COMP2610 / COMP6261 Information Theory

Lecture 1: Introduction

Australian
National
University

July 23, 2018

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- Ancient times: **Matter** — atoms

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- **Engineering** (your telephone for example)
- **Computing** (What is that computers do? *They process information*)

References for the curious . . . for interest only!

1. Tom Siegfried, *The Bit and the Pendulum: From Quantum Computing to M Theory-The New Physics of Information*, Wiley 2000
2. Giles Brassard, Is information the Key?, *Nature Physics* 1, 1-4, October 2006
3. John Archibald Wheeler, Information, Physics, Quantum: The Search for Links, in *Proceedings of the 3rd International Symposium on the Foundations of Quantum Mechanics,* Tokyo, (1989)
4. John Archibald Wheeler with Kenneth Ford, *Geons, Black Holes, and Quantum Foam: A Life in Physics*, W.W. Norton and Company, 1998; Chapter 15 "It from Bit"
5. Paul Davies and Niels Henrik Gregersen, *Information and the Nature of Reality*, Cambridge University press 201
6. Andreas Wagner, From bit to it: how complex metabolic network transforms information into living matter, *BMC Systems Biology*, 1(33), 2007
7. Hector Z ntific (2013)
8. Rolf Lan *f Theoretical Physic*
9. Rolf Lan
10. Antoni *Nature* 48 187-19
11. Juan M.R. Parrondo, Jordan M. Horowitz and Takahiro Sagawa, Thermodynamics of Information, *Nature Physics*, 11, 131-139, (February 2015)
12. Jean-Marie Lehn, Perspectives in Supramolecular Chemistry —– From Molec Processing and Self-Organization, *Angewandte Chemie International Ed* ber 1990)
13. Jean-Marie Lehn, *Supramolecular chemistry - scope and perspectives - mol* , Nobel Prize Lecture, (8 December 1987)
14. John Maynard Smith, The concept of information in biology, *Philosop*
15. Ladislav Kovac, Information and knowledge in biology: time for reappraisal, *Plant Signalling and behaviour* 2(2), 65-73 (2007)
16. David Easley and Jon Kleinberg, *Networks, crowds and markets: reasoning about a highly connected world*, Cambridge University Press (2010).
17. Friedrich A. Hayek, The use of knowledge in society, *The American Economic Review*, 35(4), 519-530 (1945)
18. George J. Stigler, The Economics of Information, *The Journal of Political Economy* 69(3), 213-225 (1961)
19. Joseph E. Stiglitz, *Information and the change in the paradigm in economics*, Nobel Prize Lecture 8 (December 2001)
20. Warwick Anderson and Ian R. Mackay, Fashioning the immunological self: the biological individuality of F. Macfarlane Burnet, *Journal of the History of Biology*, 47, 147–175, (2014)

What Is Information? (1)

According to a dictionary definition, information can mean

1. Facts provided or learned about something or someone:
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- Better to ask what happens to it? "Grothendieck's Relative method"

What is Information? (2)

In this course: information in the context of *communication* (includes information storage).

- Exp
  info
  deri

- Claude Shannon (1948): "Amount of unexp
  contains"
  - A theory of information **transmission**

What is Information? (3)

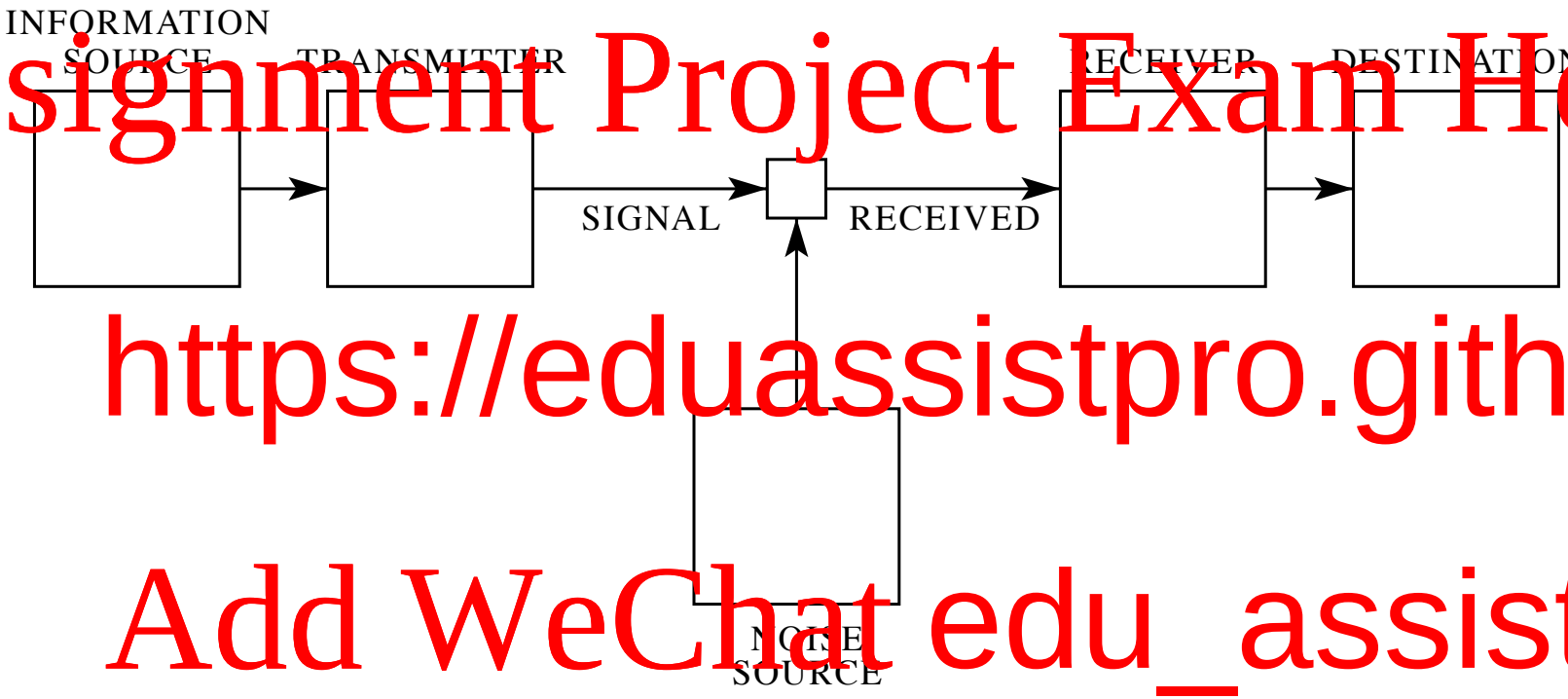

Fig. 1 — Schematic diagram of a general communication system.

From Claude Shannon, A Mathematical Theory of Communication, *Bell System Technical Journal* (1948).

What Is Information? (4)

Information is a message that is *uncertain* to receivers:

- If we receive something that we already knew with absolute certainty then it is non-informative
- Unc
- We will deal with uncertainty using probabilit

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Information Theory

Information theory is the study of the fundamental *limits* and *potential* of the **representation** and **transmission** of information.

Example 1: What Number Am I Thinking of?

- I have in mind a number that is between 1 and 20
- You are allowed to ask me one question at a time
- I can only answer yes/no
- Yo
- Wh

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Your strategy + my answers = a code for e

Some variants:

- What if you knew I never chose prime numbers?
- What if you knew I was twice as likely to pick numbers more than 10?
- What if you knew I only ever chose one of 7 or 13?

Example 2: How Much Is Information Worth?

Simplified Version of “Deal or No Deal”

$1000 Hidden in one of 16 cases.

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4. Which range out of 0–3, 4–7, 8–11, or 12–15 the

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Key Question:

- Can we use these ideas to *quantify* information?

Example 3: Redundancy and Compression

Cn y rd ths sntnc wtht ny vwls?

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Can you read this sentence without any vowels?

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- App

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(For the moment think of "bit" as "number of yes/no qu

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Key Question:

- How much redundancy can we *safely* remove?
  (Note: "rd" could be "read", "red", "road", etc.)

Example 4: Error Correction

Hmauns hvae the aitliby to cerroct for eorrrs in txet and iegmas.

Key Question:

- How much noise is it possible to correct for and how?

A Summary of the History of Information Theory

1920s : Nyquist & Hartley at Bell Labs

1940 : Turing and Good at Bletchley Park (WWII)

1942 : Hedy Lamarr and George Antheil

1

1951 : Huffman Coding

1958 : Peter Elias: "Two Famous Papers"

1970 : "Coding is Dead"

1970- : Revival with advent of digital computing
CDs, DVDs, MP3s, Digital TV, Mobiles, Internet, Deep-space comms (Voyager), ...

More on the History of Information Theory

&

Information Theory and the Digital Age

by Aftab, Cheung, Kim, Thakkar, and Yeddanapudi.

`http://web.mit.edu/6.933/www/Fall2001/Shannon2.pdf`

Brief Overview of Course

- How can we quantify information?
  - Basic Definitions and Key Concepts
  - Probability, Entropy & Information

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  - Algorithmic Information Theory

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- What is randomness? [Marcus Hutter]
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COMP2610/COMP6261 (Information Theory)

We will study the fundamental limits and potential of the *representation* and *transmission* of information.

- Mathematical Foundations
- Pro
- Coding and Compression
- Communication
- Kolmogorov Complexity (Guest Lecture)

Learning Outcomes

From `https://wattlecourses.anu.edu.au/course/view.php?id=25550`:

1. Understand and apply **fundamental concepts** in information theory such as probability, entropy, information content and their inter-relationships
2. Un
3. Co bles
4. Imp **lgorithms**
5. Understand the relationship of information t **Bayesian inference** in data modelling ar
6. Understand some key **theorems** and **inequalities** that quantify essential limitations on compression, communication and inference
7. Know the basic concepts regarding **communications over noisy channels**

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  - “Do you know your `for` loops from yo

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Outline

Course Overview

See Wattle site (authoritative)

- Lectures: 23 $\times$ 1 hour (two lectures per week); one public holiday
- By me, except one guest lecture by Marcus Hutter (Aside: about me).
- Tut
- Ass
  below)
- Final Exam (60%) Hurdle assessment: You pass the course. (New this year!)
- **Late Submission Policy: late submissions get zero marks — 100% penalty.**

Expectations

See the newly published expectations document:

`https://wattlecourses.anu.edu.au/pluginfile.php/1760092/course/section/423322/Learning%20expectations.pdf`

Key points:

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- Learning mathematical material is hard and cannot be delegated or outsourced. "There is no royal road to geometry." Don't kid yourself!

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- In a nutshell: The secret of success is *deliberate practice.*

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For an alternative take – David MacKay's Lectures:

`http://www.inference.phy.cam.ac.uk/itprnn_lectures/`

Consultation & Other Issues

Consultation:

- Best way to contact the course lecturers and tutors is via **email**

- If yo
- Em

up to three days as a normal response time

- **Technical questions**: encouraged to pos
- Request for clarifying assignment: **must be** posted on Wattle

What's Next?

- If you are not comfortable about your probability and algebra skills, start today on improving them

- Get

- Sign up to a tutorial (will open tomorrow, time an