A framework for symbolic communication in sensor networks

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<th>Agenda</th>
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<td>2. The model</td>
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<td>3. Simulation experiments</td>
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Adaptive language group

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- How did language first come into existence?
- What mechanisms underlie the language capacity?
- How can we provide computers or other artifacts with language-like capabilities?

People

Principal investigators:
Charles E. Taylor     Edward P. Stabler
Biology, UCLA        Linguistics, UCLA

Lab members:
Yoosook Lee           Greg Kobele
Yuan Yao              Ying Lin
Travis C. Collier     Edgar E. Vallejo
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Research topics

- Emergence of language
- Language learning
- Language evolution

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Methodology

- Language is viewed as a complex adaptive system
- Bottom-up approach
- Computer modelling
Computer modelling of language

1. Population of agents
2. Agent architecture
3. Interaction protocol
4. Measurements for success in communication

Applications

- Natural language processing
- Distributed autonomous vehicles
- Distributed sensors arrays
Why distributed sensor arrays?

- Appropriate domain for validating language theories
- Wide range of emerging applications

Personal research interests

- Lexicon and concept formation
- Language evolution and adaptation
Figure 1: Robot wandering in a room

Table 1: Robot movement data set
Results

<table>
<thead>
<tr>
<th>Behavior</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall following 1</td>
<td>a</td>
</tr>
<tr>
<td>Wall following 2</td>
<td>a</td>
</tr>
<tr>
<td>Random walking 1</td>
<td>b</td>
</tr>
<tr>
<td>Random walking 2</td>
<td>b</td>
</tr>
</tbody>
</table>

Table 2: Emergent categorization

Language evolution and adaptation

- Language capacity possess an innate component
- Learning modifies the evolutionary trajectories of language
- Learning allows the genetic assimilation of certain language mechanisms
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Graph showing frequency in population over generations for evolved strategies:
- Imitators
- Calculators
- Saussurians
- Randoms

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Graph showing frequency in population over generations for undetermined traits:
- Undetermined signals
- Undetermined objects
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### Conditions for symbolic communication

- Concept formation
- Symbol grounding
- Symbol acquisition
A sensor network is a 4-tuple $G = \{V, E, P_V, P_E\}$ where:

1. $V$ is a set of nodes
2. $E \subseteq V \times V$ is a set of links
3. $P_V$ is a set of functions related to properties of $V$
4. $P_E$ is a set of functions related to properties of $E$

(Zhao and Guibas, 2004)

A node is a 8-tuple $v = \{P, O, C, S, \delta, \phi, \tau, \rho\}$ where:

1. $P$ is set of sensors
2. $O$ is set of feature vectors
3. $C$ is a set of concepts
4. $S$ is a set of symbols
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5. $\delta : P \rightarrow O$ is the detection function
6. $\phi : O \rightarrow C$ is the categorization function
7. $\tau : C \rightarrow S$ is the transmission function
8. $\rho : S \rightarrow C$ is the reception function

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Successful symbolic communication

A node $v_1 = \{P_1, O_1, C_1, S_1, \delta_1, \phi_1, \tau_1, \rho_1\}$ communicates successfully to a node $v_2 = \{P_2, O_2, C_2, S_2, \delta_2, \phi_2, \tau_2, \rho_2\}$ given a feature vector $o \in O$ if the following conditions are satisfied
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1. \( \phi_1(o) = c_i \)
2. \( \tau_1(c_i) = s_i \)
3. \( \rho_2(s_i) = c_j \)
4. \( c_i = c_j \)

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**Key considerations**

- Each node talks only to its neighbors
- Communication is by broadcast
- Node layout follows an arbitrary, but fixed topology
**Vector quantization**

Figure 2: The vector quantization procedure

**Concept formation**

Figure 3: Simple competitive learning network
**Winner**

The *winner* is the concept $c_i^*$ with the weight vector $w_i^*$ that is “closest” to the feature vector $o$

$$ |w_i^* - o| \leq |w_i - o| \text{ (for all } i) $$

---

**Learning vector quantization**

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$$ \Delta w_{i^*k} = \begin{cases} 
+\eta(o_k - w_{i^*k}) & \text{if communication is successful} \\
-\eta(o_k - w_{i^*k}) & \text{if communication is unsuccessful} 
\end{cases} $$

where $\eta \in [0, 1]$ is the learning rate
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Figure 4: The learning procedure $t = 1$

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Figure 5: The learning procedure $t = 2$
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Figure 6: The SITEX00 experiment
<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clutter</td>
<td>Background</td>
</tr>
<tr>
<td>POV</td>
<td>Light Wheel</td>
</tr>
<tr>
<td>HMMWV</td>
<td>Light Wheel</td>
</tr>
<tr>
<td>5-Ton Truck</td>
<td>Heavy Wheel</td>
</tr>
<tr>
<td>Dragon Wagon</td>
<td>Heavy Wheel</td>
</tr>
<tr>
<td>LAV</td>
<td>Heavy Wheel</td>
</tr>
<tr>
<td>AAV</td>
<td>Track</td>
</tr>
</tbody>
</table>

Table 3: SITEX00 vehicles

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Training</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>POV</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>DW</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>LAV</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>AAV</td>
<td>20</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 4: Seismic data sets
### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodes</td>
<td>16-64</td>
</tr>
<tr>
<td>Neighbors</td>
<td>2-8</td>
</tr>
<tr>
<td>Categories</td>
<td>4</td>
</tr>
<tr>
<td>Symbols</td>
<td>4</td>
</tr>
<tr>
<td>Learning rate</td>
<td>0.01-0.1</td>
</tr>
<tr>
<td>Simulation steps</td>
<td>100-2000</td>
</tr>
</tbody>
</table>

Table 5: Parameters for the simulations

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Figure 7: Classification results

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<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Training</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>POV</td>
<td>90 %</td>
<td>90 %</td>
</tr>
<tr>
<td>DW</td>
<td>55 %</td>
<td>40 %</td>
</tr>
<tr>
<td>LAV</td>
<td>100 %</td>
<td>100 %</td>
</tr>
<tr>
<td>AAV</td>
<td>75 %</td>
<td>70 %</td>
</tr>
</tbody>
</table>

Table 6: Classification
Results

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>False positives</th>
<th>False negatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>POV</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>DW</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>LAV</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>AAV</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 7: Misclassification in validation

Figure 8: Communication results
Limitations

- Large numbers of examples are required for training
- High volumes of sensor data are transmitted during training

Symbol grounding

<table>
<thead>
<tr>
<th>Transmission</th>
<th>Reception</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agent 1</td>
<td></td>
</tr>
<tr>
<td>$s_1$ $s_2$ $s_3$</td>
<td>$c_1$ $c_2$ $c_3$</td>
</tr>
<tr>
<td>$c_1$ 0 0 1</td>
<td>$s_1$ 0 0 1</td>
</tr>
<tr>
<td>$c_2$ 1 0 0</td>
<td>$s_2$ 1 0 0</td>
</tr>
<tr>
<td>$c_3$ 0 1 0</td>
<td>$s_3$ 0 1 0</td>
</tr>
</tbody>
</table>

| Agent 2      |           |
| $s_1$ $s_2$ $s_3$ | $c_1$ $c_2$ $c_3$ |
| $c_1$ 1 0 0 | $s_1$ 0 1 0 |
| $c_2$ 0 1 0 | $s_2$ 0 0 1 |
| $c_3$ 0 0 1 | $s_3$ 1 0 0 |
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Transmission

<table>
<thead>
<tr>
<th></th>
<th>s_1</th>
<th>s_2</th>
<th>s_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>c_1</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>c_2</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>c_3</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Reception

<table>
<thead>
<tr>
<th></th>
<th>c_1</th>
<th>c_2</th>
<th>c_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>s_1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>s_2</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>s_3</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Agent 1

Agent 2

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Graph with nodes labeled s_1, s_2, s_3, o_1, o_2, o_3, o_4, s_i, w_ij, c_j, w_jk, o_k.
Saussurean learning

1. Imitate the transmission function of other nodes
2. Adjust the reception function in such a way that a communication to himself would be successful.

Results

Preliminary simulations showed a considerable reduction in communication events required to achieve coordination in communication.
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**Next steps**

- Classification
  - Conscience mechanisms
  - Supervised learning
- Language
  - Larger lexicon
  - Compositionality
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- Other applications
  - Habitat monitoring
  - Localization and tracking
  - Attribute based routing

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Conclusions

- Meaningful categorization and coordinated symbolic communication can emerge as self-organizing processes in sensor networks
- Symbolic communication holds promise for reducing the bandwidth requirements for sensor networks
- The understanding of the categorization and generalization capabilities of the model requires further investigations

References


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**Links**

- Adaptive Language Group  
  [http://taylor0.biology.ucla.edu/al](http://taylor0.biology.ucla.edu/al)

- Collaborative Signal and Information Processing  
  [http://aicip.ece.utk.edu/research/mufashion.htm](http://aicip.ece.utk.edu/research/mufashion.htm)

- Sensor Networks Research Group  
  [http://www.ece.wisc.edu/ sensit/](http://www.ece.wisc.edu/ sensit/)
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