Natural Language Processing

Agents that communicate

• Producing language is an action, called speech act

• Why communicate between agents?
  • Inform
    Example: It is warm outside.

  • Query
    Example: Did you see John this morning?

  • Answer
    Example: Yes, I saw John in the printer room.

  • Request or command
    Examples: Please help me carry the TV (I could use some help carrying the TV)
               Carry the TV to DL 366
Cont.

• **Promise** or **offer**

  Examples: *I'll return the midterm on Friday*
  *I'll tip you well if you bring the dish now*

• **Acknowledge** requests and offers

  Example: *OK, I'll try my best with the chef*

• **Share** feelings and experiences

  Example: *I don't like his cooking*
Fundamentals of language

• Natural language vs. formal language
  
  English vs. LISP

• Formal language is defined as a set of strings
  
  - A string is a sequence of symbols
  
  - Symbols are divided into terminal and nonterminal symbols
  
  - For English, terminal symbols include words, about 400,000 of them

• Phrase structure

  Sentence ($S$), noun phrase ($NP$), verb phrase ($VP$)

• Rewrite rules

  $$S \rightarrow NP \ VP$$
Chomsky's four grammar categories

(From simple to complex)

• Regular grammar
  - Equivalent in expressive power to finite-state automata
  - Sample rule: $S \rightarrow a\ S,\ S \rightarrow b$
  - Sample language: $a^*b^*$

• Context-free grammar
  - Equivalent to pushdown automata
  - Sample rule: $S \rightarrow a\ S\ b$
  - Sample language: $a^n b^n$

• Context-sensitive grammar
  - Equivalent to linear bounded automata
  - RHS must be no shorter than LHS
  - Sample rule: $A\ B \rightarrow B\ A$
  - Sample language: $a^n\ b^n\ c^n$

• Recursively enumerable grammar
  - Equivalent to Turing machines
  - No restriction on rewrite rules
  - Sample rule: $A\ B \rightarrow C$
  - Sample language: any
Component steps of communication

*S*: speaker; *H*: hearer; *P*: proposition; *W*: words

- **For the speaker**
  - **Intention**: *S* wants *H* to believe *P*
  - **Generation**: *S* chooses the words *W*
  - **Synthesis**: *S* utters the words *W*

- **For the hearer**
  - **Perception**: *H* hears *W'*
    Generally *W*' = *W*, but not always
  - **Analysis**
    *H* infers that *W*' has possible meanings *P*$_1$, ..., *P*$_n$
  - **Disambiguation**: *H* infers that *S* intends to convey *P*$_i$
    Ideally *P*$_i$ = *P*, but misinterpretation is possible
  - **Incorporation**: *H* decides to believe in *P*$_i$
    *H* may reject *P*$_i$ if it, among other things, is inconsistent with what *H* already believes
Wumpus World

A computer game with the following rules

- Agent's task: find the gold in the cave and climb out of it
- The beast Wumpus eats anyone in its room, plus trapping pits
- Agent and wumpus can move to adjacent room, horizontal or vertical
- Stench smell next to the wumpus
- Breeze next to a pit
- Gold glittering in its room
- Boundary wall bumps
- One arrow to shoot wumpus in facing direction
- Killed wumpus screams
- Score the time taken to get the gold, while not killed
An Illustration in the Wumpus World

Seven steps involved in communication for the example sentence: "The wumpus is dead."
Telepathic vs. Language Communication

• Telepathic communication using Tell and Ask

  Communication with Tell and Ask

  ![Diagram showing communication with Tell and Ask between two agents, Agent A and Agent B, involving KB (knowledge base) and reasoning processes.]

  KB: knowledge base

• Advantage: very efficient

• Disadvantage: inconsistent and vulnerable

• Communicating using formal language

  ![Diagram showing communication using language between two agents, Agent A and Agent B, involving KB (knowledge base) and reasoning processes.]

NLP, p. 8
Grammar for Describing the Wumpus World

• This subset of English is called language $E_0$

• The lexicon of $E_0$

Noun $\rightarrow$ stench | breeze | glitter | nothing | wumpus | pit | pits | gold | east | ...
Verb $\rightarrow$ is | see | smell | shoot | feel | stinks | go | grab | carry | kill | turn | ...
Adjective $\rightarrow$ right | left | east | south | back | smelly | ...
Adverb $\rightarrow$ here | there | nearby | ahead | right | left | east | south | back | ...
Pronoun $\rightarrow$ me | you | I | it | ...
Name $\rightarrow$ John | Mary | Boston | Aristotle | ...
Article $\rightarrow$ the | a | an
Preposition $\rightarrow$ to | in | on | near | ...
Conjunction $\rightarrow$ and | or | but | ...
Digits $\rightarrow$ 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9
Language $E_0$, cont.

- **The grammar of $E_0$**

  **Rewrite rules**
  
<table>
<thead>
<tr>
<th>Rewrites</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S \rightarrow NP \ VP$</td>
<td>I + feel a breeze</td>
</tr>
<tr>
<td>$S \rightarrow S \ Conjunction \ S$</td>
<td>I feel a breeze + and + I smell a wumpus</td>
</tr>
<tr>
<td>$NP \rightarrow Pronoun$</td>
<td>I</td>
</tr>
<tr>
<td>$NP \rightarrow Noun$</td>
<td>pits</td>
</tr>
<tr>
<td>$NP \rightarrow Article \ Noun$</td>
<td>the + wumpus</td>
</tr>
<tr>
<td>$NP \rightarrow Digit \ Digit$</td>
<td>3 4</td>
</tr>
<tr>
<td>$NP \rightarrow NP \ PP$</td>
<td>the wumpus + to the east</td>
</tr>
<tr>
<td>$NP \rightarrow NP \ RelClause$</td>
<td>the wumpus + that is smelly</td>
</tr>
<tr>
<td>$VP \rightarrow Verb$</td>
<td>stinks</td>
</tr>
<tr>
<td>$VP \rightarrow VP \ NP$</td>
<td>feel + a breeze</td>
</tr>
<tr>
<td>$VP \rightarrow VP \ Adjective$</td>
<td>is + smelly</td>
</tr>
<tr>
<td>$VP \rightarrow VP \ PP$</td>
<td>turn + to the east</td>
</tr>
<tr>
<td>$VP \rightarrow VP \ Adverb$</td>
<td>go + ahead</td>
</tr>
<tr>
<td>$PP \rightarrow Preposition \ NP$</td>
<td>to + the east</td>
</tr>
<tr>
<td>$RelClause \rightarrow that \ VP$</td>
<td>that + is smelly</td>
</tr>
</tbody>
</table>
Components of NLP
(Natural language processing)

• **Syntactic Analysis (Parsing)**
  - Recover phrase structure from sentences

• **Semantic Interpretation**
  - Extract meaning from sentences

• **Pragmatic Interpretation**
  - Incorporating the current situation

• **Disambiguation**
  - Chooses the best interpretation if more than one is found
Syntactical Analysis

- A simple bottom-up parsing algorithm for context-free grammar

  - Form a forest list containing a sequence of words
  - Find a rewrite rule whose RHS matches a subsequence of forest
  - Replace the subsequence by the LHS of the rule
  - If forest contains the starting node (S) of the grammar, exit with success; else, go to Step 2.

- A parsing example for "The wumpus is dead."

<table>
<thead>
<tr>
<th>The forest list</th>
<th>Subsequence</th>
<th>Rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>The wumpus is dead</td>
<td>The</td>
<td>Article $\rightarrow$ the</td>
</tr>
<tr>
<td>Article wumpus is dead</td>
<td>wumpus</td>
<td>Noun $\rightarrow$ wumpus</td>
</tr>
<tr>
<td>Article Noun is dead</td>
<td>Article Noun</td>
<td>NP $\rightarrow$ Article Noun</td>
</tr>
<tr>
<td>NP is dead</td>
<td>is</td>
<td>Verb $\rightarrow$ is</td>
</tr>
<tr>
<td>NP Verb dead</td>
<td>dead</td>
<td>Adjective $\rightarrow$ dead</td>
</tr>
<tr>
<td>NP Verb Adjective</td>
<td>Verb</td>
<td>VP $\rightarrow$ Verb</td>
</tr>
<tr>
<td>NP VP Adjective</td>
<td>VP Adjective</td>
<td>VP $\rightarrow$ VP Adjective</td>
</tr>
<tr>
<td>NP VP</td>
<td>NP VP</td>
<td>S $\rightarrow$ NP VP</td>
</tr>
</tbody>
</table>
Definite Clause Grammar (DCG)

- Problems with context-free syntactic analysis
  - Purely syntactic, with no meaning associated
  - Grammar is context-free, while natural language is context-sensitive

- Proposed solution uses the power of first-order predicate logic
  - Rewrite rules can be expressed in first-order logic

### Rules

<table>
<thead>
<tr>
<th>First-order logic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S \rightarrow NP \ VP$</td>
</tr>
<tr>
<td>$NP(s_1) \land VP(s_2) \Rightarrow S(Append(s_1,s_2))$</td>
</tr>
<tr>
<td>$Noun \rightarrow stench...$</td>
</tr>
<tr>
<td>$(s = &quot;stench&quot; \lor ...) \Rightarrow Noun(s)$</td>
</tr>
</tbody>
</table>

- A grammar can be written in logic, called logic grammar

- Definite clause logic grammar uses only definite clauses
  - All definite clauses have the form $A_1 \land A_2 \land ... \Rightarrow C_1$
    - one consequent, and zero or more antecedents
DCG, cont.

- To avoid being too verbose, we use the following special DCG notation for rewrite rules

  - Rule $X \rightarrow YZ \ldots$ translates as $Y(s_1) \land Z(s_2) \land \ldots \Rightarrow X(Append(s_1,s_2,\ldots))$
  - Rule $X \rightarrow \text{word}$ translates $X(["\text{word}"])$
  - Rule $X \rightarrow Y \mid Z \mid \ldots$ translates as $Y'(s) \lor Z'(s) \lor \ldots \Rightarrow X(s)$, where $Y'$ is the logic translation of the DCG expression $Y$ (it may not be a single nonterminal symbol)

- Extensions

  - Nonterminal symbols can be augmented with extra arguments (such as $sem$ for semantics)
  - A variable can appear on the RHS of a DCG rule
  - Logical tests can appear on the RHS in braces

- An example for describing numbers in DCG

  **DCG Rules**

  - $Digit(sem) \rightarrow sem \{0 \leq sem \leq 9\}$
  - $Number(sem) \rightarrow Digit(sem)$
  - $Number(sem) \rightarrow Number(sem_1) \land Digit(sem_2)$
    \[
    \{sem = 10 \times sem_1 + \text{sem}_2\}
    \]

  **First-order logic**

  - $(s=[sem]) \Rightarrow Digit(sem,s)$
  - $Digit(sem,s) \Rightarrow Number(sem,s)$
  - $Number(sem_1,s_1) \land Digit(sem_2,s_2)$
    \[
    \land \text{sem} = 10 \times \text{sem}_1 + \text{sem}_2 \Rightarrow
    \]
  - $Number(sem, \text{Append}(s_1,s_2))$
Augmenting a Grammar

• Overgeneration problem

Examples: *Me sees glitter*  
*Go me the gold* rather than *Give me the gold*

• The grammar of $E_1$ to represent noun cases  
(subjective vs. objective)

\[
S \rightarrow NP(Subj) \ VF | \ ...
\]
\[
NP(\text{case}) \rightarrow Pronoun(case) | Noun | Article Noun | ... \]
\[
VP \rightarrow VP \ NP(\text{Obj}) | ... \]
\[
PP \rightarrow Preposition \ NP(\text{Obj}) \]
\[
Pronoun(\text{Subj}) \rightarrow I | you | he | she | ... \]
\[
Pronoun(\text{Obj}) \rightarrow me | you | him | her | ... \]
Augmenting a Grammar, cont.

• Verb subcategorization
  • It states which verbs can be followed by which other categories
  • Provided as a subcategorization list

• Some examples

<table>
<thead>
<tr>
<th>Verb</th>
<th>Subcats</th>
<th>Example verb phrase</th>
</tr>
</thead>
<tbody>
<tr>
<td>give</td>
<td>[NP, PP]</td>
<td>give the gold in 3 3 to me</td>
</tr>
<tr>
<td></td>
<td>[NP, NP]</td>
<td>give me the gold</td>
</tr>
<tr>
<td>smell</td>
<td>[NP]</td>
<td>smell a wumpus</td>
</tr>
<tr>
<td></td>
<td>[Adjective]</td>
<td>smell awful</td>
</tr>
<tr>
<td></td>
<td>[PP]</td>
<td>smell like a wumpus</td>
</tr>
<tr>
<td>is</td>
<td>[Adjective]</td>
<td>is smelly</td>
</tr>
<tr>
<td></td>
<td>[PP]</td>
<td>is in 2 2</td>
</tr>
<tr>
<td></td>
<td>[NP]</td>
<td>is a pit</td>
</tr>
<tr>
<td>died</td>
<td>[]</td>
<td>died</td>
</tr>
<tr>
<td>believe</td>
<td>[S]</td>
<td>believe the smelly wumpus in 2 2 is dead</td>
</tr>
</tbody>
</table>
Augmenting a Grammar, cont.

- Verb subcategorization can be implemented by parameterizing \( VP \) into \( VP(subcat) \)

- Generative capacity of augmented grammars
  - In general, it goes beyond context-free grammar
  - Example: the context-sensitive language \( a^n b^n c^n \)

\[
S(n) \rightarrow A(n) \ B(n) \ C(n) \\
A(0) \rightarrow \varepsilon \quad A(n+1) \rightarrow a \ A(n) \\
B(0) \rightarrow \varepsilon \quad B(n+1) \rightarrow b \ B(n) \\
C(0) \rightarrow \varepsilon \quad C(n+1) \rightarrow c \ C(n)
\]
Semantic Interpretation

*Produce logical expression*

- **Compositional semantics**
  - The semantics of any phrase is a function of the semantics of the parts of the phase
  - Does not depend on the context of the phrase
  - Similar to context-free

- **NL does not satisfy compositional semantics**

- **Divide NL semantics into two parts**
  - Semantic interpretation, that satisfies compositional semantics
  - Disambiguation that handles multiple interpretations, produced by compositional semantic interpretation
Semantics of "John loves Mary"

- $\lambda$-expression (lambda) is used as placeholder in functions and predicates

  - Ex: "are from the same state but different cities"
    
    $\lambda x,y \text{ state}(x) = \text{state}(y) \land \text{city}(x) \neq \text{city}(y)$

  - Arguments to an $\lambda$-expression plug into placeholders to yield a standard term or sentence

    $[\lambda x,y \text{ state}(x) = \text{state}(y) \land \text{city}(x) \neq \text{city}(y)](\text{John},\text{Mary})$

    yields

    $\text{state}(\text{John}) = \text{state}(\text{Mary}) \land \text{city}(\text{John}) \neq \text{city}(\text{Mary})$

- Same usage as in LISP

- VP "loves Mary" expressed as a $\lambda$-expression with

  - $\lambda x \text{ Loves}(x,\text{Mary})$

- NP "John" expressed as object to VP with relational semantics

  - $S(\text{rel}(\text{obj})) \rightarrow \text{NP}(\text{obj}) \text{ VP}(\text{rel})$
"John loves Mary", cont.

- Together we have

  - \((\lambda x \text{ Loves}(x,\text{Mary}))(\text{John})\) or equivalently
    
    \(\text{Loves}(\text{John},\text{Mary})\)

- Overall semantics expressed as DCG augmentations

  \[S(\text{rel}(\text{obj})) \rightarrow \text{NP}(\text{obj}) \text{ VP}(\text{rel})\]
  \[\text{VP}(\text{rel}(\text{obj})) \rightarrow \text{Verb}(\text{rel}) \text{ NP}(\text{obj})\]
  \[\text{NP}(\text{obj}) \rightarrow \text{Name}(\text{obj})\]

  \(\text{Name}(\text{John}) \rightarrow \text{John}\)
  \(\text{Name}(\text{Mary}) \rightarrow \text{Mary}\)
  \(\text{Verb}(\lambda x \lambda y \text{ Loves}(x,y)) \rightarrow \text{loves}\)

- A parse tree with semantic interpretation

```
S(Loves(John, Mary))
   /
  /  
VP(\lambda x \text{ Loves}(x, mary))
   /
  /   
NP(John)  
   /
  / 
Name(John) Verb(\lambda y \lambda x \text{ Loves}(x,y))
    /
   / 
John  loves
    /
   / 
John  Mary
```
Semantics of $E_1$

- A more complex sentence "Every agent smells a wumpus"

  - Its semantics:
    \[
    \forall a \, \text{Agent}(a) \Rightarrow \exists w \, \text{Wumpus}(w) \land \\
    \exists e \, e \in \text{Perceive}(a, w, \text{Nose}) \land \text{During}(\text{Now}, e)
    \]

  - NP: $NP(\forall a \, \text{Agent}(a) \Rightarrow ...)$

  - VP: $VP(\exists w \, \text{Wumpus}(w) \land \\
    \exists e \, e \in \text{Perceive}(..., w, \text{Nose}) \land \text{During}(\text{Now}, e))$

- Hard to do plug-in due to mutual references

- Introduce quasi-logical form bridging syntax and semantics

  - Include first-order predicate logic, lambda expressions, and a quantified term
    
    Eg: $[\forall a \, \text{Agent}(a)]$ used as a logical term

  - Quantified terms can be used as arguments to predicates

  - "Every agent smells a wumpus" expressed in quasi-logic

    \[
    \exists e \, (e \in \text{Perceive}([\forall a \, \text{Agent}(a)], [\exists w \, \text{Wumpus}(w)], \text{Nose}) \land \text{During}(\text{Now}, e))
    \]
Semantics of $E_1$, cont.

- One can summarize basic steps involved in obtaining quasi-logical form for semantic interpretation

- E.g., the semantic parse tree for the sentence "Every agent smells a wumpus"
Semantics of $E_1$, cont.

• Grammar $E_2$, which is $E_1$ with semantics, is below

$$S(\text{rel}(\text{obj})) \rightarrow \text{NP(\text{obj}) \ VP(\text{rel})}$$
$$S(\text{conj}(\text{sem}_1,\text{sem}_2)) \rightarrow S(\text{sem}_1) \ \text{Conjunction(\text{conj}) \ S(\text{sem}_2)}$$

$$\text{NP(\text{sem})} \rightarrow \text{Pronoun(\text{sem})}$$
$$\text{NP(\text{sem})} \rightarrow \text{Name(\text{sem})}$$
$$\text{NP([q x \text{sem}(\text{x})])} \rightarrow \text{Article(q) \ Noun(\text{sem})}$$
$$\text{NP([q x \text{obj} \land \text{rel}(\text{x})])} \rightarrow \text{NP([q x \text{obj}]) \ PP(\text{rel})}$$
$$\text{NP([q x \text{obj} \land \text{rel}(\text{x})])} \rightarrow \text{NP([q x \text{obj}]) \ RelClause(\text{rel})}$$
$$\text{NP([\text{sem}_1,\text{sem}_2])} \rightarrow \text{Digit(\text{sem}_1) \ Digit(\text{sem}_2)}$$

**VP rules for subcategorization**

$$\text{VP(\text{sem})} \rightarrow \text{Verb(\text{sem})}$$
$$\text{VP(\text{rel}(\text{obj}))} \rightarrow \text{VP(\text{rel}) \ NP(\text{obj})}$$
$$\text{VP(\text{sem}_1(\text{sem}_2))} \rightarrow \text{VP(\text{sem}_1) \ Adjective(\text{sem}_2)}$$
$$\text{VP(\text{sem}_1(\text{sem}_2))} \rightarrow \text{VP(\text{sem}_1) \ PP(\text{sem}_2)}$$

**VP rules for adjuncts (such as time and place for verbs)**

$$\text{VP(\lambda x \text{sem}_1(x) \land \text{sem}_2(\text{EVENT-VAR(\text{sem}_1)}))} \rightarrow \text{VP(\text{sem}_1) \ PP(\text{sem}_2)}$$
$$\text{VP(\lambda x \text{sem}_1(x) \land \text{sem}_2(\text{EVENT-VAR(\text{sem}_1)}))} \rightarrow \text{VP(\text{sem}_1) \ Adverb(\text{sem}_2)}$$

$$\text{RelClause(\text{sem})} \rightarrow \text{that} \ \text{VP(\text{sem})}$$

$$\text{PP(\lambda x \text{rel}(\text{x,\text{obj}))} \rightarrow \text{Preposition(\text{rel}) \ NP(\text{obj})}$$

• **Further combination with case and subcategorization**
Convert Quasi-logical Form to Logical Form

- \( \forall x P(x) \) within a quasi-logical form QLF becomes \( \forall x P(x) \implies QLF \)
  - The term within QLF is replaced by \( x \)

- \( \exists x P(x) \) within QLF becomes \( \exists x P(x) \land QLF \)

- Example: "John loves everyone"
  - \( \exists e e \in Loves(John,[\forall p Person(p)]) \) converts to \( \forall p Person(p) \implies Loves(John, p) \)
Pragmatic Interpretation

• **Indexicals**: phrases that refer to the current situation
  
  • Example: "I was in Dayton yesterday"  
    "I" and "yesterday" are indexicals, whose interpretations depend on who uttered the sentence and when

  • Use Skolem functions in place of indexicals, which can later be filled in through situational inference about a speech act, such as information about speaker and time of the action

• **Anaphora**: phrases that refer to objects mentioned previously

  • Example: "Mary was sick. She went to a hospital."  
    - Who is *she*?

  • Anaphoric inference requires processing of previous sentences and thorough understanding

  • A more difficult example: "After John proposed to Mary, they found a priest and got married. For the honeymoon, they went to Hawaii".  
    - Who are *they*? What is *the honeymoon*?

• Some consider finding intentions of a query as part of pragmatic interpretation

  • Example: "Do you know the time?"
Disambiguation

- Most utterances are ambiguous
  
  - A few examples from newspaper headlines

  *Squad helps dog bite victim*
  *Red-hot star to wed astronomer*
  *Helicopter powered by human flies*
  *Once-sagging cloth diaper industry saved by full dumps*

  - Strong context dependence

  *He is taking care of this street*

    - for police
    - for mail carrier
    - for gang member

- Sources of ambiguity

  - **Lexical ambiguity**: multiple meanings for one word
  - **Syntactic ambiguity**: multiple parse trees for one sentence. *Ex: Ed went to school with a friend*
  - **Semantic ambiguity**. *Ex: He is the printer man*
  - **Referential ambiguity**. Pronouns, etc.
  - **Pragmatic ambiguity**. *Ex: I'll meet you next Thursday*
  - **Vagueness**. *Ex: The dish is spicy*

- Ambiguity is not necessarily bad
Disambiguation, cont.

- Disambiguation can be formulated as diagnostic inference

- It requires a combination of four models
  
  - A world model: the prior probability for a fact
  - A mental model: the probability that the speaker intends to communicate this fact, given that it occurs
  - A language model: the probability of choosing a certain string of words, given speaker's intention
  - An acoustic model: the probability of choosing a certain sequence of phones, given words

- It works much like in speech recognition
Applications of NLP

• Machine translation

• Human-computer dialogue and interface
  
  • ELIZA (Weizenbaum, 1965): keywords-based NL dialogue system, with little understanding
  • LUNAR (Woods, 1973): answering NL questions, about lunar rock and soil samples
  • CHAT (Pereira, 1983): answering NL queries about geography. An excerpt:

    Q: Which countries are bordered by two seas?
    A: Egypt, Iran, Israel, Saudi Arabia and Turkey
    Q: What are the countries from which a river flows into the Black sea?
    A: Romania, Soviet Union
    Q: What is the total area of countries south of the equator and not in Australasia?
    A: 10,228,000 square miles
    Q: What is the ocean that borders African countries and that borders Asian countries?
    A: Indian Ocean
Applications of NLP, cont.

• PEGASUS (Zue, et al., 1994): speech and NL understanding system for on-line air travel planning. An example:

  Traveller: I want to go from Boston to San Francisco
  PEGASUS: What date will you be travelling on?
  Traveller: October 20th

  .......
  Traveller further provided the following information:
  nonstop, cheapest fare, returning on Sunday, etc.,
  through the dialogue

  PEGASUS provided a confirmed reservation,
  satisfying all the above demands

• Information Retrieval

• Database access using natural language input
• Content-based document retrieval (e.g.: find all stories about Bill Clinton)
• Web-based search
Natural Language Processing

Summary

• Big successes in small domains

• Big market for NLU products

• NLP is AI-hard
  • Huge amount of knowledge about the world is required
  • A good model for the listener is required
  • Demand for communication efficiency leads to large contextual and social effects