Communication amid Uncertainty

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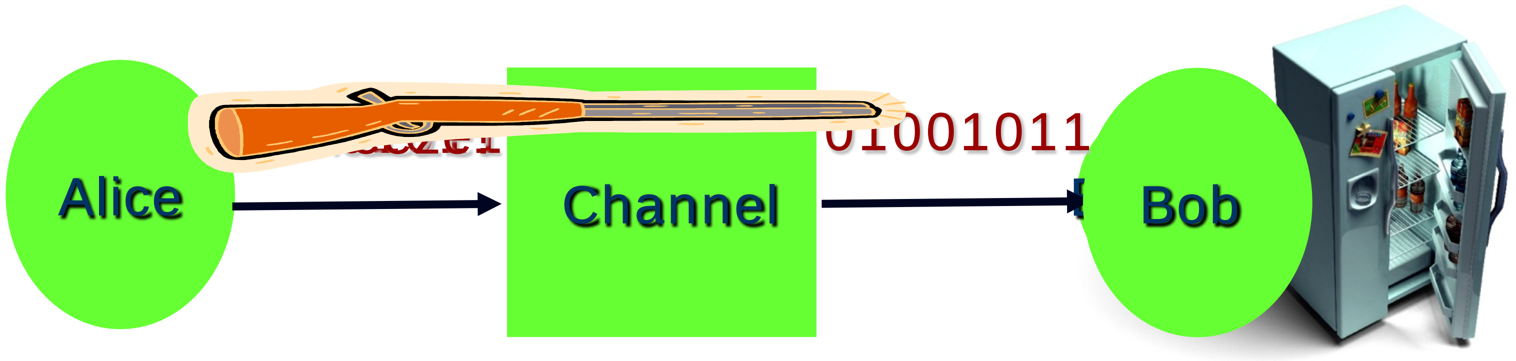
Based on:

- Universal Semantic Communication – Juba & S. (STOC 2008)
- Goal-Oriented Communication – Goldreich, Juba & S. (JACM 2012)
- Compression without a common prior … – Kalai, Khanna, Juba & S. (ICS 2011)
- Efficient Semantic Communication with Compatible Beliefs – Juba & S. (ICS 2011)

The Meaning of Bits

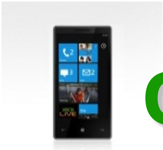


- Is this perfect communication?

- What if Alice is trying to send instructions?
  - In other words … an algorithm
  - Does Bob understand the correct algorithm?
  - What if Alice and Bob speak in different (programming) languages?
- Root Cause: Uncertainty …

Importance of semantics

- Why is semantics (relatively) important today?
  - Factor 1: Success of the Shannon program:
    - Reliability, in syntactic sense, has been achieved.
  - Factor 2: Communication vs. Computing.

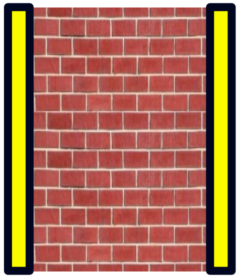


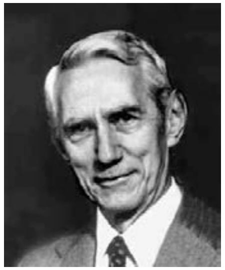
Communication vs. Computation

- Interdependent technologies: Neither can exist without other
- Technologies/Products/Commerce developed (mostly) independently.
  - Early products based on clean abstractions of the other.
  - Later versions added other capability as afterthought.
  - Today products … deeply integrated.
- Deep theories:

Well separated … and have stayed that way

Turing '36





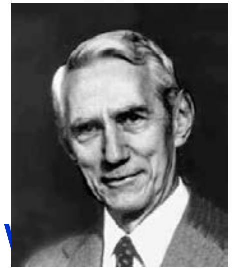
Shannon '48

Time for the theoretical wall to come down?

Consequences of the wall

- Computing theory:
  - Fundamental principle = Universality
  - You can program your computer to do whatever you want.

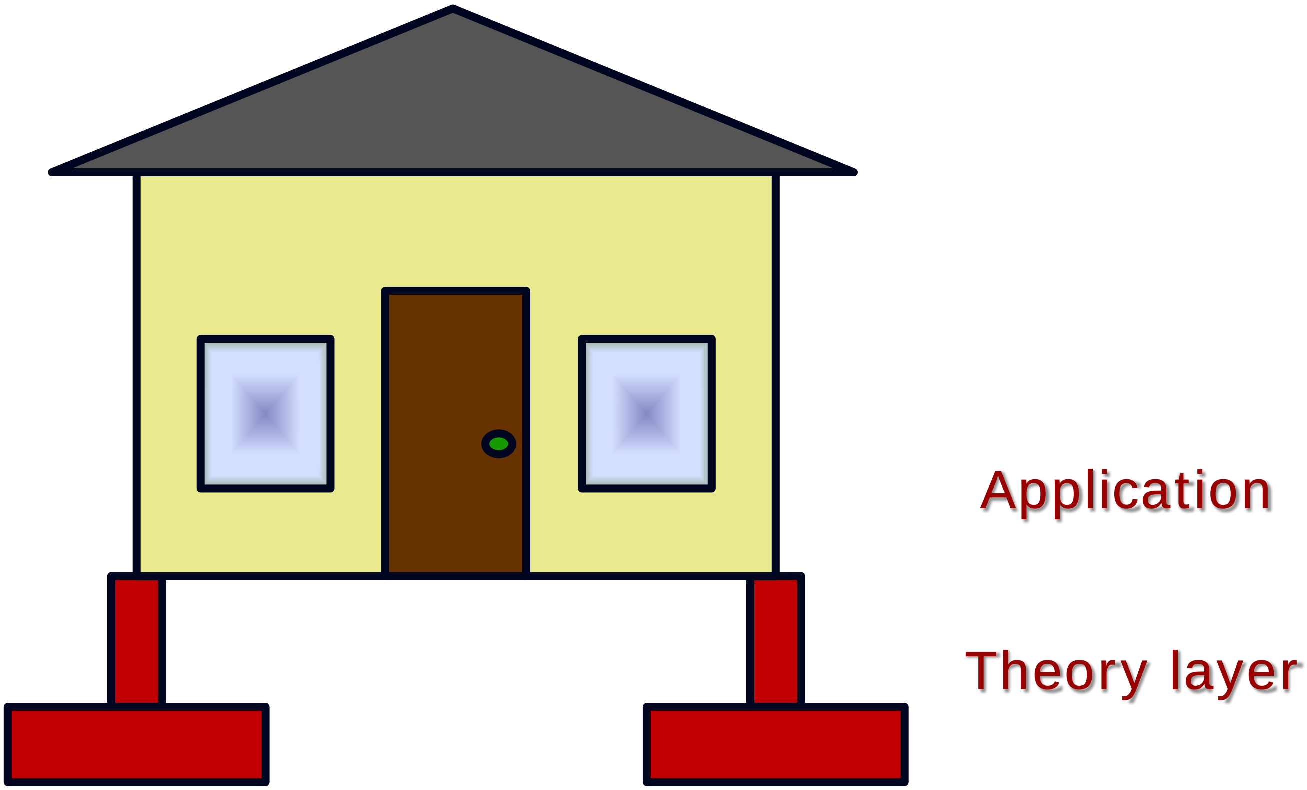
- Communication principle:
  - Centralized design (Encoder, Decoder, Compression, IPv4, TCP/IP).
  - You can NOT program your device!



- Contradiction! But does it matter?
  - Aren't communicating+computing systems just fine?
  - Theory matters!

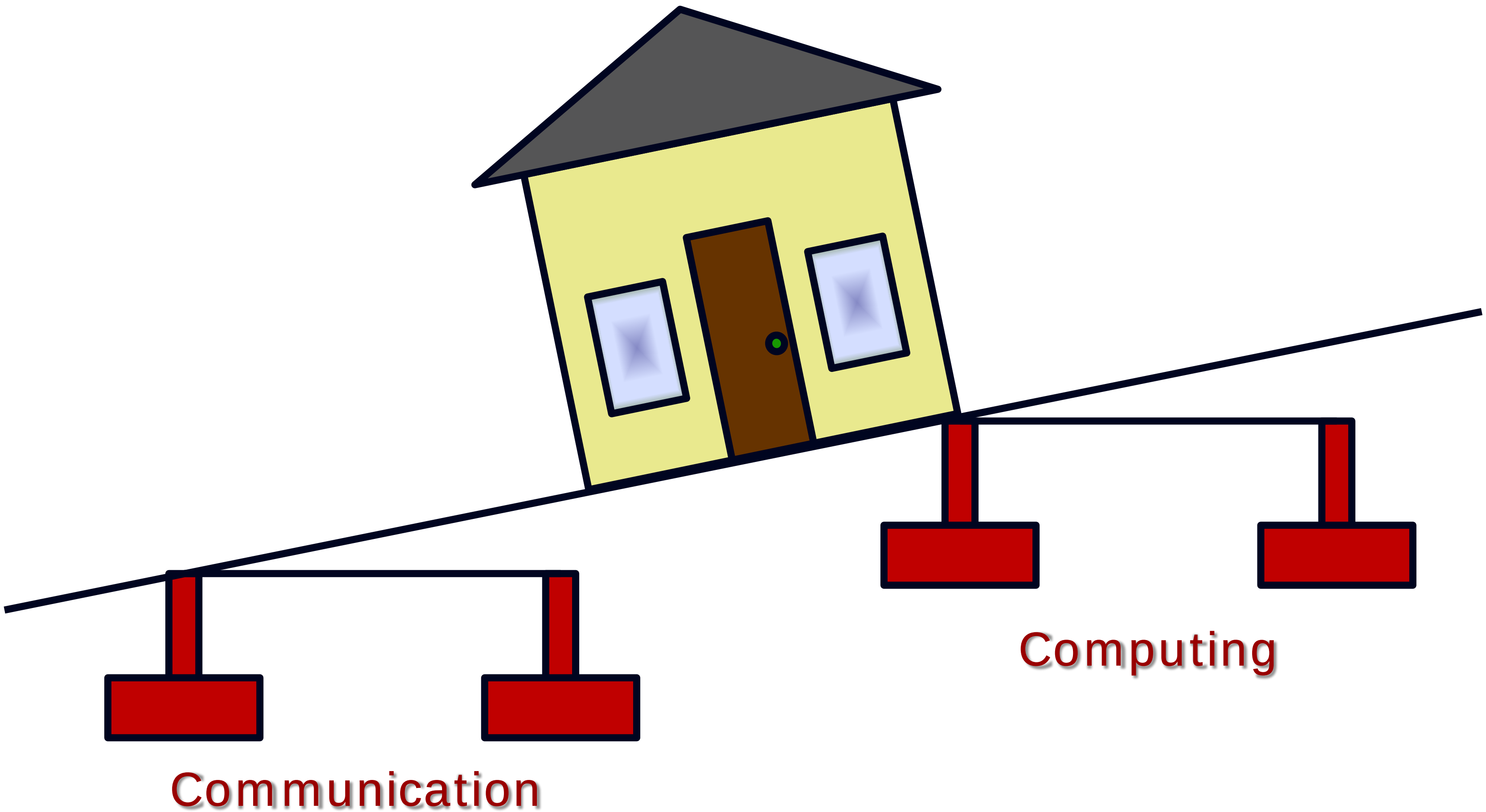
Role of theory?

- Ideally: Foundations of practice!



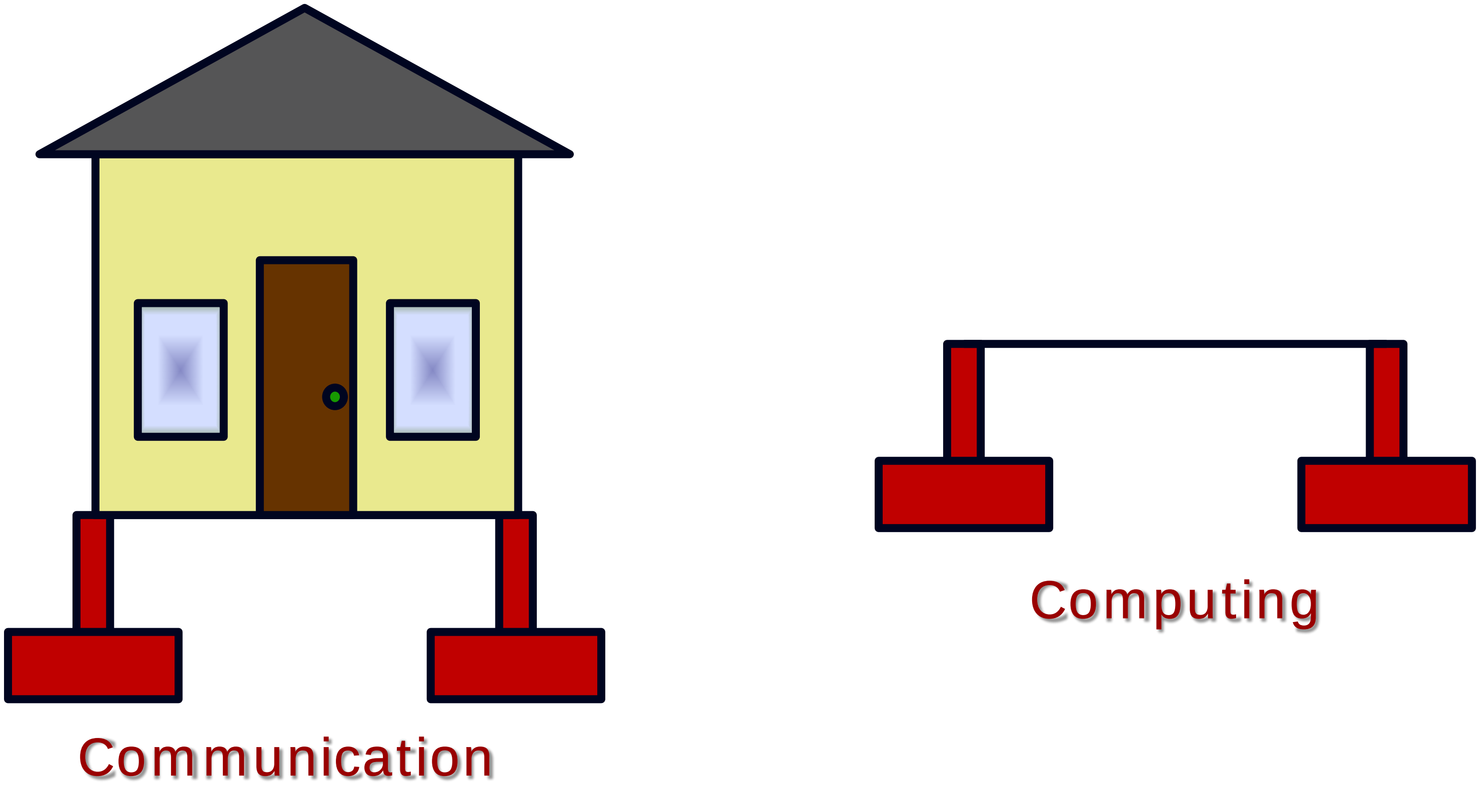
Communication vs. Computing

- Option 1



Communication vs. Computing

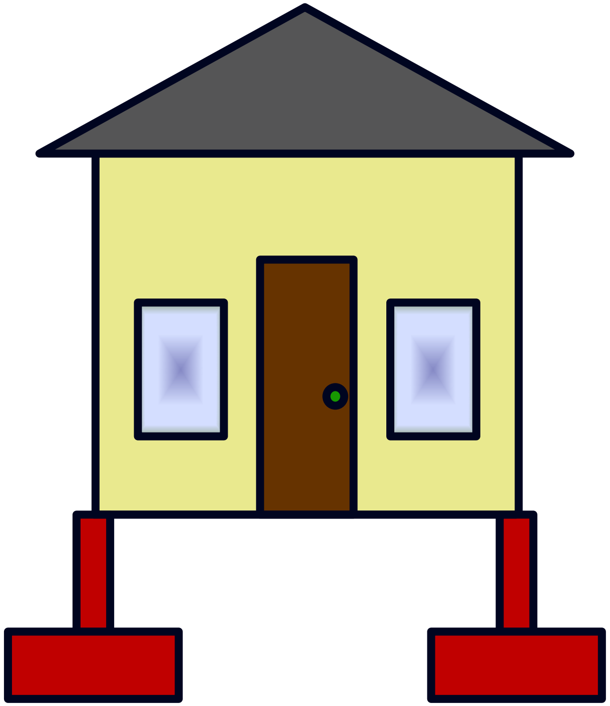
- Option 2



Communication vs. Computing

- Option 3

Communication



Computing

Good News/ Bad News

- Good: We are mostly practicing option 2 or 3!
- Bad:
  - Lost opportunities.
  - Vulnerabilities.
  - Inefficiency.
  - Incompatibilities.

Uncertainty in Communication?

- Always has been a central problem:
  - But usually focusses on uncertainty introduced by the channel
  - Standard Solution:
    - Use error-correcting codes
    - Significantly:
      - Design Encoder/Decoder jointly
      - Deploy Encoder at Sender, Decoder at Receiver

New Era, New Challenges:

- Interacting entities not jointly designed.
  - Can’t design encoder+decoder jointly.
  - Can they be build independently?
  - Can we have a theory about such?
    - Where we prove that they will work?
    - Hopefully:
      - YES
      - And the world of practice will adopt principles.

Example 1

- Intersystem communication?
  - Google+ ↔ Facebook friendship ?
  - Skype ↔ Facetime chat?

- Problem:
  - When designing one system, it is <u>uncertain</u> what the other's design is (or will be in the future)!

Example 2

- Heterogenous data?
  - Amazon-marketplace spends N programmer hours converting data from mom-n-pop store catalogs to uniform searchable format.
  - Healthcare analysts spend enormous #hours unifying data from multiple sources.
- Problem: Interface of software with data:
  - Challenge:
    - Software designer uncertain of data format.
    - Data designer uncertain of software.

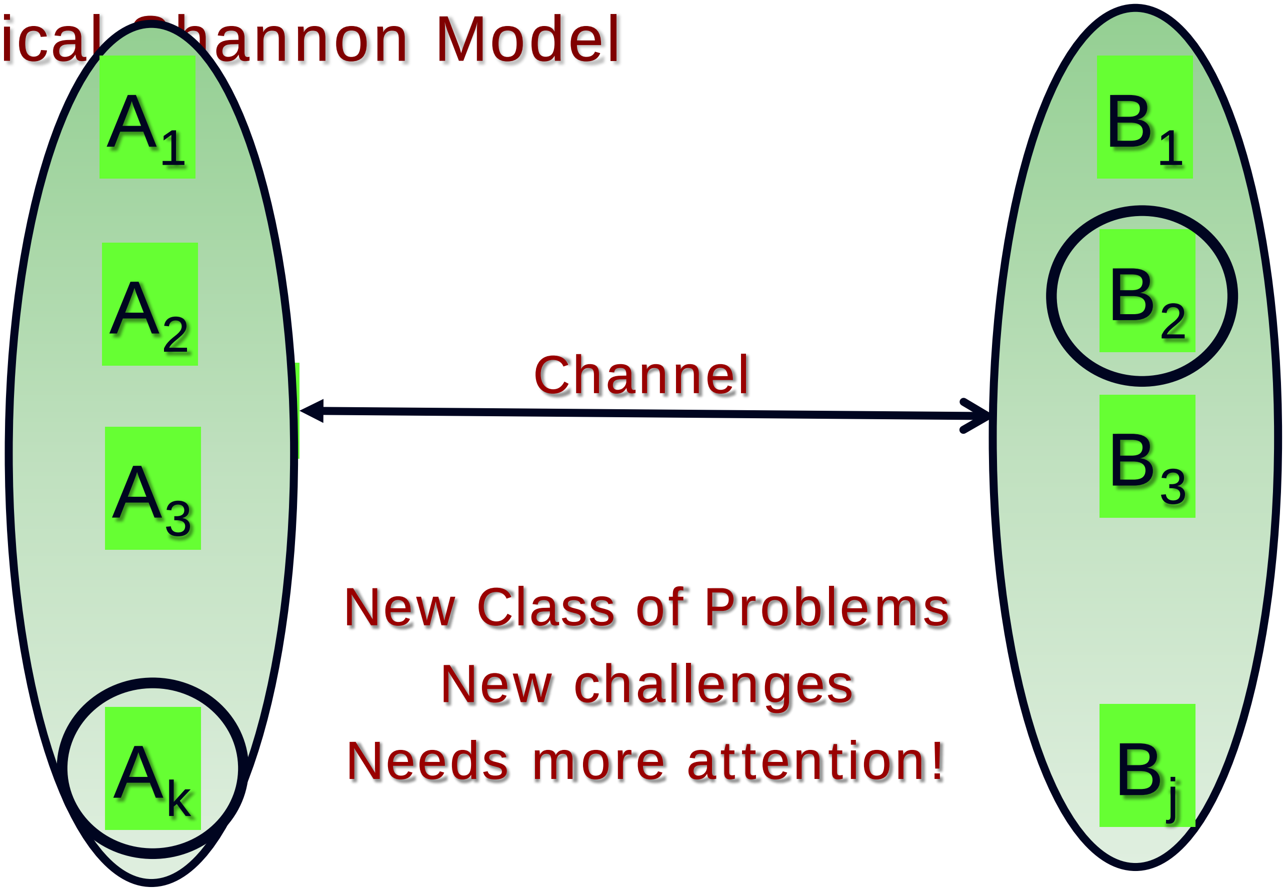
Example 3

- Archiving data
  - Physical libraries have survived for 100s of years.
  - Digital books have survived for five years.
  - Can we be sure they will survive for the next five hundred?

- Problem: Uncertainty of the future.
  - What systems will prevail?
  - Why aren't software systems ever constant?

Modelling uncertainty

Semantic Communication Model
Classical Shannon Model



New Class of Problems

New challenges

Needs more attention!

Nature of uncertainty

- A_i's, B_j's differ in beliefs, but can be centrally programmed/designed.
  - [Juba,Kalai,Khanna,S.'11] : Compression in this context has graceful degradation as beliefs diverge.
- A_i's, B_j's differ in behavior:
  - Nothing to design any more.
  - Best hope: Can highlight certain A_i's (universalists) that can interact successfully with many B_j's
  - [Juba,S'08; Goldreich,J,S'12; J,S'11]: "All is not lost, if we keep goal of communication in mind"
  - Details don't fit in margin …

II: Compression under uncertain beliefs/priors

Motivation: Human Communication

- Human communication (dictated by languages, grammars) very different.
  - Grammar: Rules, often violated.
  - Dictionary: Often multiple meanings to a word.
  - Redundant: But not as in any predefined way (not an error-correcting code).
  - Our thesis: Emerges from uncertainty:
    - Sender of message uncertain about receiver's background/context/prior.
    - Will try to explain in the context of Redundancy

Natural Communication

- To send a "message"
  - Humans have a repertoire of choices of words/phrases (from dictionary/language).
  - Some are shorter than others.
- Why the variation? How are options used?
  - If sender understands receiver well … then use short message.
    - Compression is a natural instinct
  - If not, use longer, redundant choice.
  - But understanding is never perfect!
- Can we formalize use of such redundancy?

Model: Communication amid uncertainty

- Wish to design encoding/decoding schemes (E/D) to be used as follows:
  - Sender has distribution P on M = {1,2,…,N}
  - Receiver has distribution Q on M = {1,2,…,N}
  - Sender gets $X \in M$
  - Sends E(P,X) to receiver.
  - Receiver receives Y = E(P,X)
  - Decodes to $\hat{X}$ = D(Q,Y)

  - Want: X = $\hat{X}$ (provided P,Q close),
    - While minimizing $Exp_{X \leftarrow P} |E(P,X)|$

Contrast with some previous models

- Universal compression?
  - Doesn't apply: P,Q are not finitely specified.
  - Don't have a sequence of samples from P; just one!
- K-L divergence?
  - Measures inefficiency of compressing for Q if real distribution is P.
  - But assumes encoding/decoding according to same distribution Q.
- Semantic Communication:
  - Uncertainty of sender/receiver; but no special goal.

Closeness of distributions:

- P is α-close to Q if for all $X \in M$,

$$\frac{1}{\alpha} \leq \frac{P(X)}{Q(X)} \leq \alpha$$

- P α-close to Q $\Rightarrow$ $D(P||Q), D(Q||P) \leq \log \alpha$.

Dictionary = Shared Randomness?

- Modelling the dictionary: What should it be?

- Simplifying assumption – it is shared randomness, so …

- Assume sender and receiver have some shared randomness R and X is independent of R.
  - Y = E(P,X,R)
  - $\hat{X}$ = D(Q,Y,R)

- Want $\forall X,\ \Pr_R\left[\hat{X} = X\right] \geq 1 - \epsilon$

Solution (variant of Arith. Coding)

- Use R (randomness/dictionary) to define sequences
  - $R_1[1], R_1[2], R_1[3], \ldots$ (encoding of message 1)
  - $R_2[1], R_2[2], R_2[3], \ldots$ (encoding of message 2)
  - ...
  - $R_N[1], R_N[2], R_N[3], \ldots$ (encoding of message N)
- $E_\alpha(P, x, R) = R_x[1 \ldots L]$, where L chosen s.t. $\forall z \neq x$

  Either $R_z[1 \ldots L] \neq R_x[1 \ldots L]$

  Or $P(z) < \frac{P(x)}{\alpha^2}$
- $D_\alpha(Q, y, R) = \text{Max. Likelihood Decoding}$

  $= \text{argmax}_{\hat{x}} \{Q(\hat{x})\}$ among $\hat{x} \in \{ z \mid R_z[1 \ldots L] = y\}$

Performance

- Obviously decoding always correct.
- Easy exercise:
  - $\text{Exp}_X\ [E(P,X)] = H(P) + 2\log\alpha$
- Limits:
  - No scheme can achieve $(1-\epsilon)\cdot[H(P)+\log\alpha]$
  - Can reduce randomness needed.

Implications

- Reflects the tension between ambiguity resolution and compression.
  - Larger the α ((estimated) gap in context), larger the encoding length.
- Coding scheme reflects the nature of human process (extend messages till they feel unambiguous).
- The “shared randomness” is a convenient starting point for discussion
  - Dictionaries do have more structure.
  - But have plenty of entropy too.
  - Still … should try to do without it.

A teaser:

- Can we do this deterministically?
- Suppose you and I have a ranking of N players.
  - Rankings $\pi, \sigma : [N] \rightarrow [N]$
- Further suppose we know the rankings are close.
  - $\forall\ i \in [N]: |\pi(i) - \sigma(i)| \leq 2$.
- You want to know: Is $\pi^{-1}(1) = \sigma^{-1}(1)$
- How many bits do I need to send to you (non-interactively).
  - $O(1)$?
  - $O(\log N)$?
  - $O(\log \log \log N)$?

III: Uncertainty on Action: Goal-Oriented Communication

Back to meaning

- What if sender is sending instructions?
  - Sender and receiver are uncertain about each other's "instruction ↔ bits" association?
  - Can we ensure receiver decodes the right instructions?
- Translation of bits to instructions?
  - Well studied in language/computer science.
  - (Many) "Complete" languages/codebooks exist.
    - Each translates bits to meaning.
    - All equivalent (upto "Kolmogorov constant")
    - But not same.

Goal of communication

- Easy negative result:
  - (Due to plethora of languages/codebooks): In finite time, **can't** guarantee "receiver understands instructions."
  - Is this bad?
    - If receiver can not distinguish correct instructions from incorrect ones, why should it try to do so?
- Goals of communication:
  - Communication is not an end in itself, it a means to achieving some end.
  - Hopefully receiver wishes to achieve a goal and using information from sender to achieve this goal.
  - Semantic communication:
    - Help communication achieve its goal.
    - Use progress towards goal to understand meaning.

Utility of Communication?

- The lens of computational complexity:
  - To prove some resource is useful:
    - Step 1: Identify hardest problems one can solve without the resource.
    - Step 2: Show presence of resource can help solve even harder problems.
- Classical resources:
  - CPU speed, Memory, Non-determinism, Randomness …
- In our case:
  - Communication in presence of understanding.
  - Communication w/o understanding.

Computation as a goal [Juba & S. '08]

- Model: Simple user talking to powerful server.
  - Class of problems user can solve on its own:

    ~ probabilistic polynomial time (P).
  - Class of problems user can solve with perfect understanding of server:

    ~ Any problem. (Even uncomputable!)
  - Class of problems user can solve without understanding of server:

    ~ Polynomial space.
- Roughly: If you are solving problems and can verify solutions, then this helps. If you have a solution, you are done. If not, you've found some error in communication.
- Moral: Communication helps, even with misunderstanding, but misunderstanding introduces limits.

Summarizing results of [GJS 2012]

- But not all goals are computational.
  - We use communication mostly for (remote) control.
  - Intellectual/informational goals are rare(r).
- Modelling general goals, in the presence of misunderstanding:
  - Non-trivial, but can be done.
  - Results extend those from computational setting:
    - Goals can be achieved if user can sense progress towards goal, servers are “forgiving” and “helpful”

Useful lessons

- User/Server can be designed separately.
- Each should attempt to model its “uncertainty” about the other.
- Each should plan for uncertainty:
  - Server: By assuming some short “interrupt” sequence.
  - User: By always checking its progress.

Future goals

- Broadly:
  - Information-theoretic study of human communication, with uncertainty as an ingredient.
    - Should exploit natural restrictions of humans:
      - Limited ability to learn/infer/decode.
      - Limited bandwidth.
  - Conversely, use human interactions to create alternate paradigms for “designed communications.
    - Place semantics on solid foundations.

Thank You!