuipers, AAMAS 2017
Williams & Scheutz, RAS 2017

Applications: (2) Alpine Search and Rescue Robotics (Collaboration with University of Bremen)





Williams, Yazdani, Suresh, Scheutz & Beetz, Autonomous Robots, 2018
Williams & Scheutz, RSS 2017

But language alone isn’t everything!

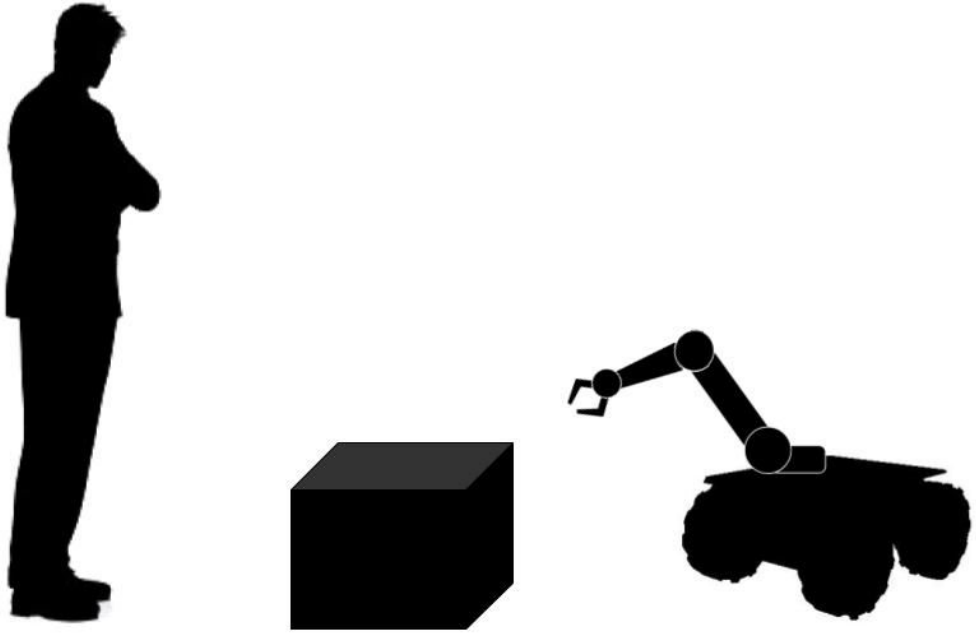
Deictic Gesture

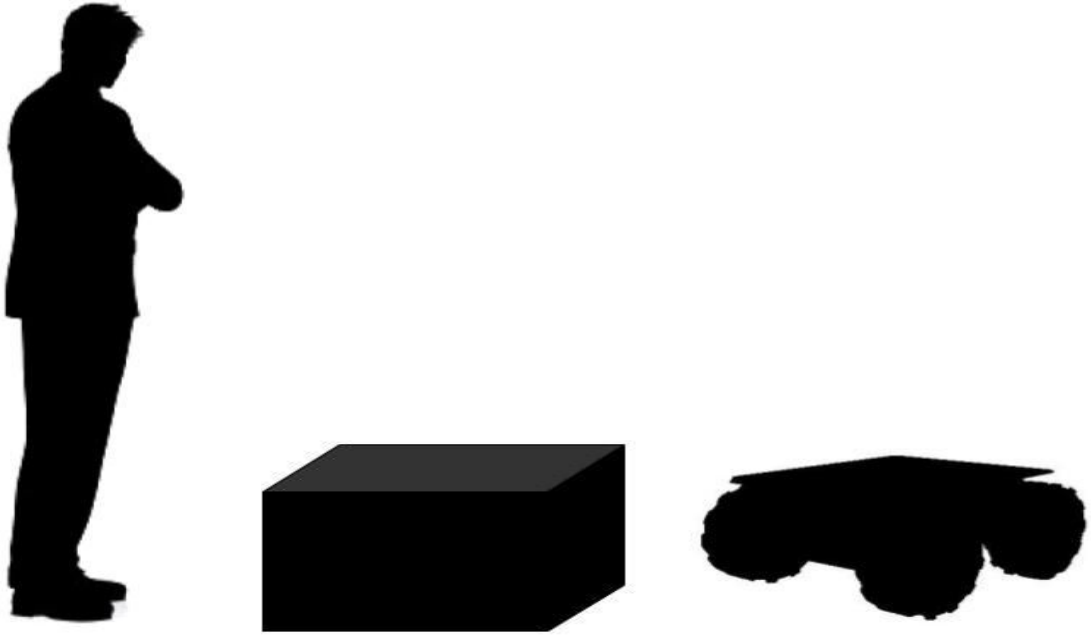
Rabinowitch et al., HRI 2010

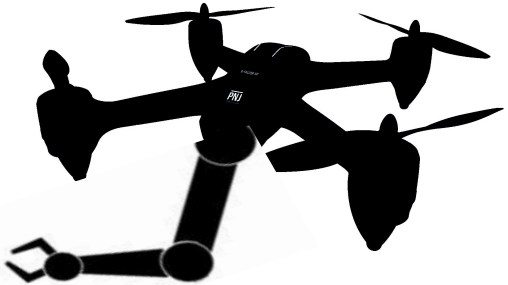
St. Clair, Mead and Mataric, HRI 2011

Salem et al., IJSR, 2013

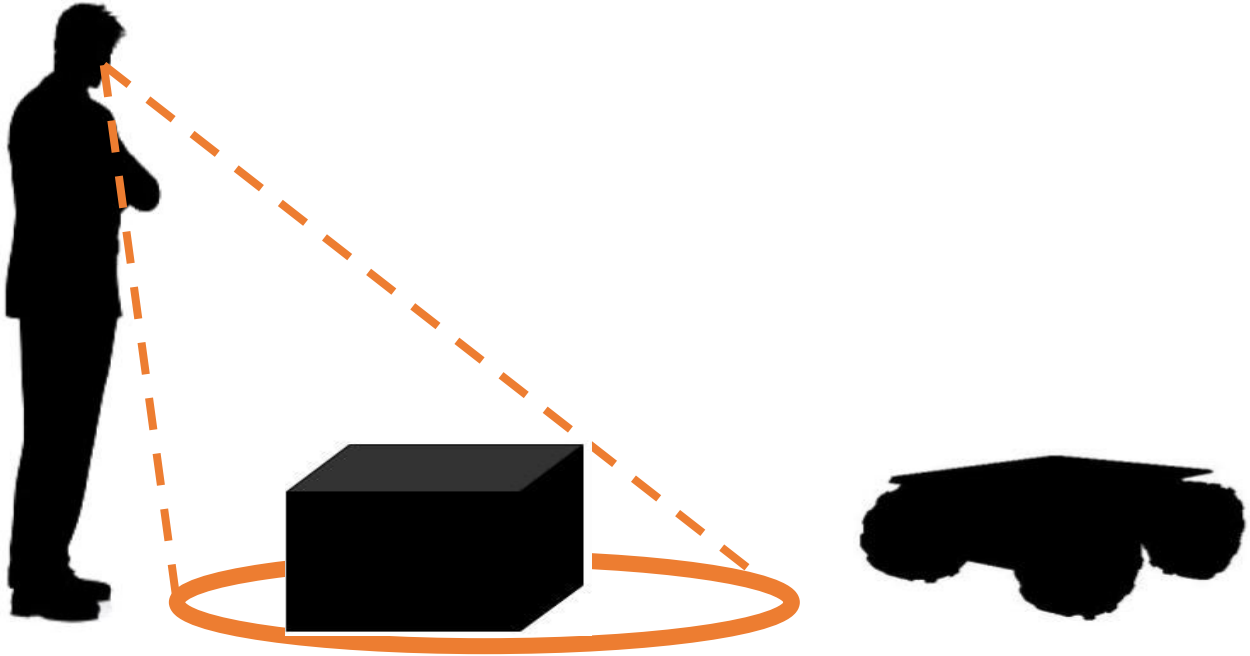
Liu et al., IJSR 2017

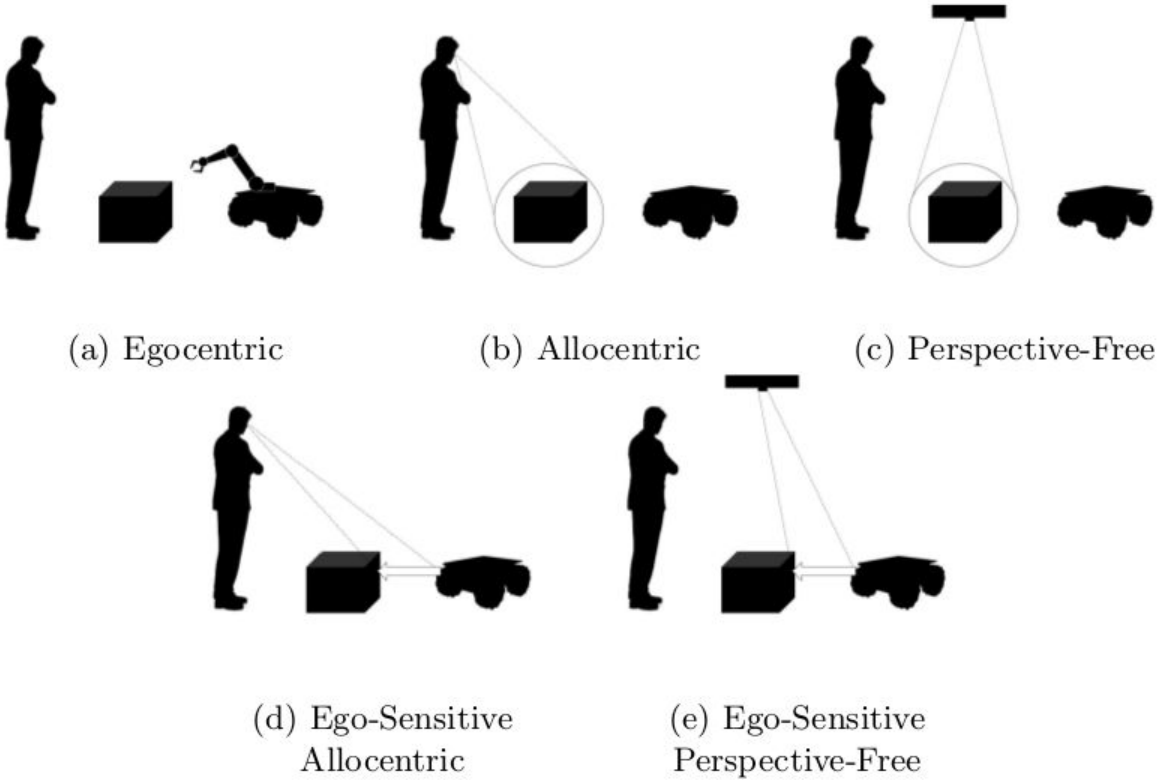






If robots can't generate physical deictic gesture, how else could they draw their teammates' attention to their target referents?



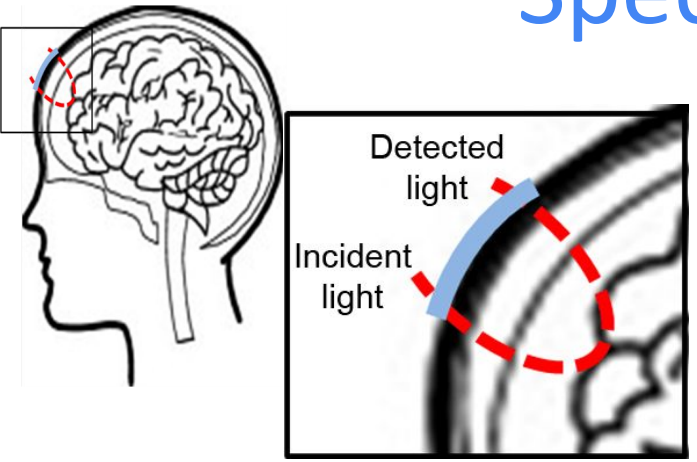


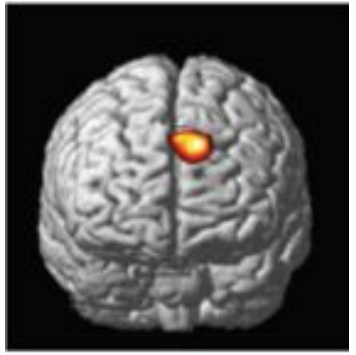
Williams, Tran, Rands and Dantam, VAMR 2018

Category	(Dynamic) Legibility	(Local) Privacy
Egocentric	Low	Low
Allocentric	High	High
Perspective-Free	High	Low

How can we choose between communication modalities?

Background: Functional Near Infrared Spectroscopy (fNIRS)





Why use fNIRs in HCI and the social sciences?

- Non-invasive, highly practical for ecologically valid experiments
- Easy set up
- Robust to noise
- High spatial resolution (comparable to fMRI)
- New…

Neurophysiological States of Interest

- Perceptual Modality
  - Auditory (none/low/high)
  - Visual (none/low/high)
- Negative Affect (none/low/high)
- Cognitive Load
  - Working memory load (none/low/high)
  - Visual search load (none/low/high)
  - Spatial attention (none/low/high)
  - Response inhibition (none/low/high)
  - Visual lexical processing (none/low/high)

Should a robot pursue communication at all?

Expectation:

If **Working Memory load** or **Negative Affect** are high…
maybe come back later.

Should a robot use a fully descriptive or concise referring expression?

Expectation:

If **Working Memory load** is high, the target is already expected to be in WM, or **auditory perceptual load** is high, use a concise form.

If **Response Inhibition** is low, use a full referring form.

Should a robot use a gesture in conjunction with its language?

Expectation:

If the user is performing a **Visual Search Task**, only generate a gesture if you believe the target is relevant to that task!
If **visual perception load** is high, don't use a gesture.

Should physical or visual gesture be used?

Expectation:

If **Response Inhibition** is high, use a physical gesture.
If the user is performing a **visual search task**, and the target is relevant to the user's task, use a visual gesture.

Questions?