Efficient Semantic Communication & Compatible Beliefs

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Part I: Background on Semantic Communication

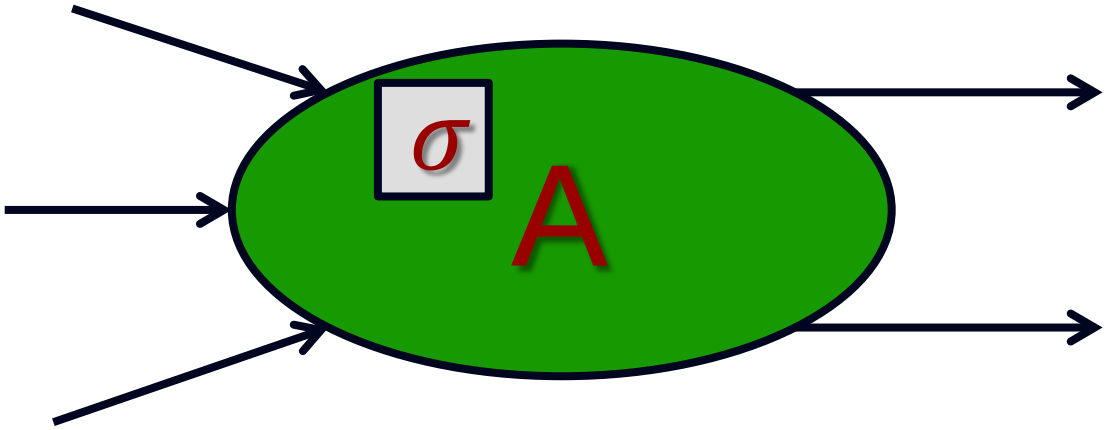
Semantic Communication: Motivation

- First era of communication: Reliable Wires
  - Essentially done: wires are very reliable; performance can be enhanced (maybe) quantitatively but not qualitatively.
- Can we get endpoints to also be reliable?
  - Modern systems have “smart” endpoints.
  - Smart implies capability.
  - Smart implies diversity.
    - But diversity implies (potential) misunderstanding.
- Semantic Communication [Goldreich,Juba+S ‘10]
  - Detect/Correct Misunderstanding.

Semantic Communication: Model - I

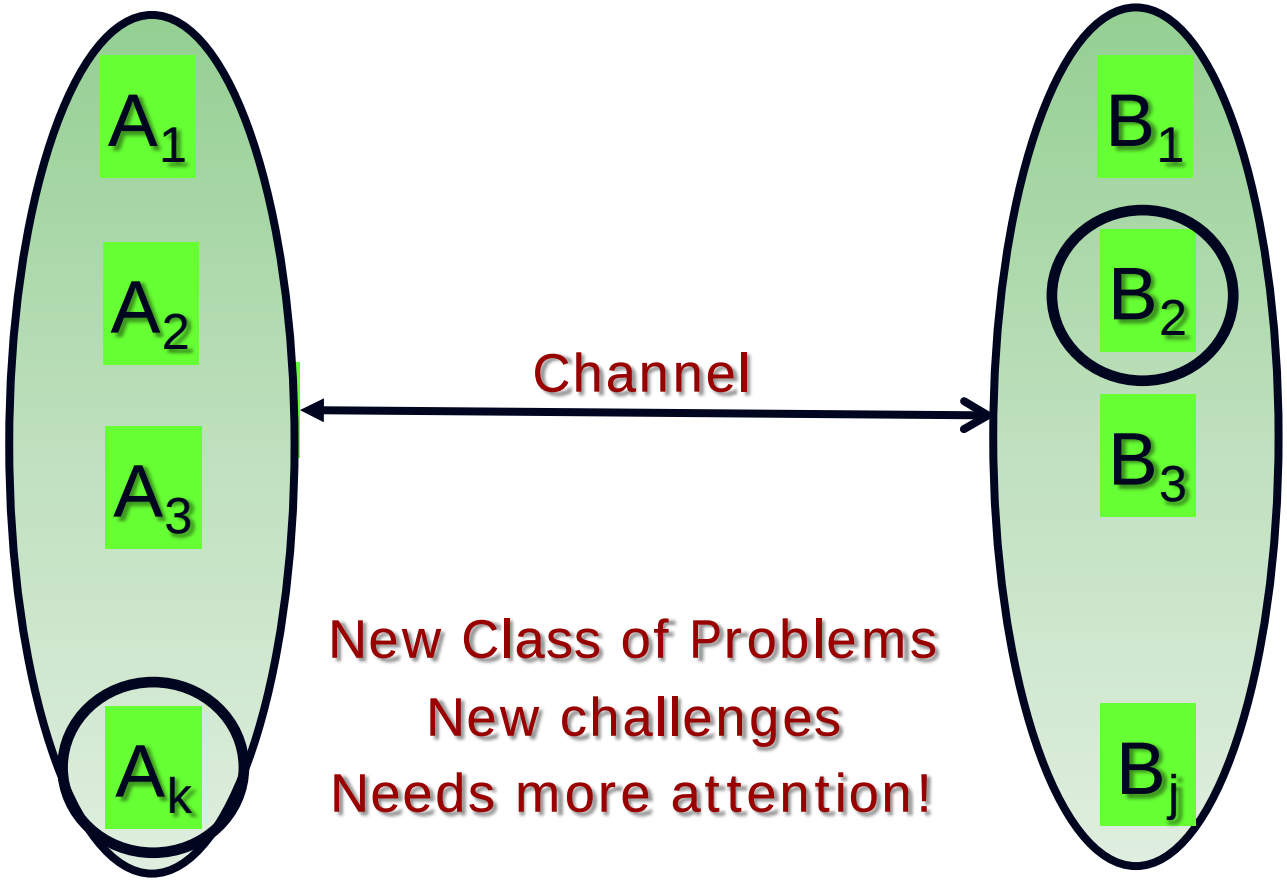
- General Model: Two "smart" interacting agents: User and Server; User wishes to accomplish some Goal, and Server is trying to help User.

- Interacting agents?
  - Agent: State x Inputs → New State x Outputs



Semantic Communication: Model - II

- Uncertainty about the receiver:
  (User doesn't know server; vice versa).



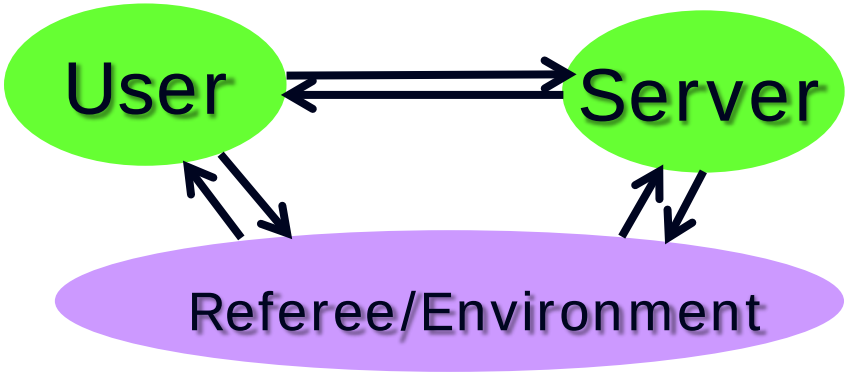
Semantic Communication: Model - IIIa

- Goal-oriented communication:
  - User attempting to reach some goal.
  - How to model this?

- Classical approaches:
  - Some function of state of user, or some function of transcript of interaction etc.
  - Fails in "semantic/uncertainty" setting.

  - Our [GJS] approach: Introduce a (hypothetical) third agent.

Semantic Communication: Model - IIIb



- Referee
  - Poses tasks to user.
  - Judges success.
- Generic Goal specified by $(R, B, \check{U}, \check{S})$
  - R = Referee (just another agent)
  - B = Boolean Function determining if the state evolution of the referee reflects successful achievement of goal.
  - $\check{U}, \check{S}$ = Class of users/servers.
  - (All finitely specified)u
- Which goals can be achieved universally?

Basic Definitions: Helpfulness, Universality, Sensing

- What makes a server helpful?
  - S is G-helpful, if there exists a user who can achieve goal (efficiently) for every starting state of S.
- Universality:
  - User U is universal if it achieves G with every G-helpful server.
- Sensing?
  - Roughly, Goal G can be sensed if there exists an efficient algorithm that scan use (with their inputs) to see if Referee will accept.

Principal Thesis and Theorem

- Thesis: Every Goal of communication captured in our model (by appropriate choice of $(R, B, \check{U}, \check{S})$)

- Theorem: Goal is universally achievable if and only if there exists a sensing function (for "one-shot" goals).

Proof + Insights

- Positive results by enumeration.
- Negative? Mostly by definition.

- Insights:
  - Servers should know how to be “interrupted”. (How else can they function independent of complexity of their own state?)
  - Short “interrupt” signal helps.
  - Goals should be “sense”ible.

Part II: Beliefs & Compatibility

Motivation

- Why does natural (human) communication differ so much from designed communication?
  - Languages are ambiguous
  - They violate their own grammatical rules
  - They are needlessly redundant at times, and noisily compressed at other times?
- Can we use information theory to explain such phenomena (departures from information theory)?
  - Use fact that natural communication deals with uncertainty about server.

Does Semantic Communication help?

- Pros:
  - Does deal with uncertainty about servers.
- Cons:
  - Seems quite inefficient (user is enumerating all servers?).
  - Seems to throw away all “knowledge” about server (that might yield efficiency).
  - Is universality really a goal? Is it not at odds with “use of knowledge”

Beliefs in Semantic Communication

- Addition to the model, to include beliefs of user and server.
- Each server and user has associated belief.
- Belief of Server S = D_S = Distribution on Users
- Belief of User U = D_U = Distribution on Servers
- Compatibility?

Compatibility of Beliefs

- For user U, Consider the distribution $\overline{D}_U$ on users obtained as follows:
  - Sample Server S' from distribution D_U
  - Sample user U' from distribution $D_{S'}$

- Compatibility of user U with server S:
  - Measured by "proximity" of $\overline{D}_U$ with D_S
  - Our choice: U is α-compatible with S if

$$1 - \frac{1}{2}|\overline{D}_U - D_S|_1 \geq \alpha$$

Server Performance?

- What does it mean that server has a belief about users? How is it reflected in server's actions?

- Performance of server S (roughly) for goal G
  = $\mathrm{Perf}_G(S)$
    = Expected time that user U chosen from distribution D_S takes to achieve goal G.

- Well-designed server should be "broad-minded" i.e., efficient against a broad distribution of users.

Universality of Users under Beliefs

- Universal User U now has beliefs on servers.
- Can expect user to do well not only on servers in the support of its beliefs, but a potentially broader set: namely servers with compatible beliefs.
- Theorem [Juba, S '11]: ∀ U, ∃ a universal user U' with same beliefs as U, whose time to achieve goal G with server S is $\frac{O(1)}{\alpha(U,S)}\mathrm{Perf}_G(S)$, provided the goal allows universal users.

Consequences/Conclusions

- Universality of communication is not at odds with efficiency.
- Efficiency comes with compatibility of communicating players.
- Universality takes care of possibility of misunderstanding, at an affordable price.

Thank You