Universal Semantic Communication

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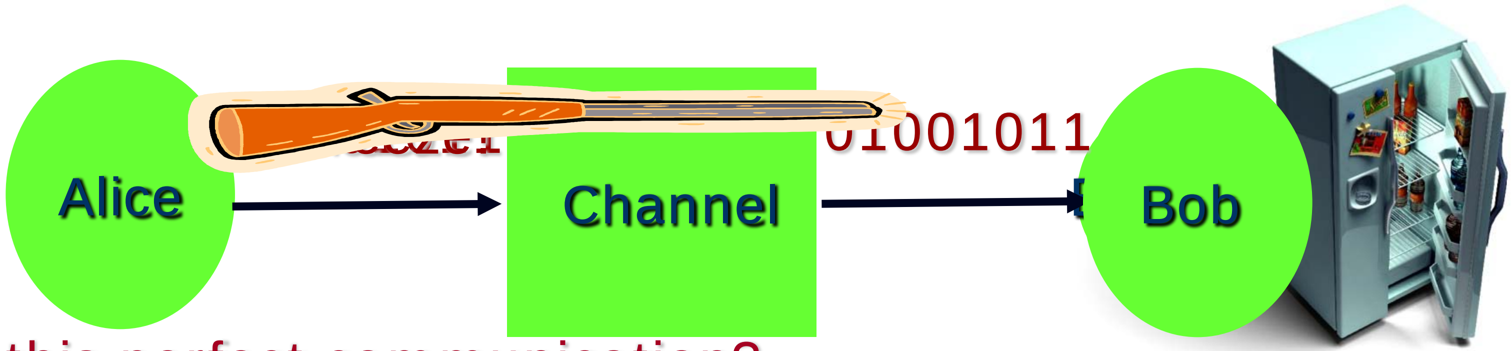
The Meaning of Bits



- Is this perfect communication?

- What if Alice is trying to send instructions?
  - Aka, an algorithm
  - Does Bob understand the correct algorithm?
  - What if Alice and Bob speak in different (programming) languages?

- Question important theoretically, and in practice of computing/communication.

This talk

- Meaning of information: Meaning via Goal-oriented communication
- Example: Computational Goal
- Going Beyond Example
  - General Goals
  - Efficiency via compatible beliefs
  - Semantics in general

Meaning? A first attempt

- Sender is sending instructions/algorithms
  - Can we understand/execute it?
- Answer: NO!
  - Under sufficient richness of language (any finite length string means anything), can never achieve this state.
- So what should we try to achieve?

Communications as a means to an end

- Communication is painful:
  - Unreliability of communication medium, misunderstanding, loss of privacy, secrecy.
- So why do it?
  - Must be some compensating gain.

- Communication should strive to achieve some goal.
- "Understanding Meaning" is when we can achieve the goal in the absence of common language.

Part II: Computational Motivation

Computational Goal for Bob

- Why does Bob want to learn algorithm?
  - Presumably to compute some function f

    (A is expected to compute this function.)
  - Lets focus on the function f.

- Setting:
  - Bob is prob. poly time bounded.
  - Alice is computationally unbounded, does not speak same language as Bob, but is "helpful".
  - What kind of functions f?
    - E.g., uncomputable, PSPACE, NP, P?

Setup

~~Bob~~ User

~~Alice~~ Server

f(x) = 0/1?

R ← $$$

q_1

Different from interactions in cryptography/security:

There, User does not trust Server, while here he does not understand her.

Computes P(x,R,a_1,…,a_k)

Hopefully P(x,…) = f(x)!

Intelligence & Cooperation?

- For User to have a non-trivial interaction, Server must be:
  - Intelligent: Capable of computing f(x).
  - Cooperative: Must communicate this to User.
- Formally:
  - Server S is <u>helpful</u> (for f) if

    ∃ some (other) user U' s.t.

    ∀ x, starting states σ of the server

    (U'(x) ↔ S(σ)) outputs f(x)

Successful universal communication

- Universality: Universal User U should be able to talk to any (every) helpful server S to compute f.

- Formally:
  - U is f-universal, if
    $\forall$ helpful S, $\forall \sigma$, $\forall$ x
    $$(U(x) \leftrightarrow S(\sigma)) = f(x) \text{ (w.h.p.)}$$

- What happens if S is not helpful?
  - Paranoid view $\Rightarrow$ output "f(x)" or "?"
  - Benign view $\Rightarrow$ Don't care (everyone is helpful)

Main Theorems [Juba & S. ‘08]

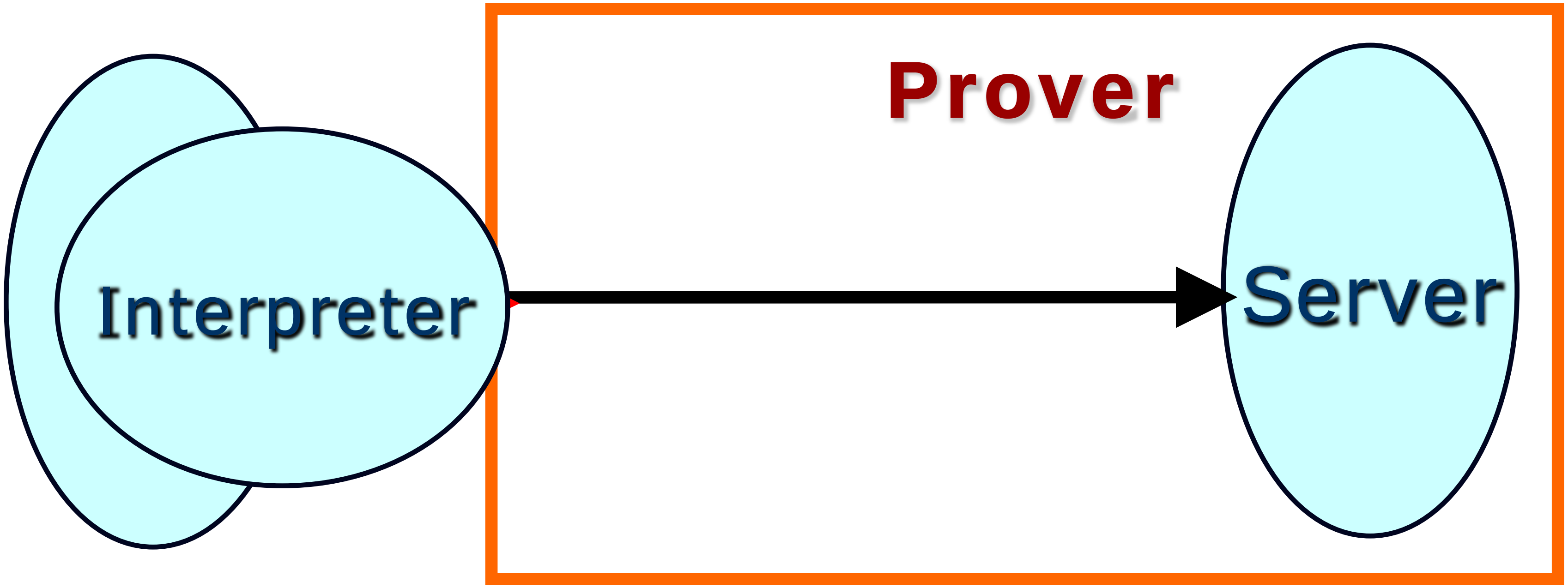
- If f is PSPACE-complete, then there exists a f-universal user who runs in probabilistic polynomial time.
  - Extends to checkable problems
    - (NP ∩ co-NP, breaking cryptosystems)
    - S not helpful ⇒ output is safe
- Conversely, if there exists a f-universal user, then f is PSPACE-computable.
  - Scope of computation by communication is limited by misunderstanding (alone).

Implications

- No universal communication protocol ☹
  - If there were, should have been able to solve every problem (not just (PSPACE) computable ones).
- But there is gain in communication:
  - Can solve more complex problems than on one's own, but not every such problem.
- Resolving misunderstanding? Learning Language?
  - Formally No! No such guarantee.
  - Functionally Yes! If not, how can user solve such hard problems?

Few words about the proof: Positive result

- Positive result: Enumeration + Interactive Proofs
- Guess: Interpreter; $b \in \{0,1\}$ (value of $f(x)$)



- Proof works $\Rightarrow f(x) = b$.
- If it doesn't $\Rightarrow$ {Interpreter or b} incorrect.

Proof of Negative Result

- L not in PSPACE ⇒ User makes mistakes.
  - Suppose Server answers every question so as to minimize the conversation length.
    - (Reasonable effect of misunderstanding).
  - Conversation comes to end quickly.
  - User has to decide.
  - Conversation + Decision simulatable in PSPACE (since Server's strategy can be computed in PSPACE).
  - f is not PSPACE-computable ⇒ User wrong.
  - Warning: Only leads to finitely many mistakes.

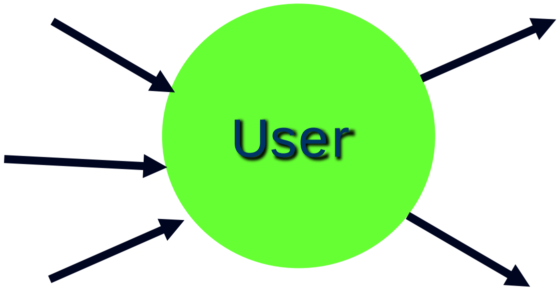
Part III: Beyond Example
III.1 General Goals

General Goals

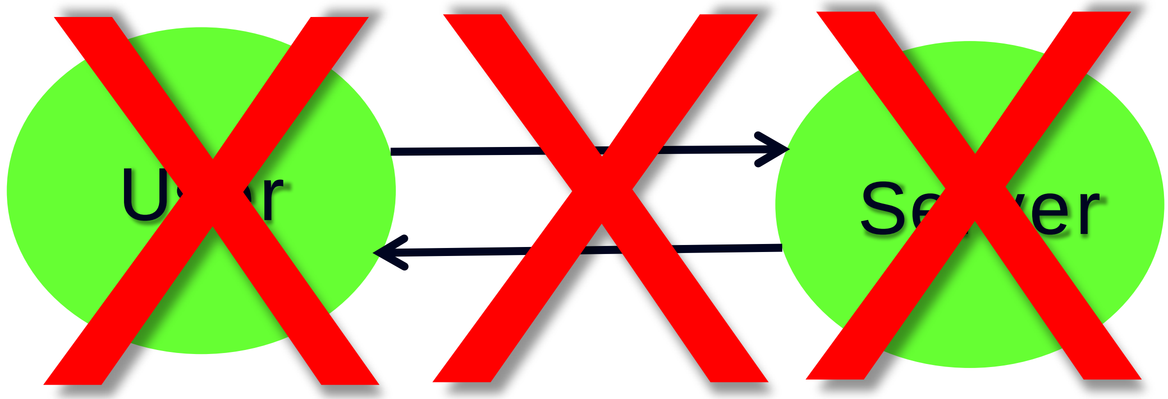
- Limitations of example:
  - Gain is computational
  - Gain possible only if Server more powerful than User (asymmetric).
- Communication (presumably) serves many other goals
  - What are they?
  - Can we capture them all in single definition?
  - Usual definitions (via transcript of interaction) inadequate in "semantic" setting.

Modelling User/Interacting agents

- (standard AI model)
- User has state and input/output wires.
  - Defined by the map from current state and input signals to new state and output signals.



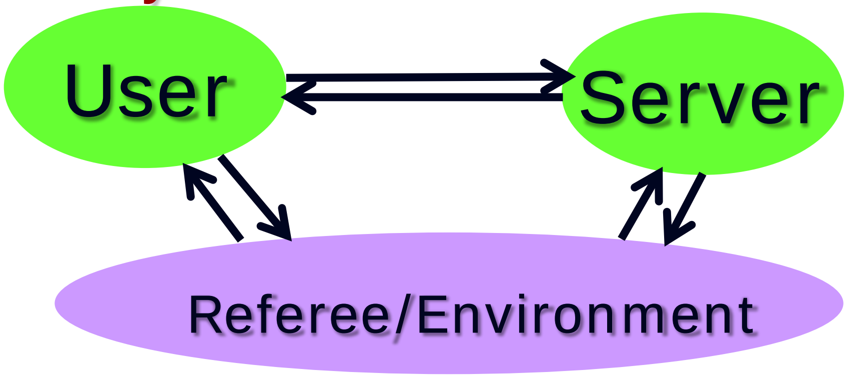
Generic Goal?



- Goal = function of ?
  - User? – But user wishes to change actions to achieve universality!
  - Server? – But server also may change behaviour to be helpful!
  - Transcript of interaction? – How do we account for the many different languages?

Generic Goals

- Key Idea: Introduce 3rd entity: Referee
  - Poses tasks to user.
  - Judges success.



- Generic Goal specified by
  - Referee (just another agent)
  - Boolean Function determining if the state evolution of the referee reflects successful achievement of goal.
  - Class of users/servers.

Results in "General Setting"

- New concept: "Sensing"
  - Ability of User to predict Referee's verdict.
    - Computational example shows this can be achieved in non-trivial ways.

- Relatively straightforward generalization of computational example:
  - Sensing (is necessary and) sufficient for achieving goals in semantic setting.

Part III: Beyond Example

III.2: Efficient Learning?

The Enumeration Bottleneck

- Enumeration of users seems inefficient, can we get around it?
  - Formally, in k time, User can only explore O(k) other users.
  - Bad News:
    - Provable bottleneck: Server could use passwords (of length log k).
  - Good News:
    - Can formalize this as only bottleneck …
      - using "Beliefs, Compatibility"

Broadmindedness, Compatible beliefs:

- Beliefs of server S:
  - Expects users chosen from distribution X.
  - Allows "typical" user to reach goal in time T.
    - # such users may be exponential
- Beliefs of user U:
  - Anticipates some distribution Y on users that the server is trying to serve.
- Compatibility: $K = (1 - |X - Y|_{TV})$
- Theorem[JS]: U can achieve goal in time poly(T/K).

Part III: Beyond Example

III.3: Semantics?

Semantic Communication

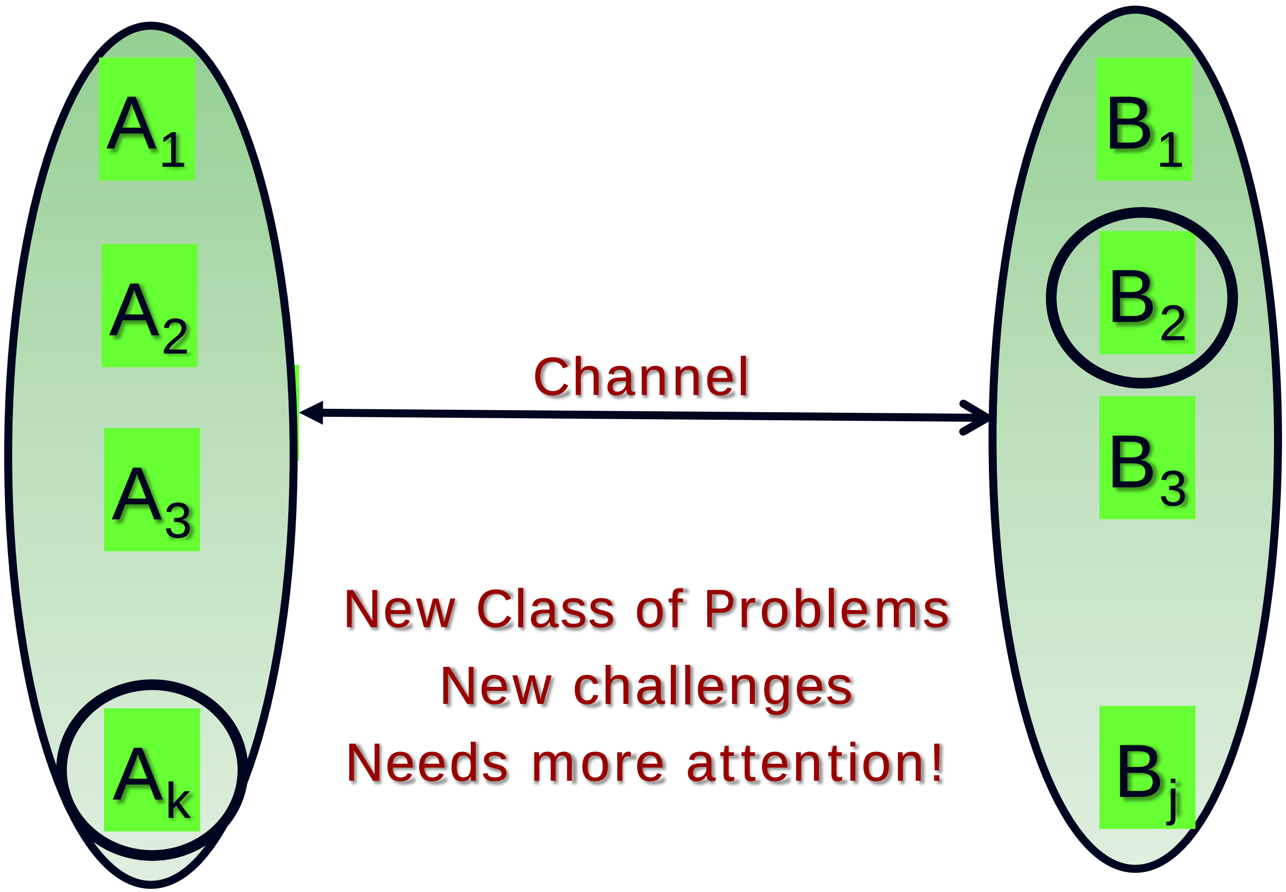
- Origins: The Gap between Turing and Shannon
  - Turing counts on reliable communication
  - Shannon counts on general computation
  - Separating theories was essential to initial progress.

- Modern technology:
  - Communication & Computation deeply intertwined.
  - Unreasonable to separate the two.
  - Semantic Communication: Prime example

A new model

Classical Shannon Model

Semantic Communication



New Class of Problems

New challenges

Needs more attention!

Compression in semantic setting

- Human-Human communication:
  - Robust, ambiguous, redundant.
- Explored in [Juba,Kalai,Khanna,S. ICS '11]
  - Thesis: Reason is diversity of audiences/their priors.
  - Leads to compression for "uncertain" priors.
  - Reveals same phenomena as natural languages:
    - Novel redundancy (increases with uncertainty), still ambiguous, but robust.

References

- Juba & S.
  - ECCC TR07-084: http://eccc.uni-trier.de/report/2007/084/
- Goldreich, Juba & S.
  - ECCC TR09-075: http://eccc.uni-trier.de/report/2009/075/
- Juba & S.
  - ICS '11: http://people.csail.mit.edu/madhu/papers/beliefs.pdf
- Juba, Kalai, Khanna & S.
  - ICS '11: http://people.csail.mit.edu/madhu/papers/ambiguity.pdf

Thank You!