PHYS 256: POCI

Physics of Information & Computation

Alexandra Jurgens
Inria Centre at the University of Bordeaux
09/01/2025

Who am I?

Marietta College

UC DAVIS
UNIVERSITY OF CALIFORNIA

CSC
UC DAVIS

Inria

University of California Davis
(Physics Department)

PhD Student

Irrational Capital

Data scientist

UC Davis (CSC)

Postdoctoral Researcher

Inria

Postdoctoral Researcher

Inria

Permanent Faculty

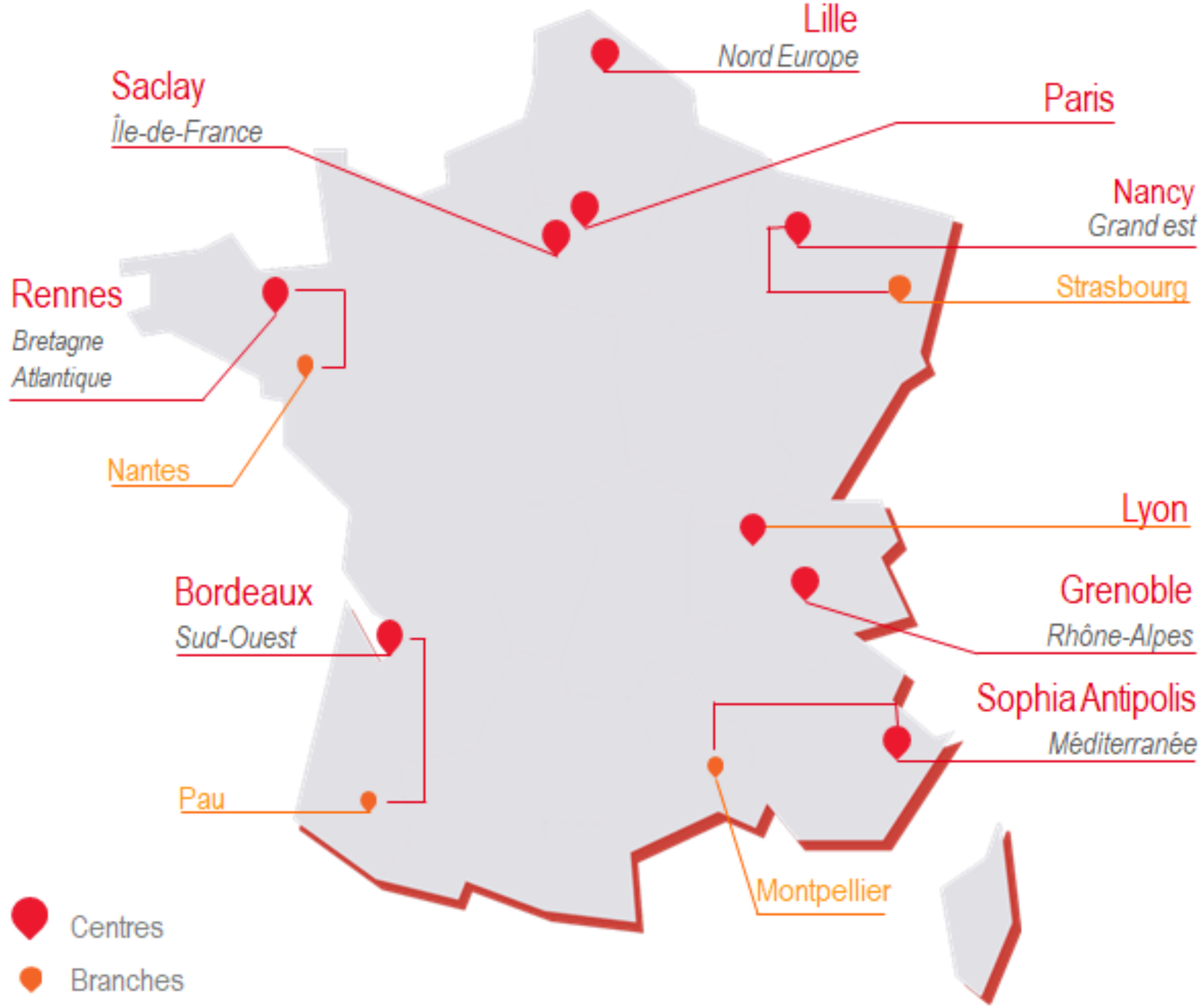
Where am I?


England
Wales
London
Cardiff
Nederland
Den Haag
Deutschland
Nordrhein-Westfalen
Leipzig
België / Belgique / Belgien
Köln
Erfurt
Dresden
Frankfurt am Main
Česko
Lëtzebuerg
Nürnberg
Guernsey
Paris
Grand Est
Baden-Württemberg
Bayern
Wien
Rennes
München
Nantes
Österreich
Schweiz/ Suisse/Svizzera/ Svizra
France
Graz
Golfo de Vizcaya - Golfe de Gascogne
Nouvelle-Aquitaine
Auvergne-Rhône-Alpes
Milano
Venezia
Slovenija
Bordeaux
Torino
Hrvatska
Oviedo / Uviéu
Genova
Monaco
Città di San Marino
Firenze
Occitanie
Vitoria-Gasteiz
Marseille
Italia
Andorra la Vella
Castilla y León
Aragón
Porto
Roma


Inria
INVENTEURS DU MONDE NUMÉRIQUE
Inria
CENTRE DE RECHERCHE BORDEAUX SUD-OUEST


Adobe Stock | #190250364

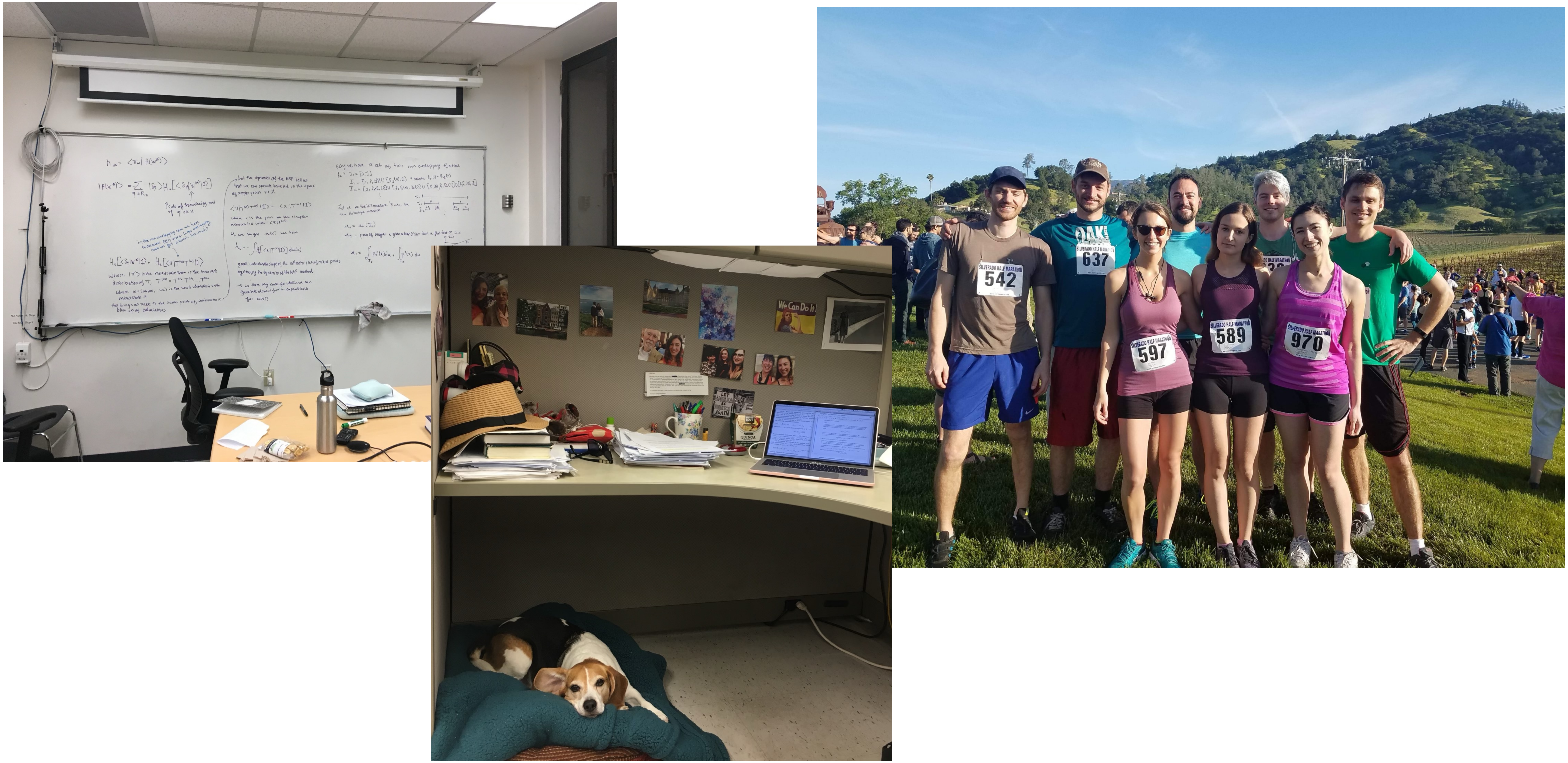
Where am I?



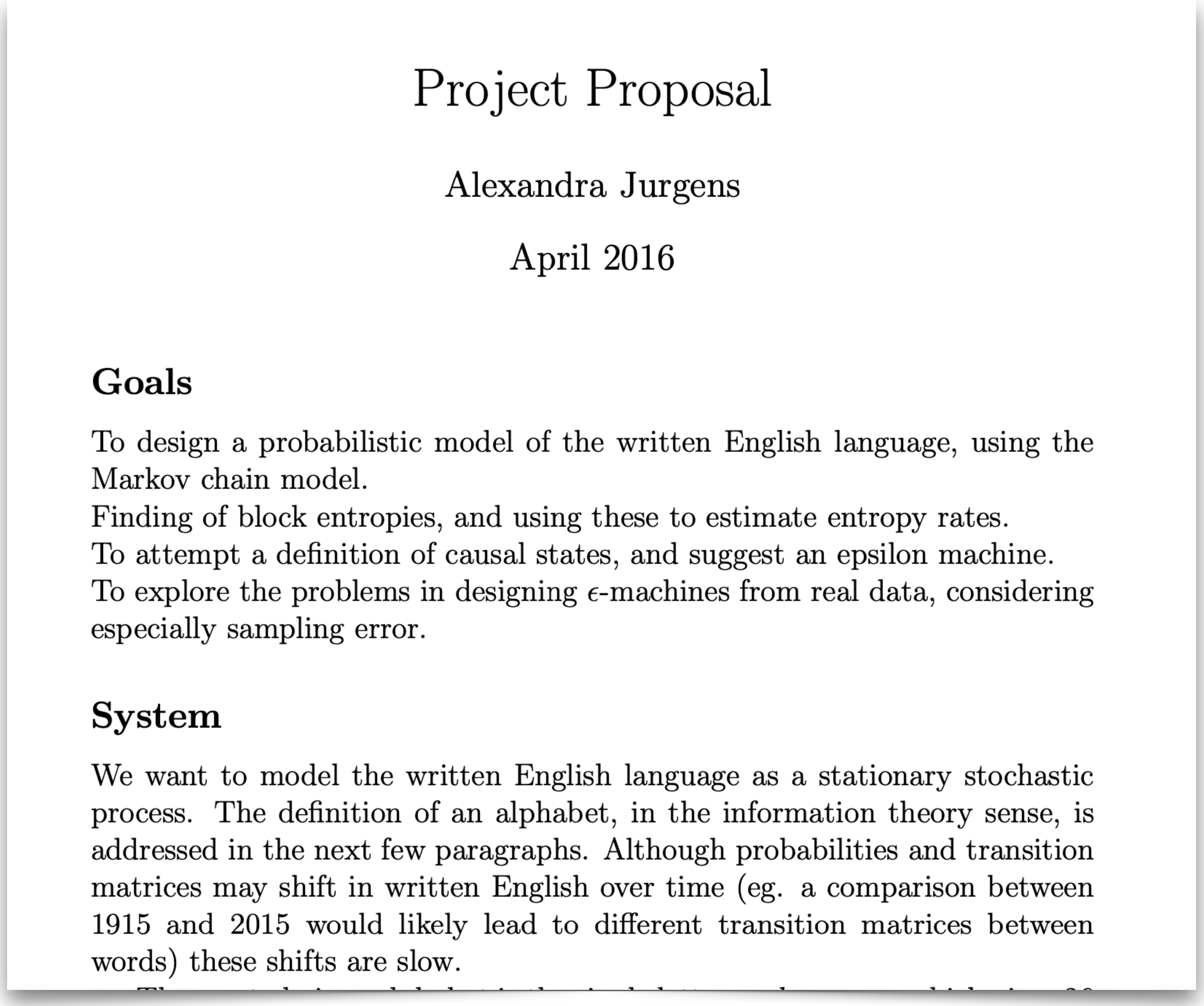
Institut national de recherche en sciences et technologies du numérique

National Institute for Research in Digital Science and Technology

UC Davis 2015 - 2021



My POCI Project



Project Proposal

Alexandra Jurgens

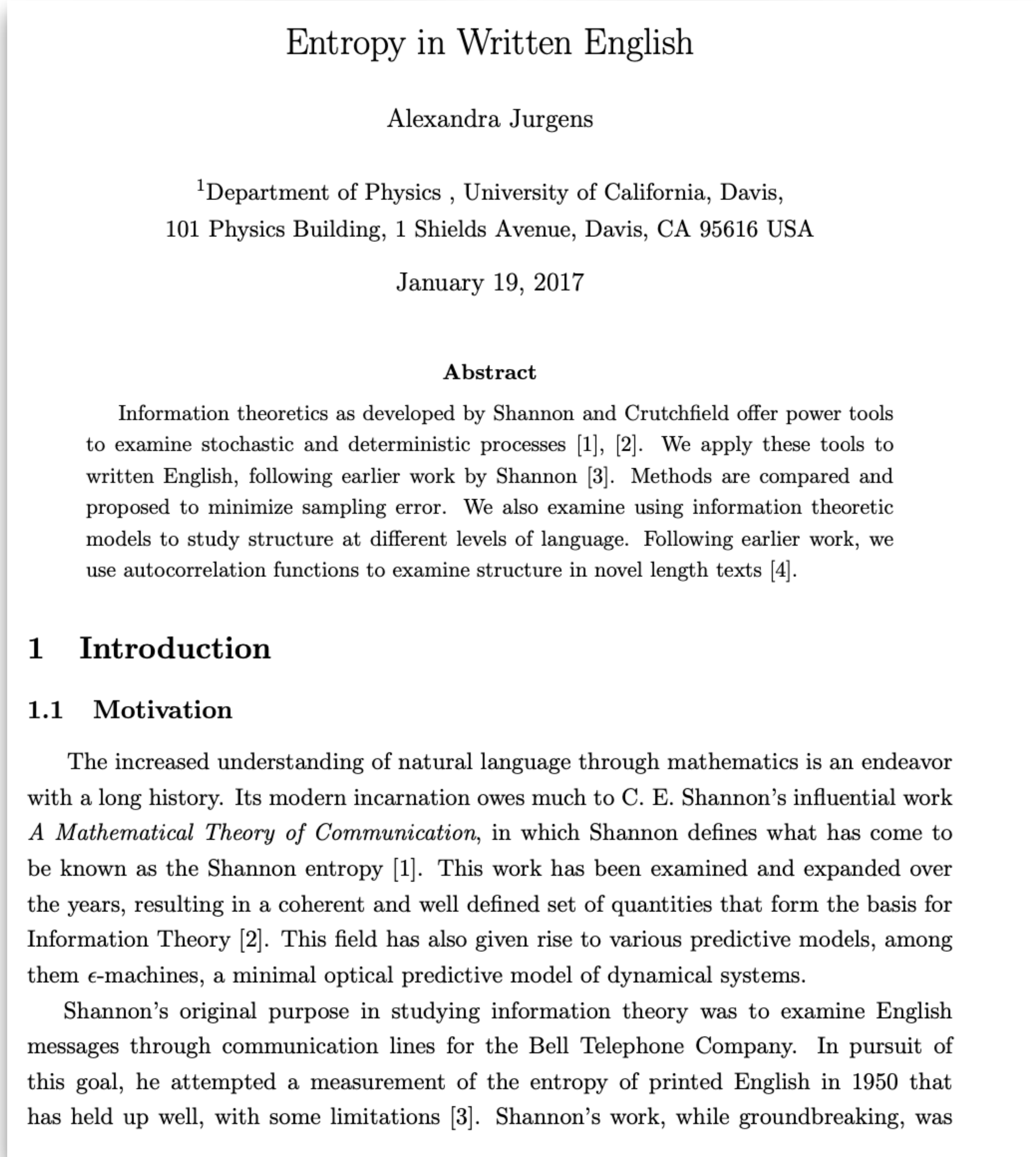
April 2016

Goals

To design a probabilistic model of the written English language, using the Markov chain model.
Finding of block entropies, and using these to estimate entropy rates.
To attempt a definition of causal states, and suggest an epsilon machine.
To explore the problems in designing ϵ-machines from real data, considering especially sampling error.

System

We want to model the written English language as a stationary stochastic process. The definition of an alphabet, in the information theory sense, is addressed in the next few paragraphs. Although probabilities and transition matrices may shift in written English over time (eg. a comparison between 1915 and 2015 would likely lead to different transition matrices between words) these shifts are slow.



Entropy in Written English

Alexandra Jurgens

[1]Department of Physics , University of California, Davis,
101 Physics Building, 1 Shields Avenue, Davis, CA 95616 USA

January 19, 2017

Abstract

Information theoretics as developed by Shannon and Crutchfield offer power tools to examine stochastic and deterministic processes [1], [2]. We apply these tools to written English, following earlier work by Shannon [3]. Methods are compared and proposed to minimize sampling error. We also examine using information theoretic models to study structure at different levels of language. Following earlier work, we use autocorrelation functions to examine structure in novel length texts [4].

1 Introduction

1.1 Motivation

The increased understanding of natural language through mathematics is an endeavor with a long history. Its modern incarnation owes much to C. E. Shannon's influential work *A Mathematical Theory of Communication*, in which Shannon defines what has come to be known as the Shannon entropy [1]. This work has been examined and expanded over the years, resulting in a coherent and well defined set of quantities that form the basis for Information Theory [2]. This field has also given rise to various predictive models, among them ϵ-machines, a minimal optical predictive model of dynamical systems.

Shannon's original purpose in studying information theory was to examine English messages through communication lines for the Bell Telephone Company. In pursuit of this goal, he attempted a measurement of the entropy of printed English in 1950 that has held up well, with some limitations [3]. Shannon's work, while groundbreaking, was

Complex Systems Topics Overview

Alan Turing

Structure

Spontaneous pattern formation?

How to detect and define?

Complexity

Emergence of "something new"

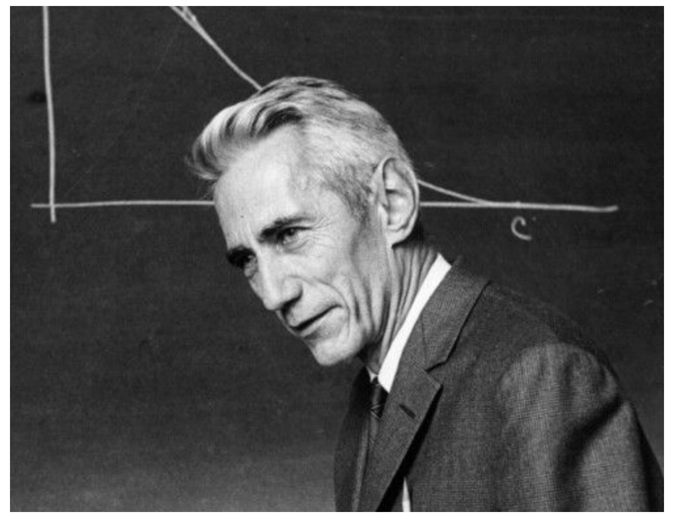
How to quantify? Build models?

Hierarchical structures?

Information

In natural systems?

Thermodynamics of information processing?

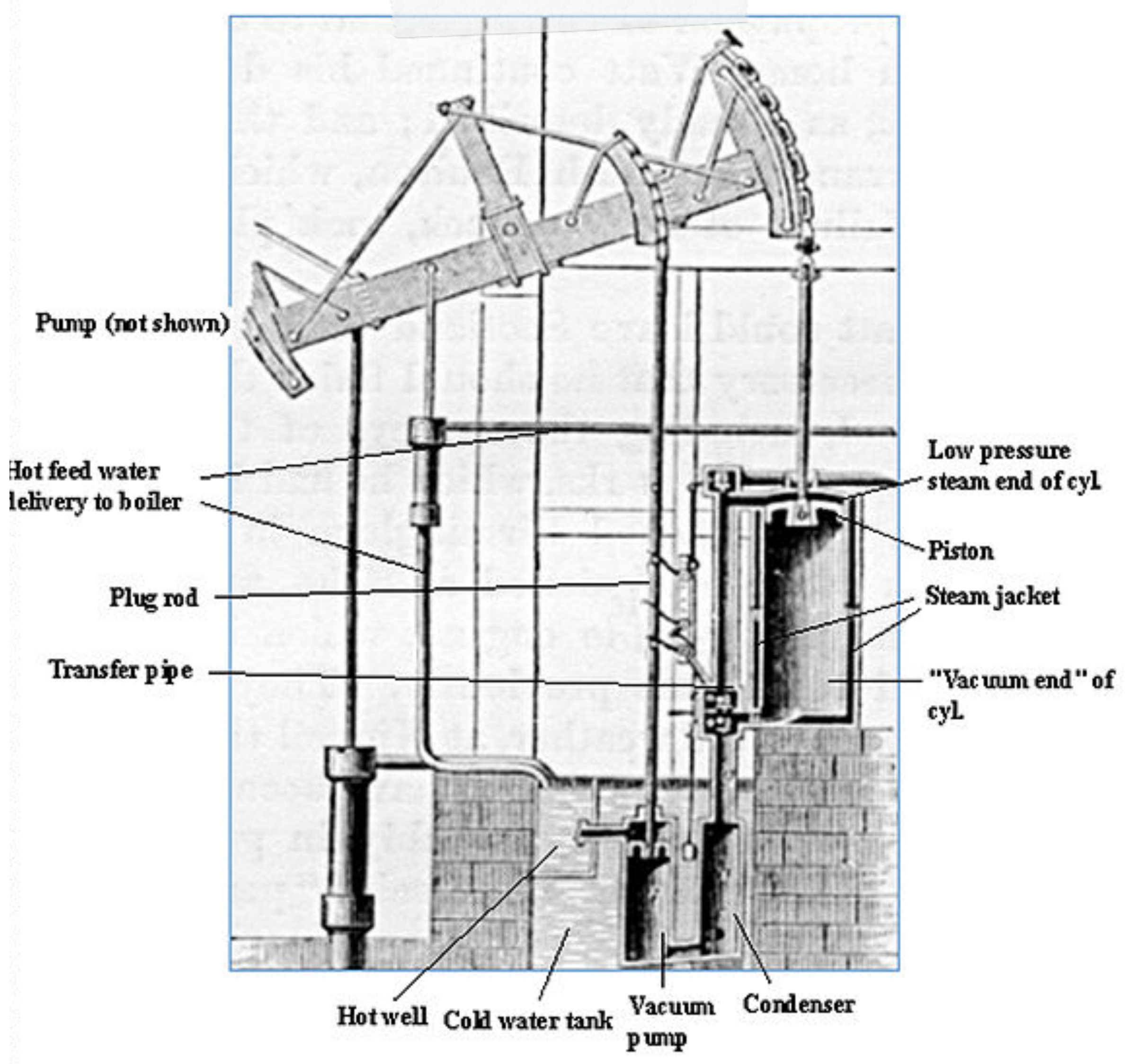


Claude Shannon

Historical Comparison

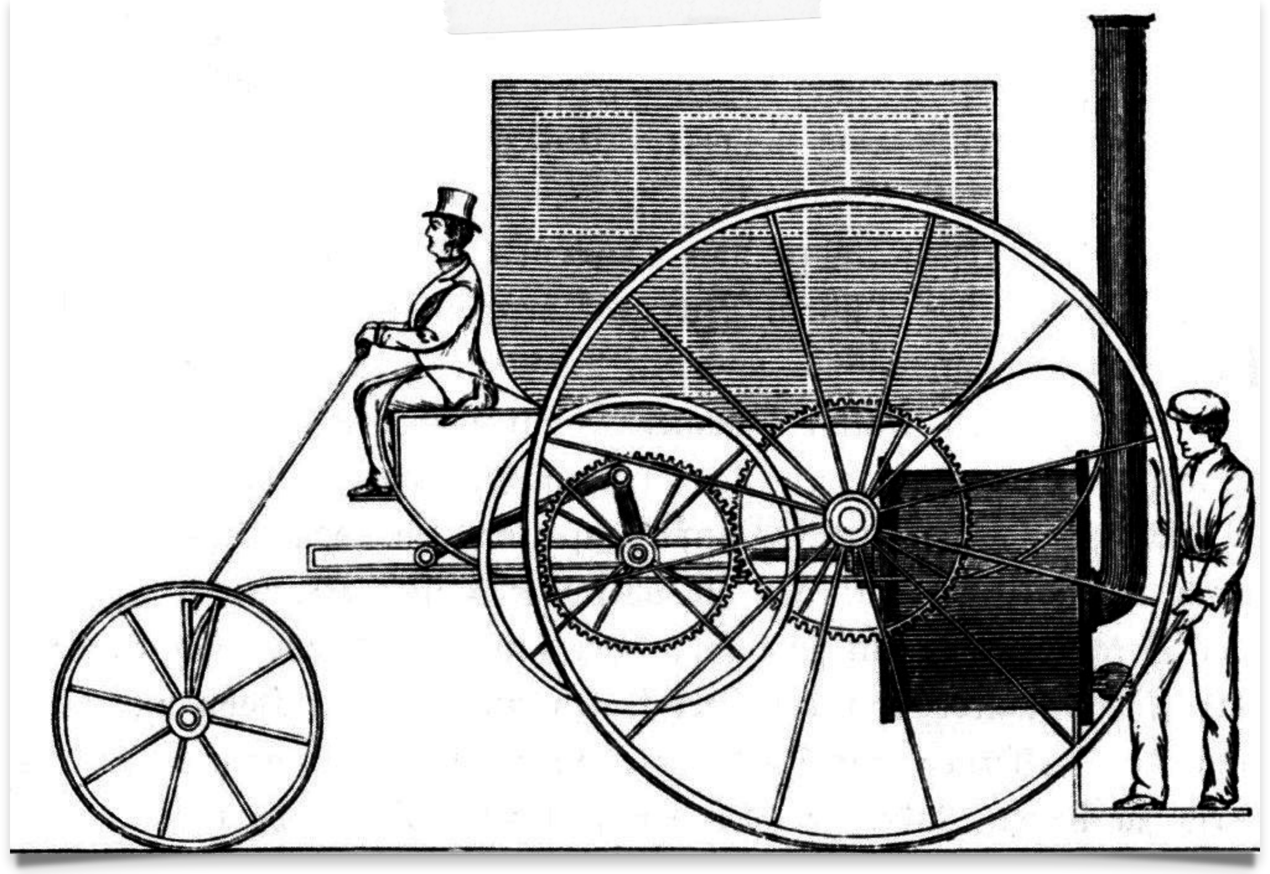
The Industrial Age $\Longleftrightarrow$ Thermodynamics

Industrial Revolution



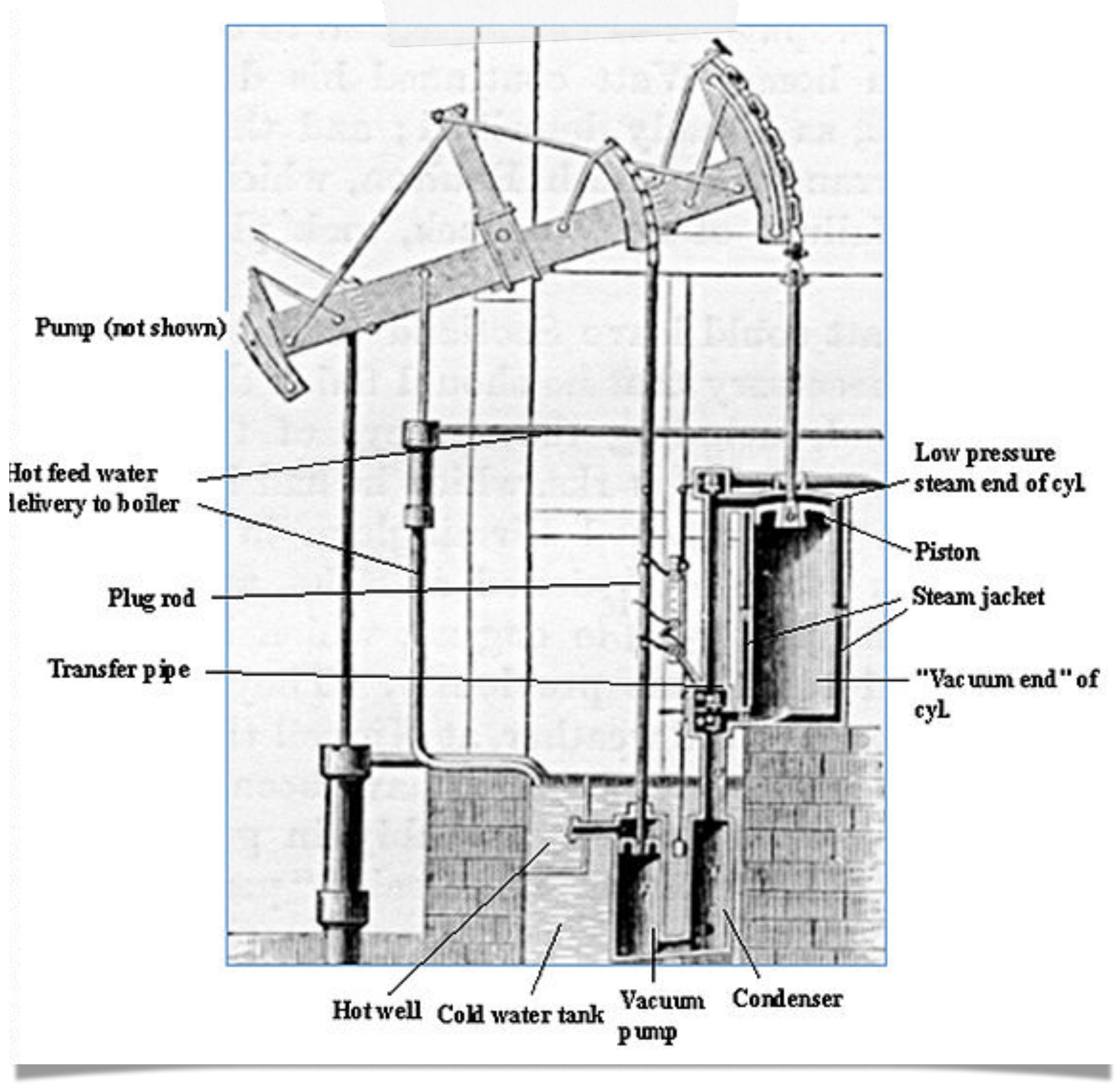
1712: Thomas Newcomen's steam engine.

1769: Cugnot's *machine à feu pour le transport de wagons et surtout de l'artillerie*



1803: Trevithick's London Steam Carriage

Dawn of Modern Physics



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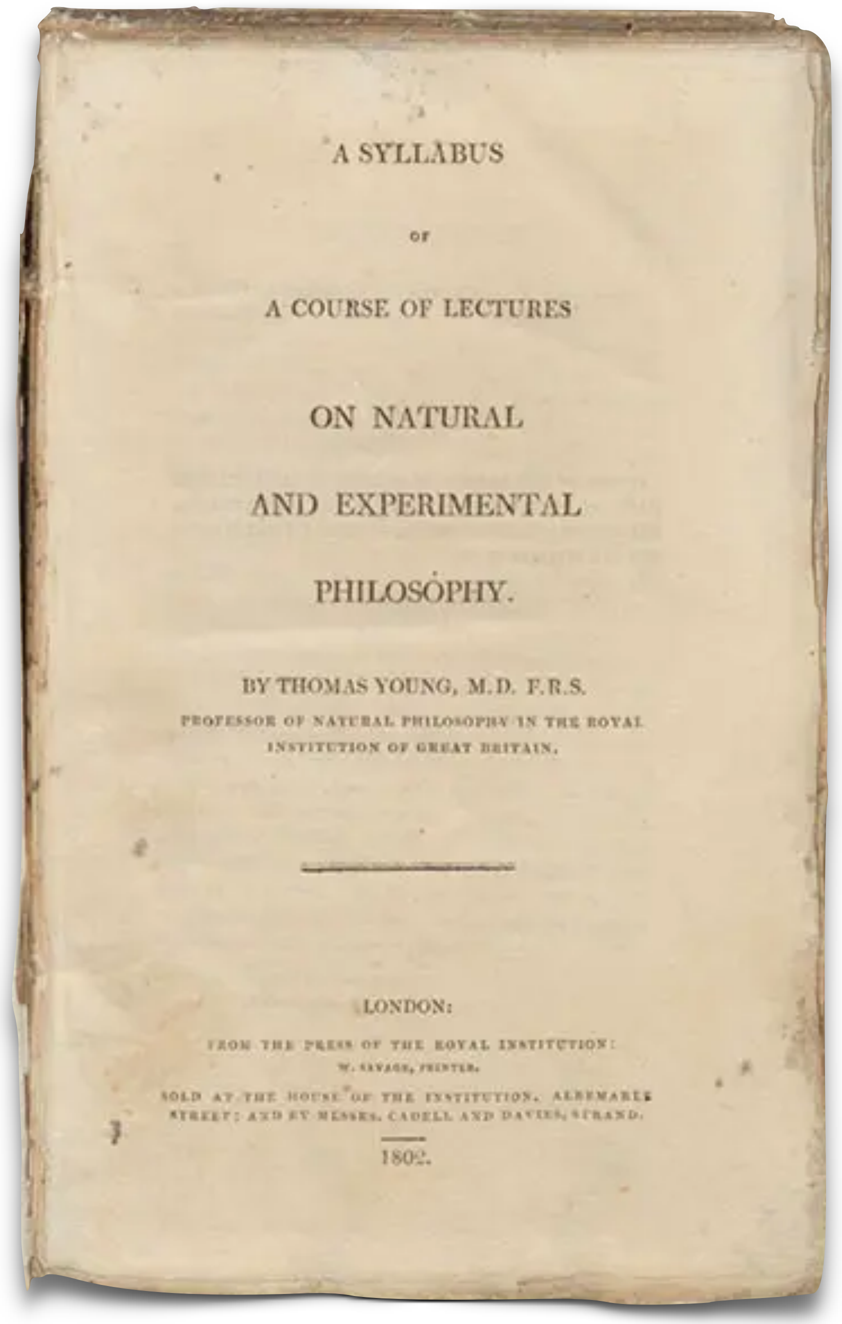


A SYLLABUS

OF

A COURSE OF LECTURES

ON NATURAL

AND EXPERIMENTAL

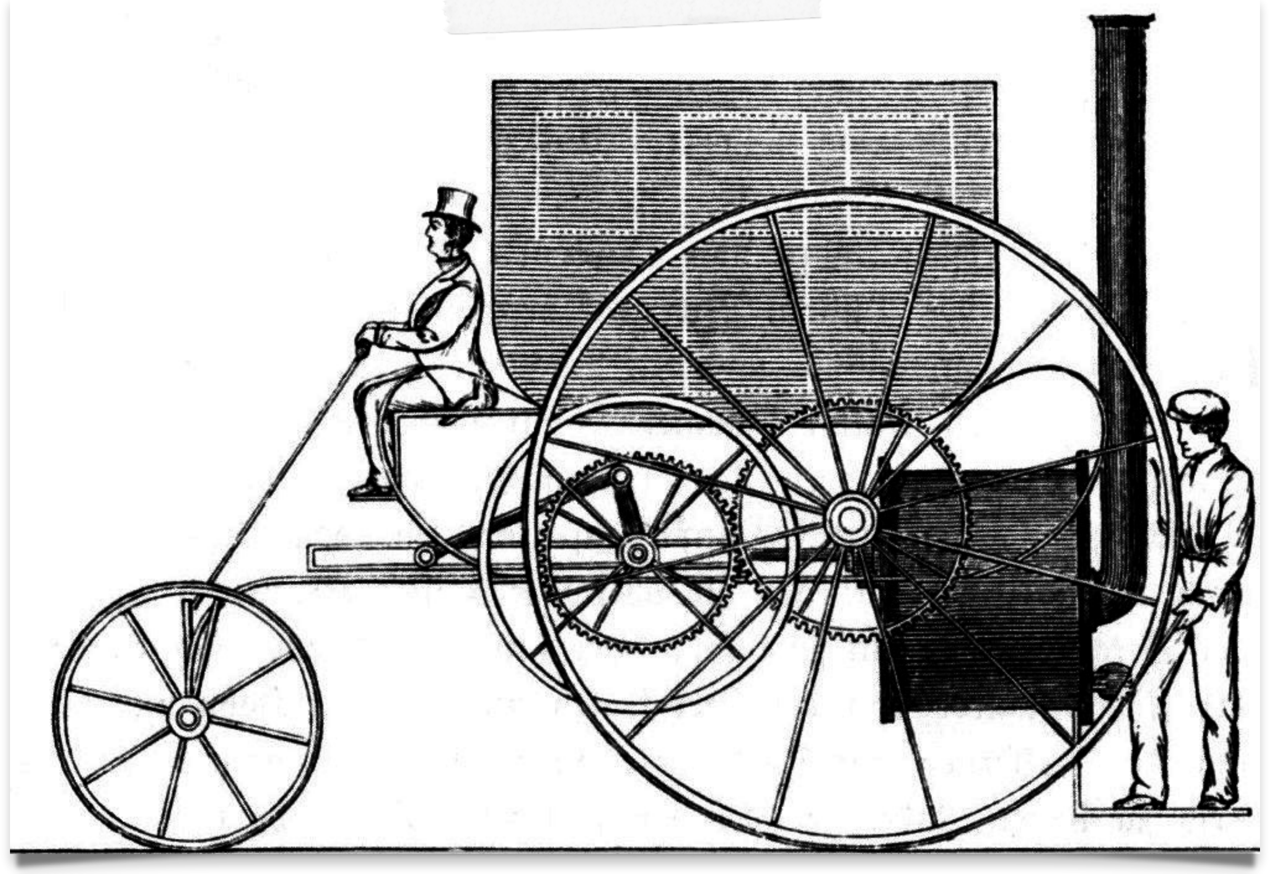
PHILOSOPHY.

BY THOMAS YOUNG, M.D. F.R.S.
PROFESSOR OF NATURAL PHILOSOPHY IN THE ROYAL
INSTITUTION OF GREAT BRITAIN.

LONDON:
FROM THE PRESS OF THE ROYAL INSTITUTION:
W. SAVAGE, PRINTER.
SOLD AT THE HOUSE OF THE INSTITUTION, ALBEMARLE
STREET; AND BY MESSRS. CADELL AND DAVIES, STRAND.

1802.

1807: Thomas Young coins "energy"



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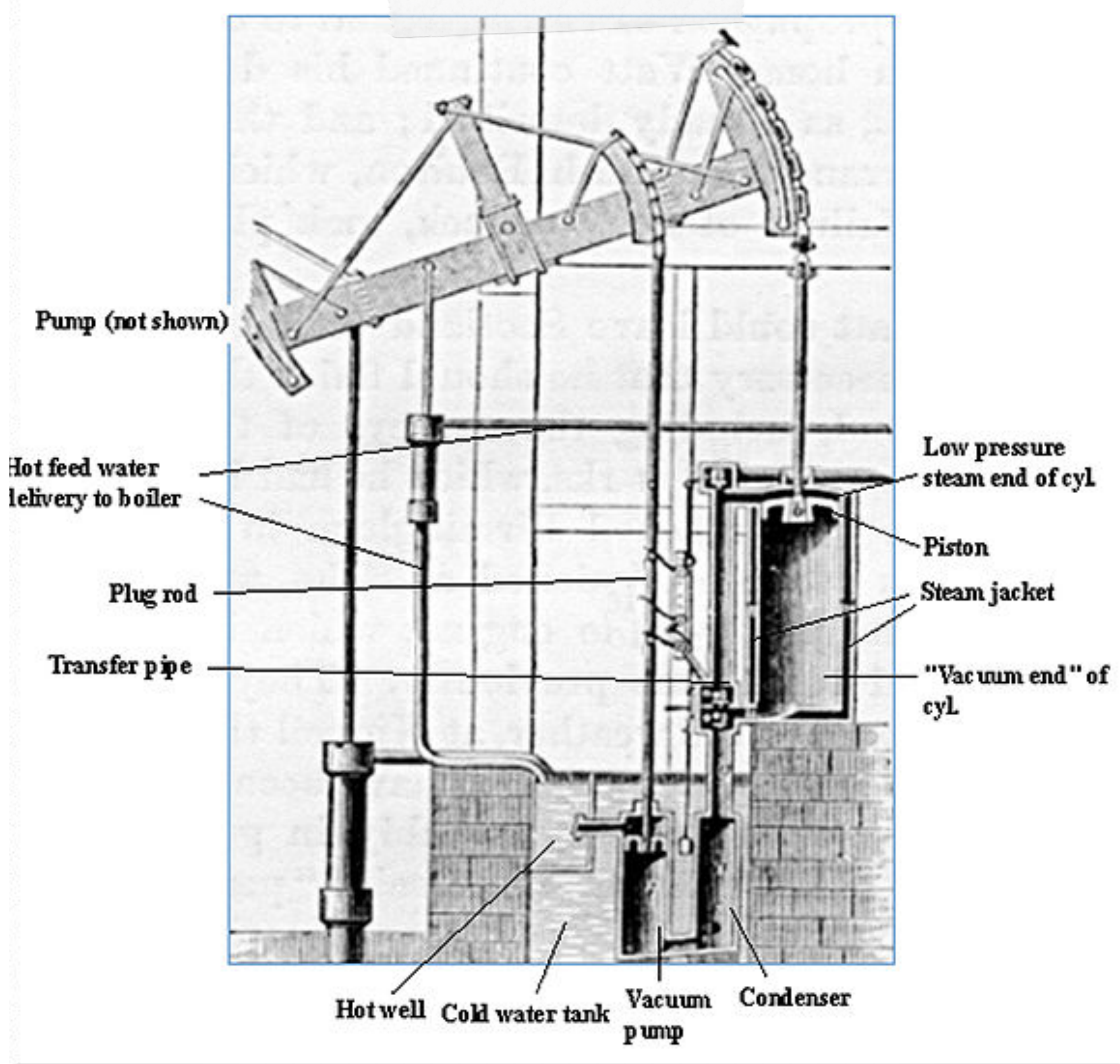
Development of Thermodynamics



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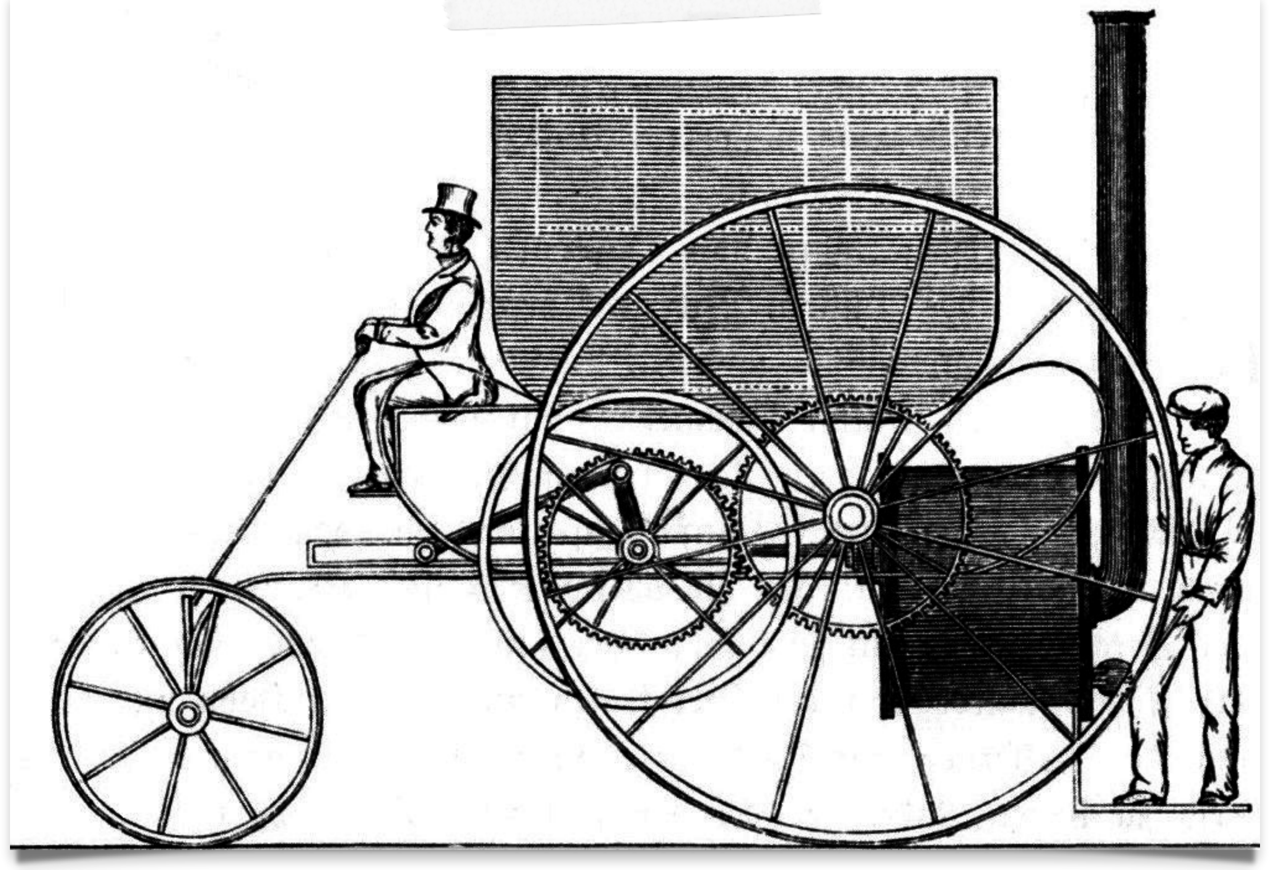

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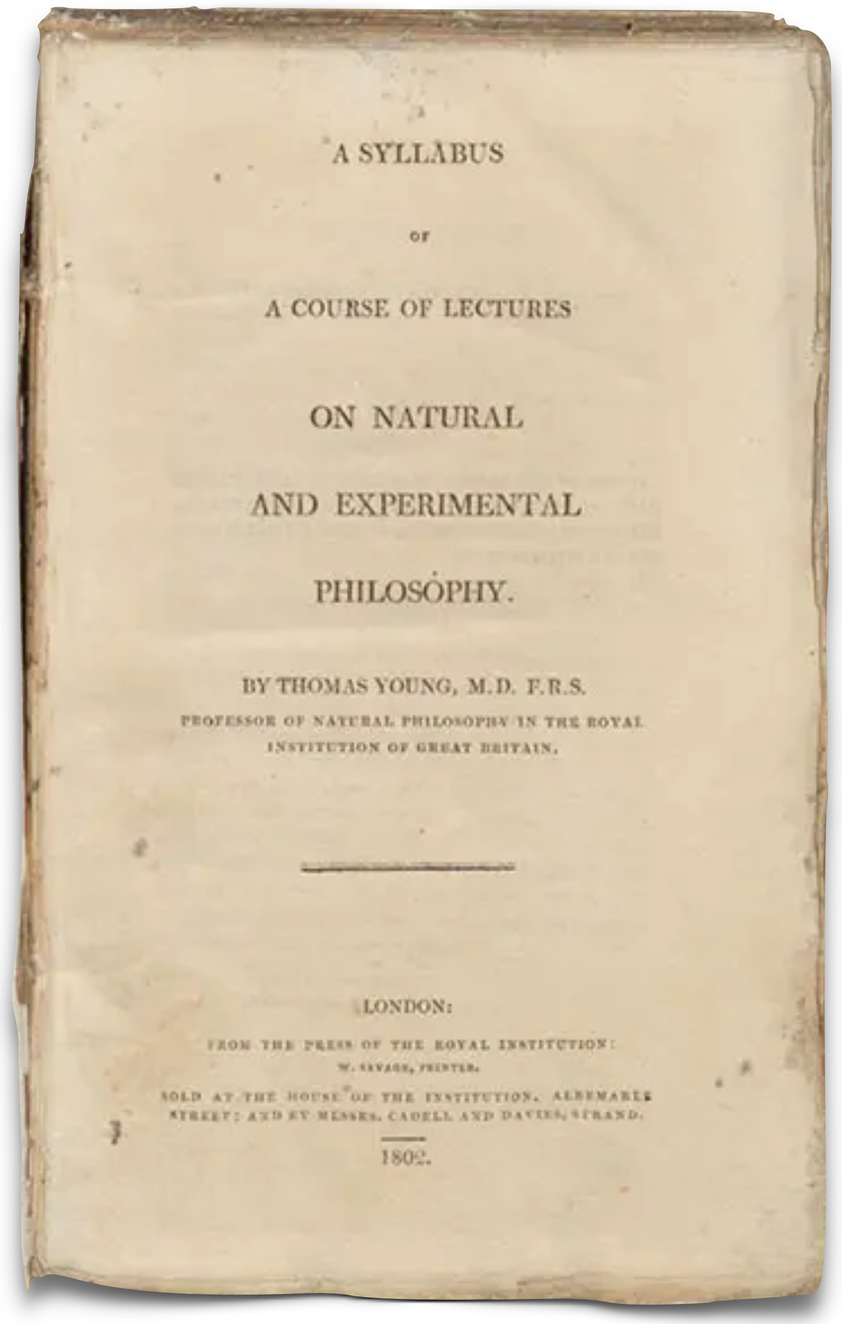

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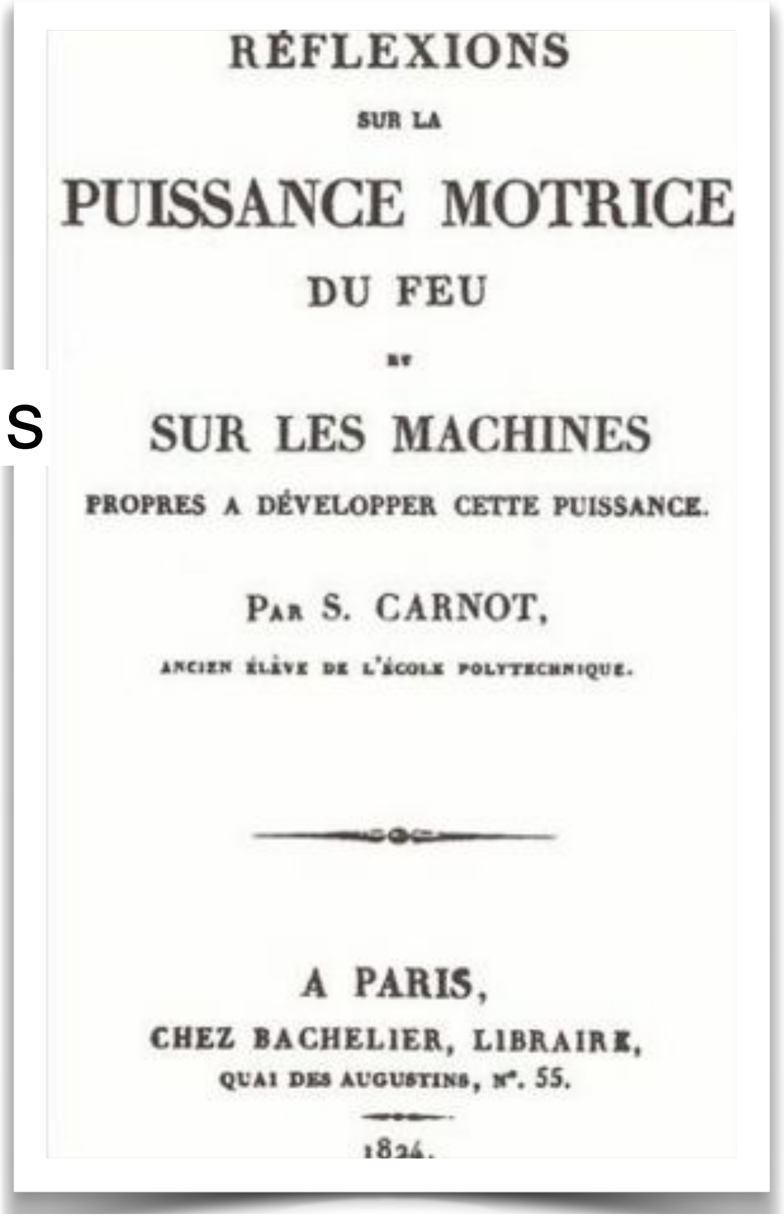


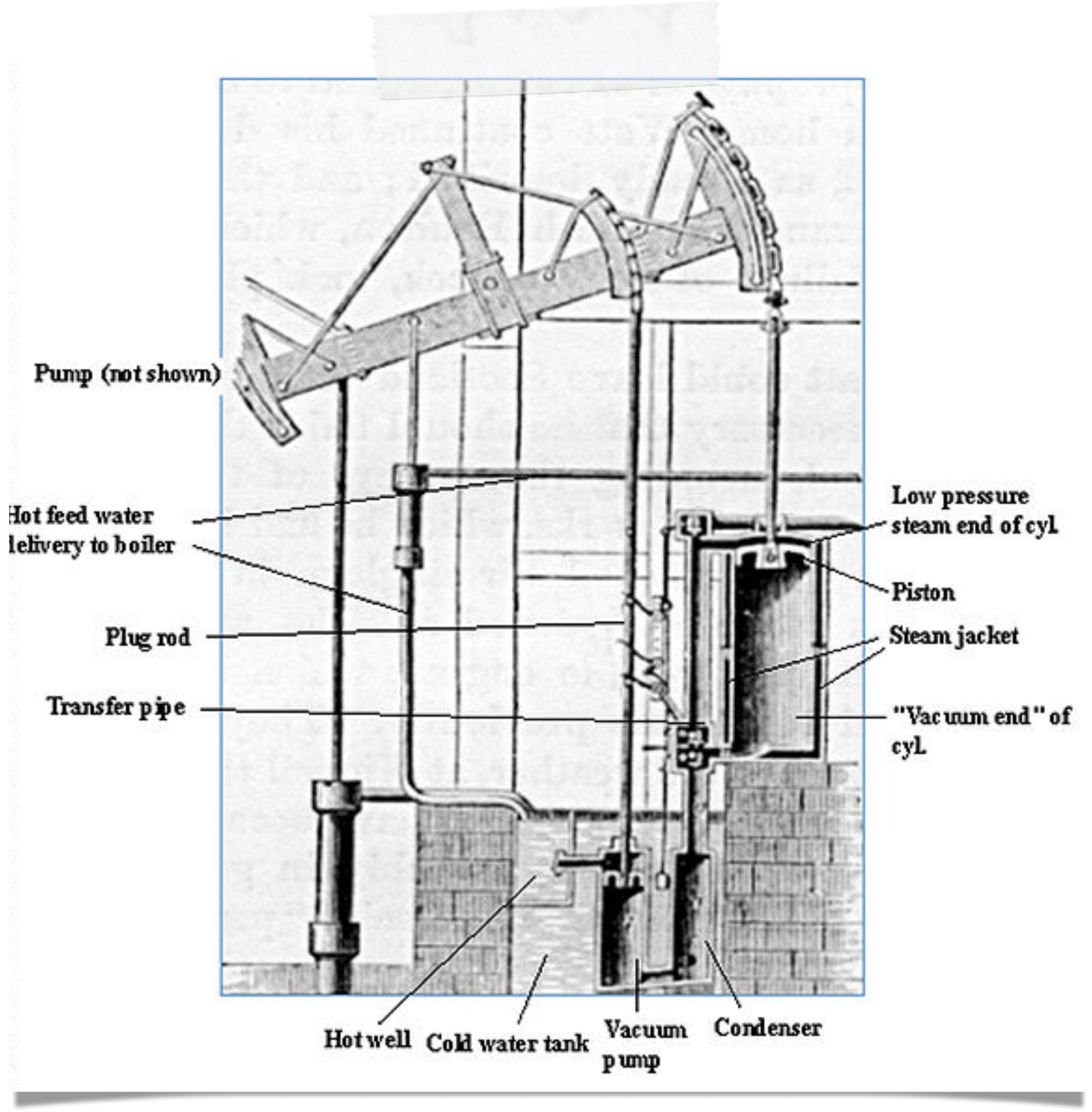
RÉFLEXIONS
SUR LA
PUISSANCE MOTRICE
DU FEU
ET
SUR LES MACHINES
PROPRES A DÉVELOPPER CETTE PUISSANCE.

PAR S. CARNOT,
ANCIEN ÉLÈVE DE L'ÉCOLE POLYTECHNIQUE.

A PARIS,
CHEZ BACHELIER, LIBRAIRE,
QUAI DES AUGUSTINS, N°. 55.
1824.

1824: Carnot proposes the 2nd law

Development of Thermodynamics



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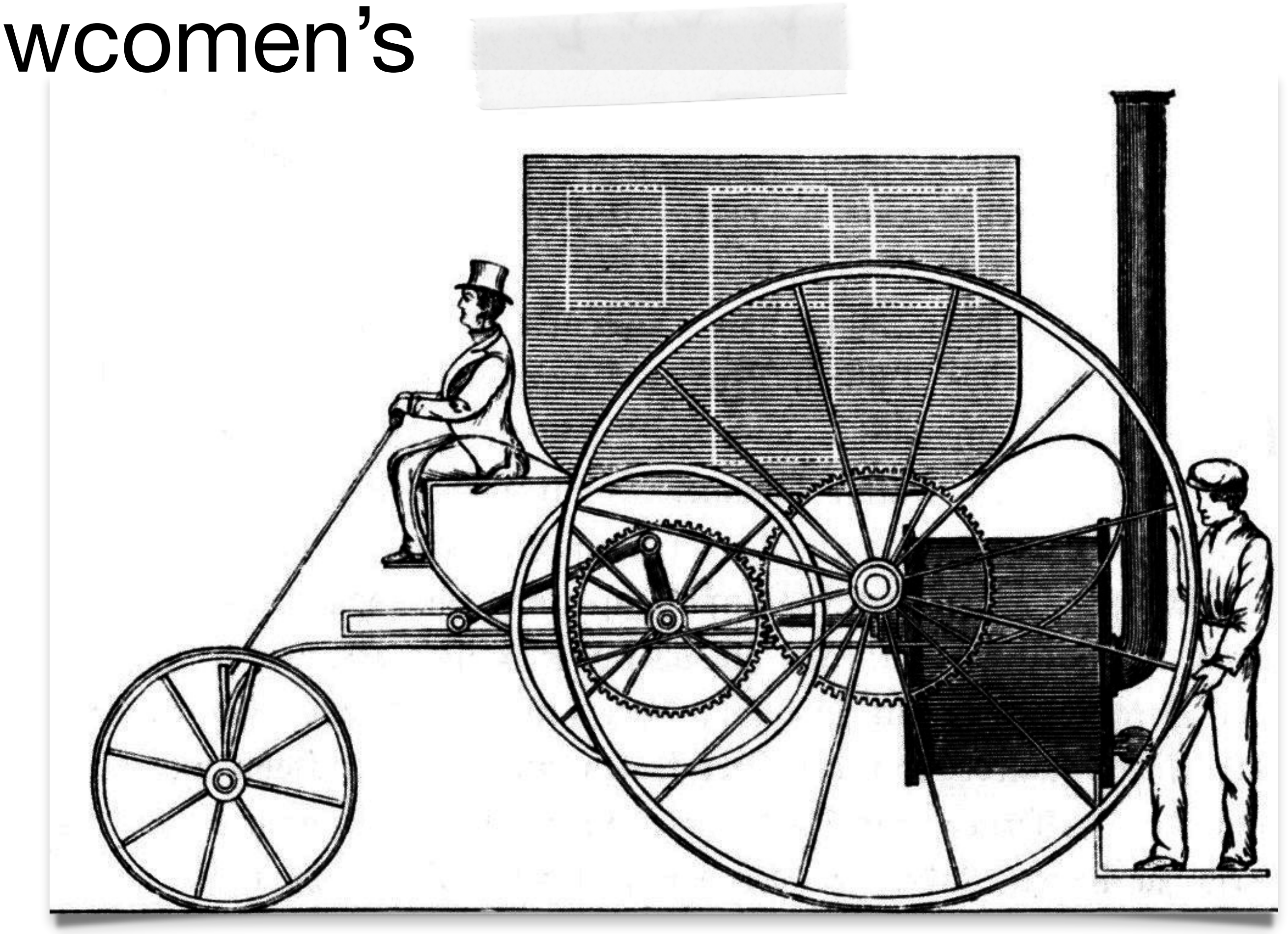

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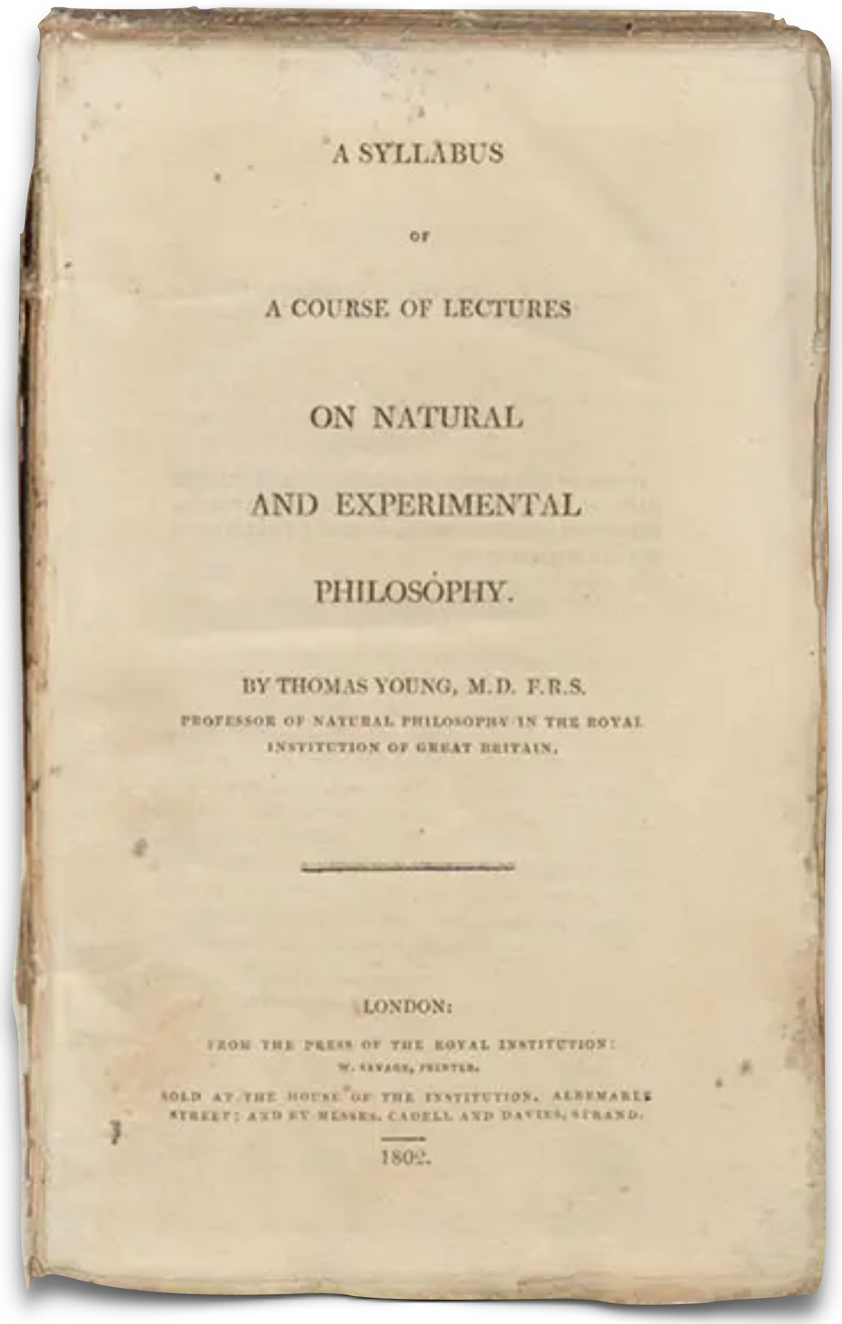

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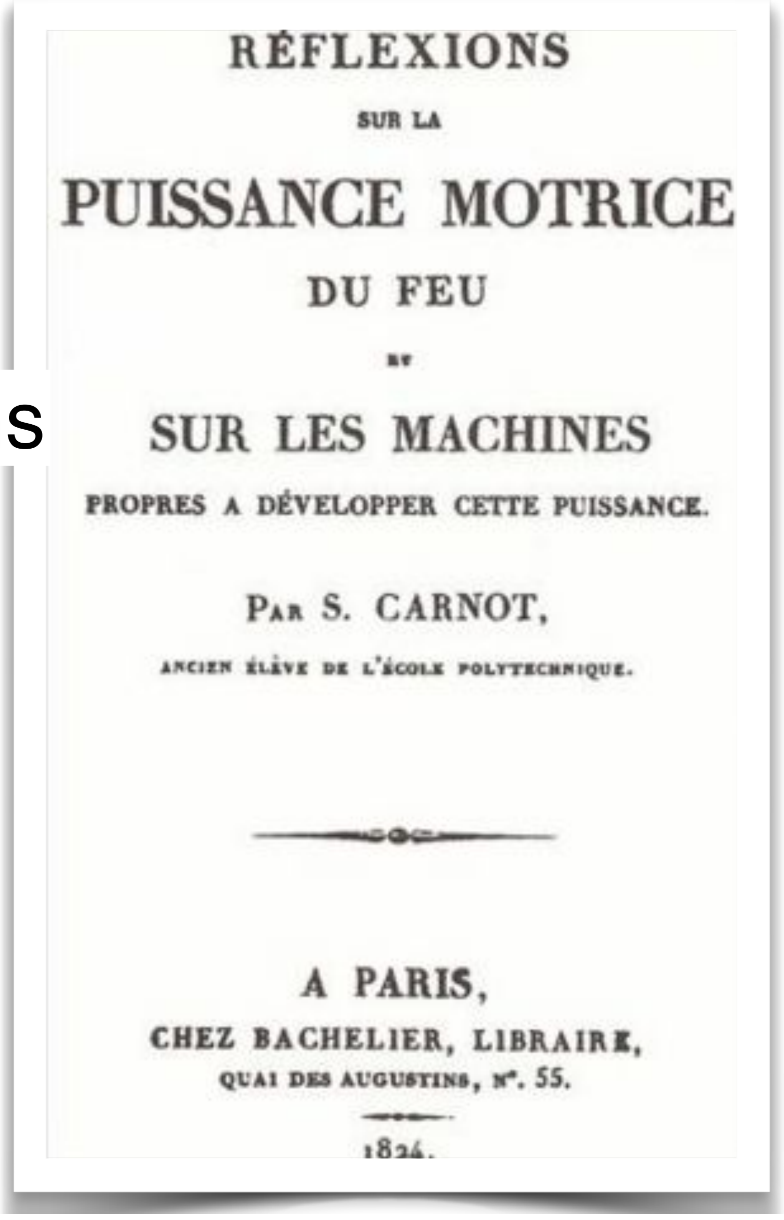

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QUAI DES AUGUSTINS, N°. 55.

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1824: Carnot proposes the 2nd law

Then:

Thomson
Kelvin
Clausius

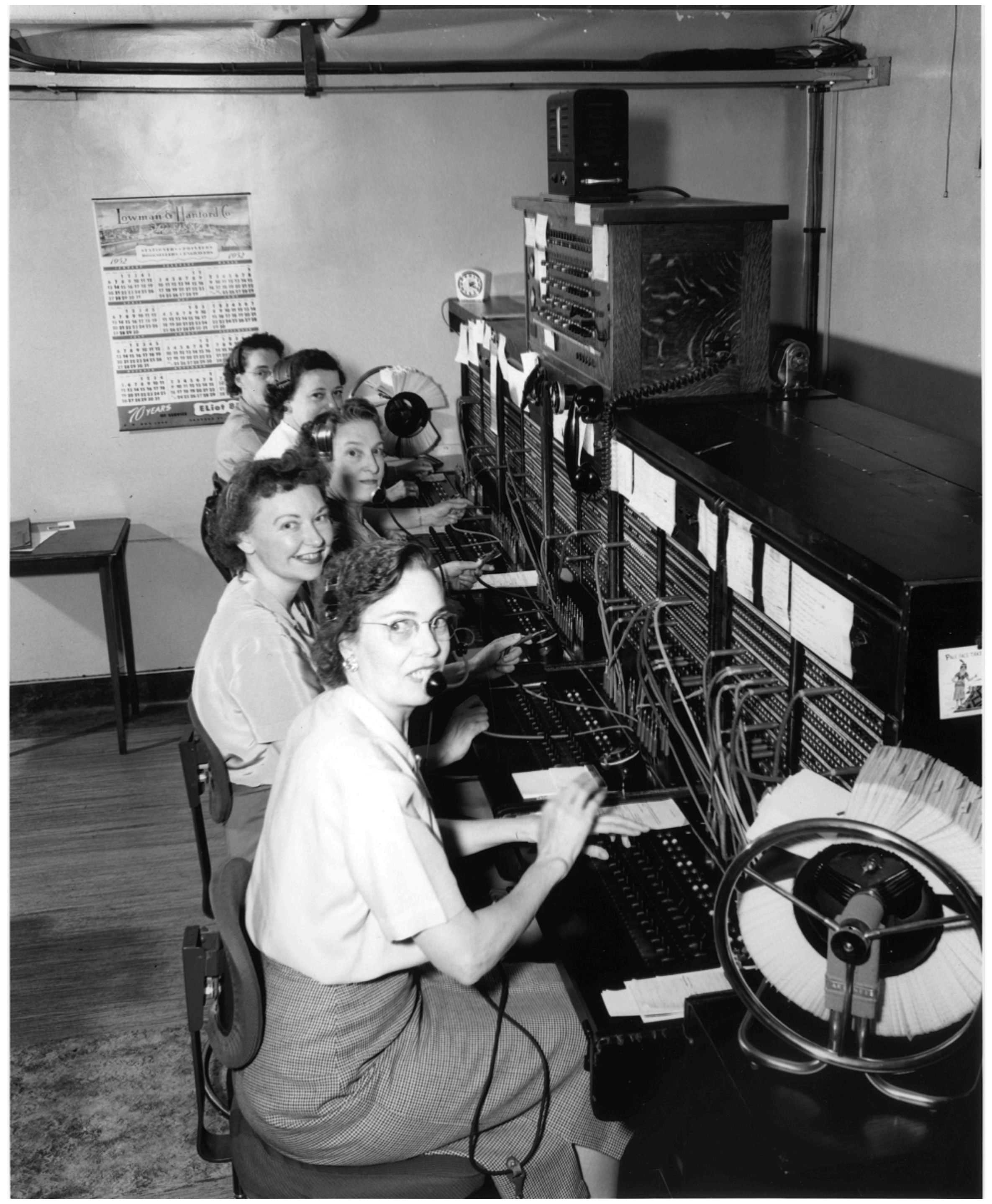
Maxwell
Boltzmann
Gibbs

so forth…

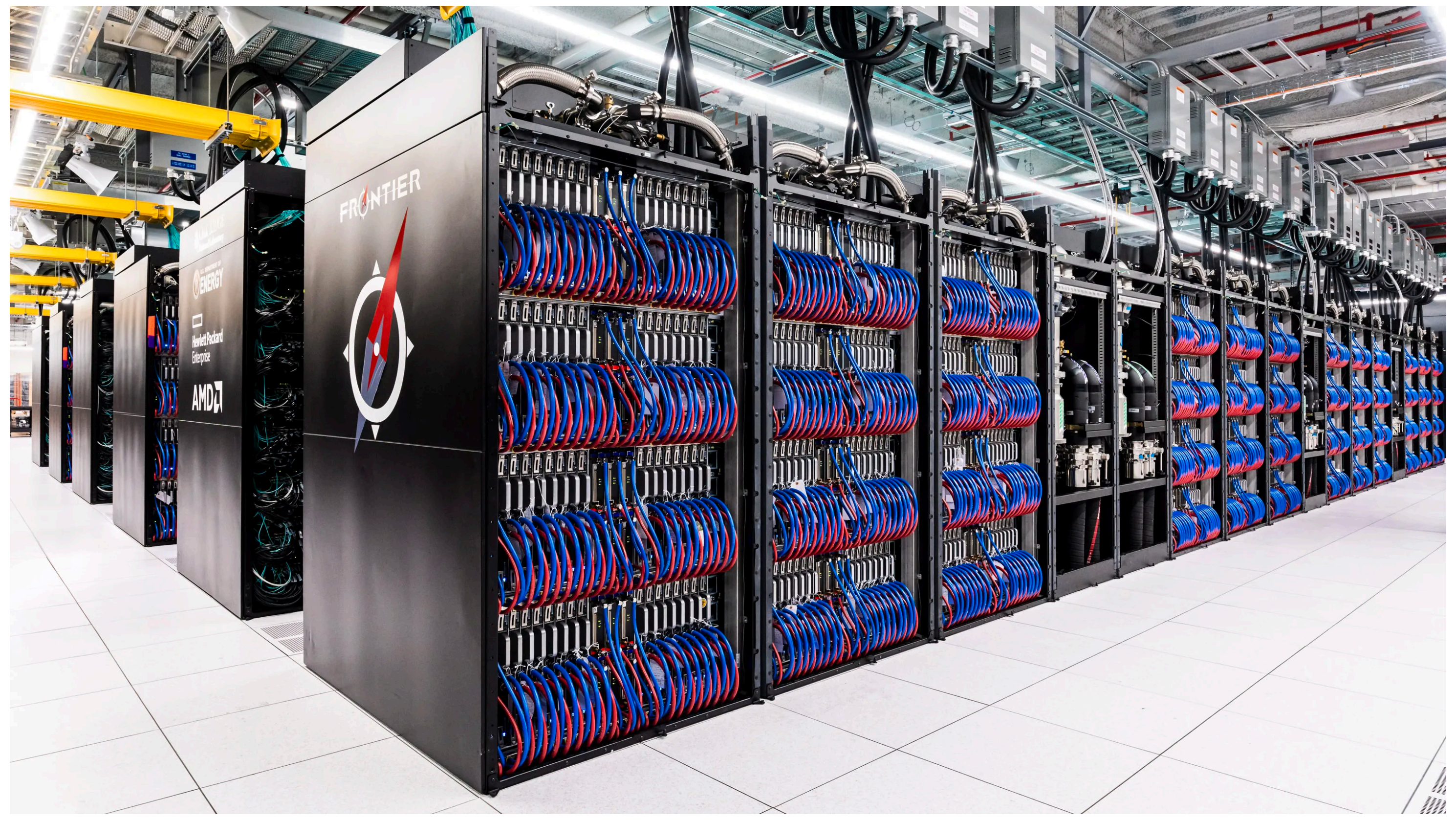
Contemporary Situation

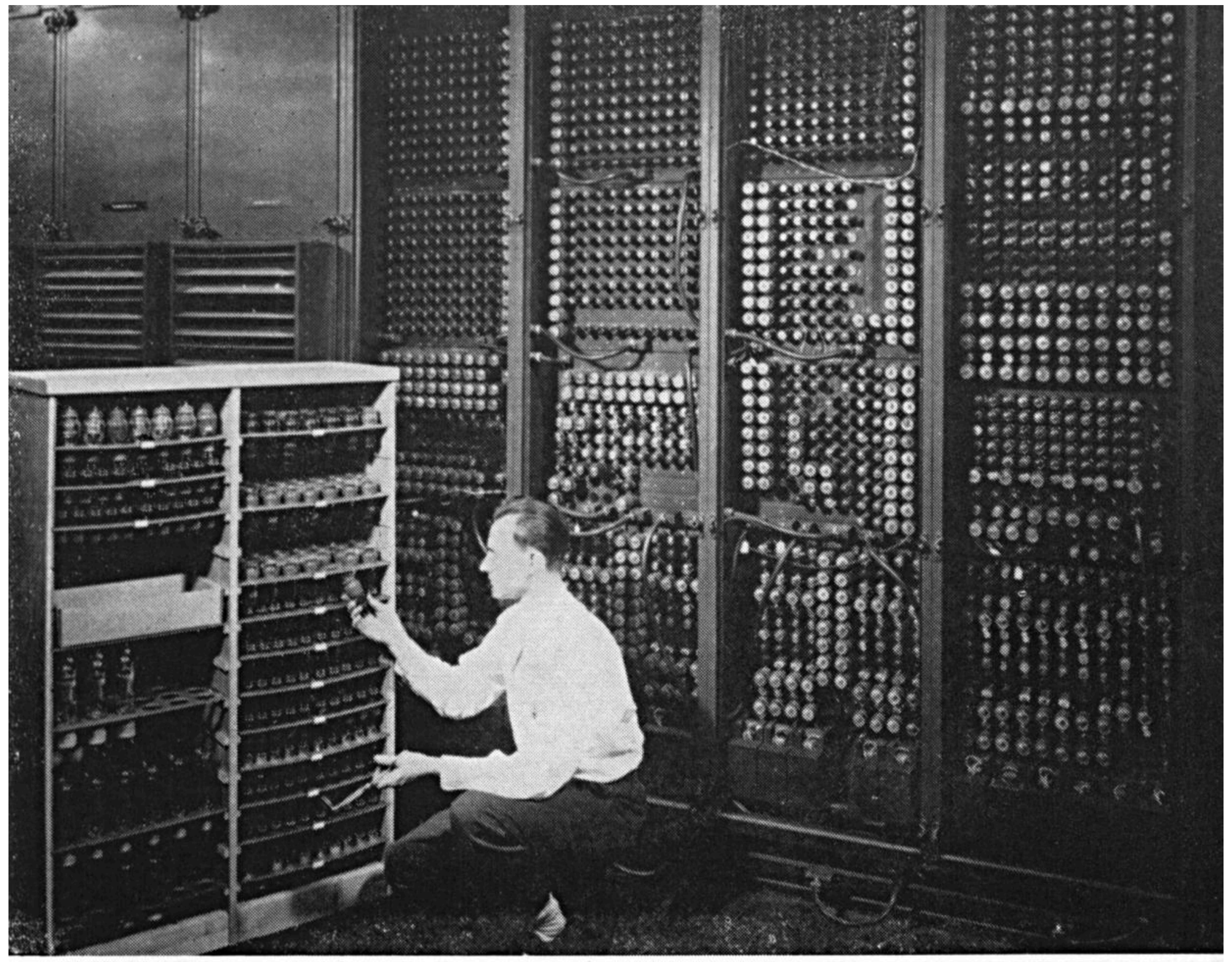
The Information Age $\Longleftrightarrow$?

Information Revolution



1952: Switchboard operators

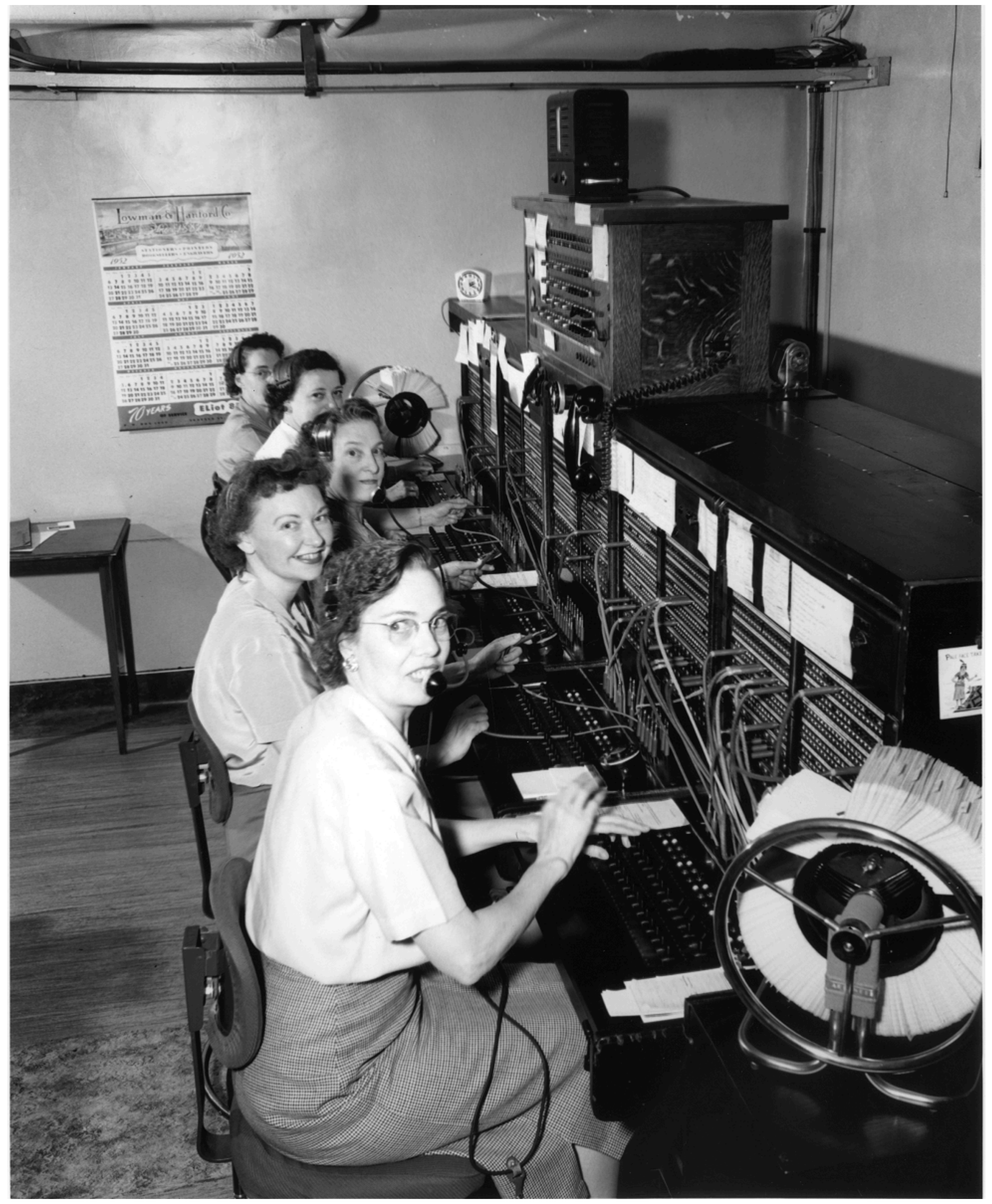




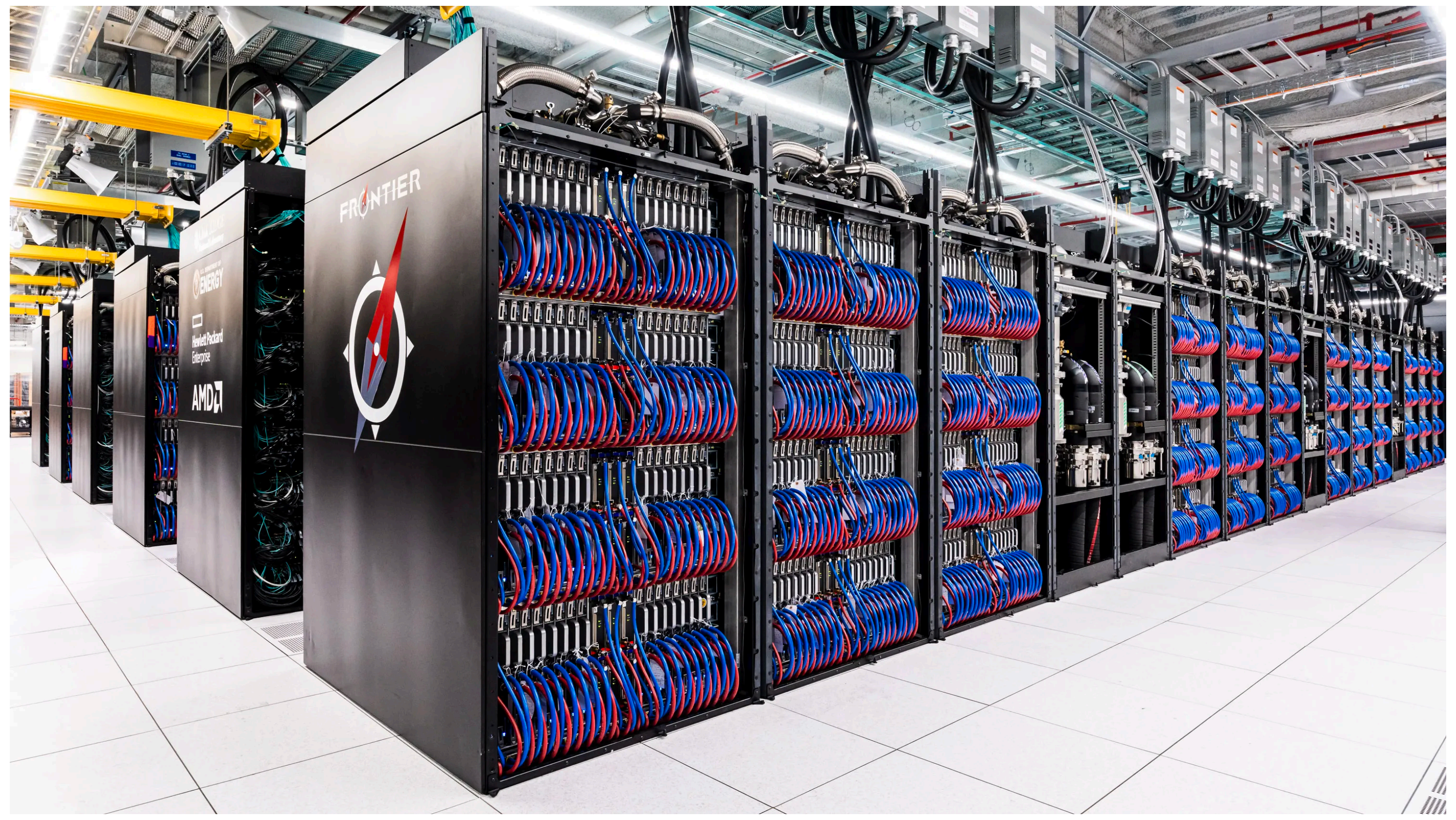
Replacing a bad tube meant checking among ENIAC's 19,000 possibilities.

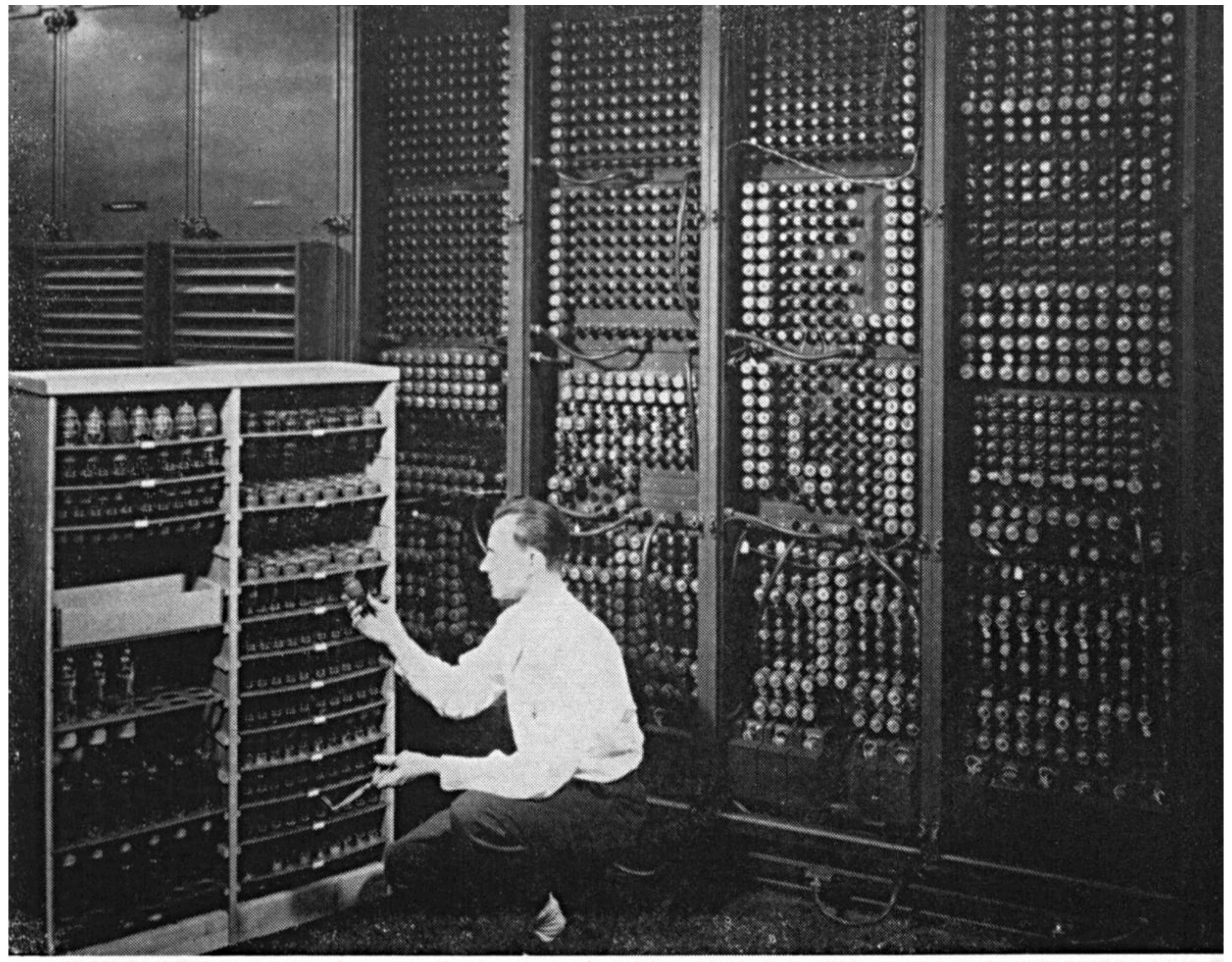
1945: ENIAC

Mathematical Formalization



1952: Switchboard operators





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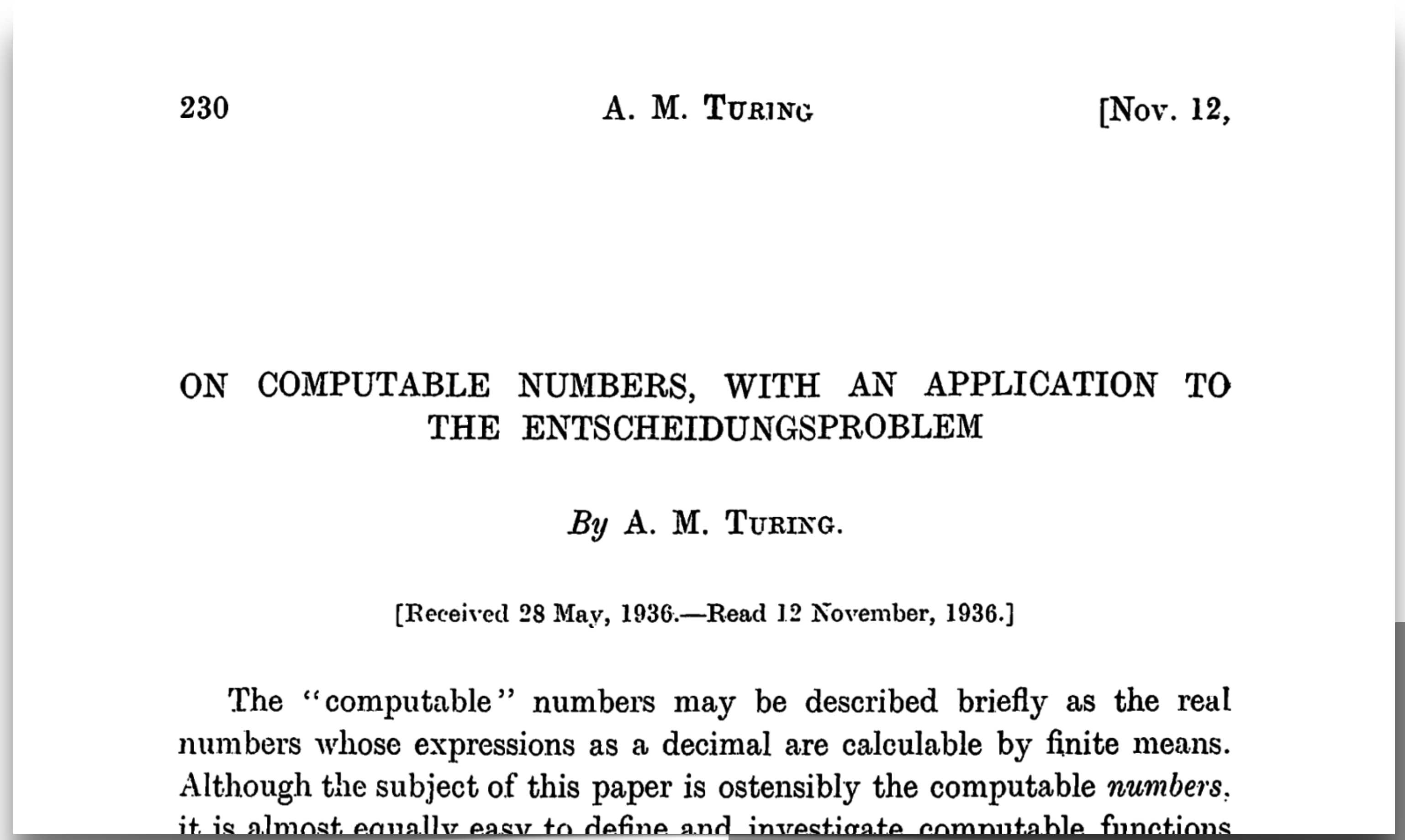


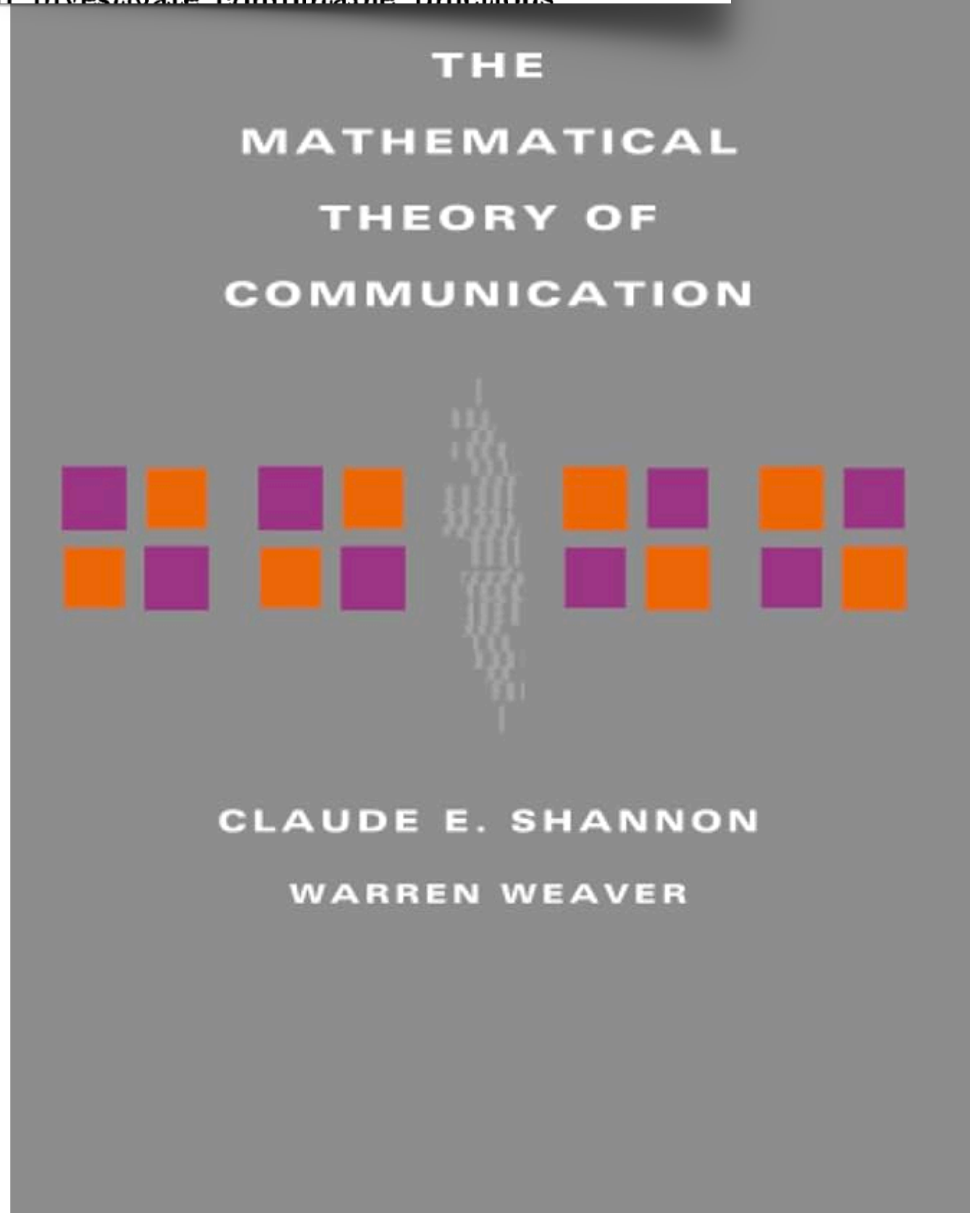
230 A. M. Turing [Nov. 12,

ON COMPUTABLE NUMBERS, WITH AN APPLICATION TO THE ENTSCHEIDUNGSPROBLEM

By A. M. Turing.

[Received 28 May, 1936.—Read 12 November, 1936.]

The "computable" numbers may be described briefly as the real numbers whose expressions as a decimal are calculable by finite means. Although the subject of this paper is ostensibly the computable *numbers*, it is almost equally easy to define and investigate computable functions

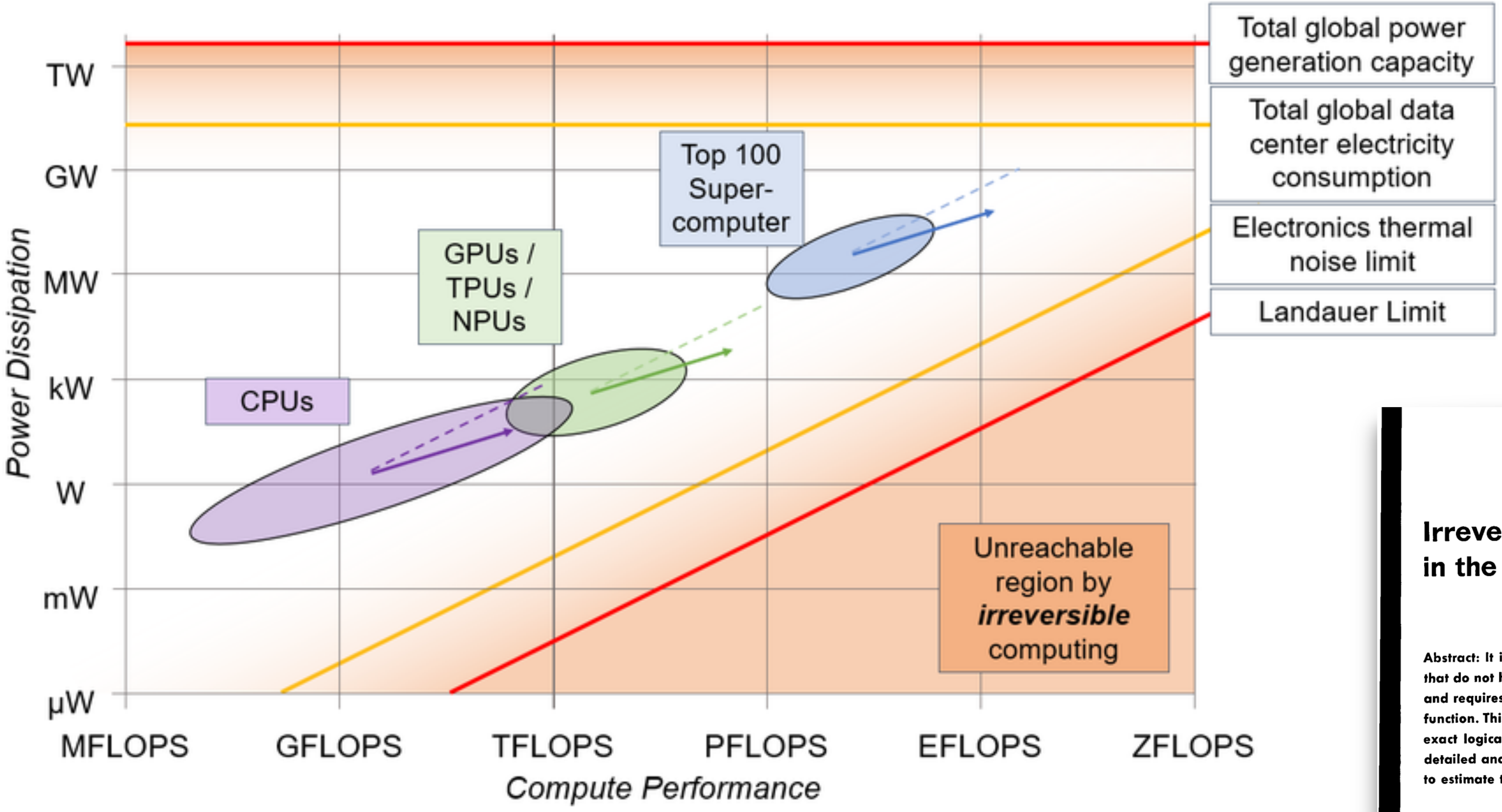


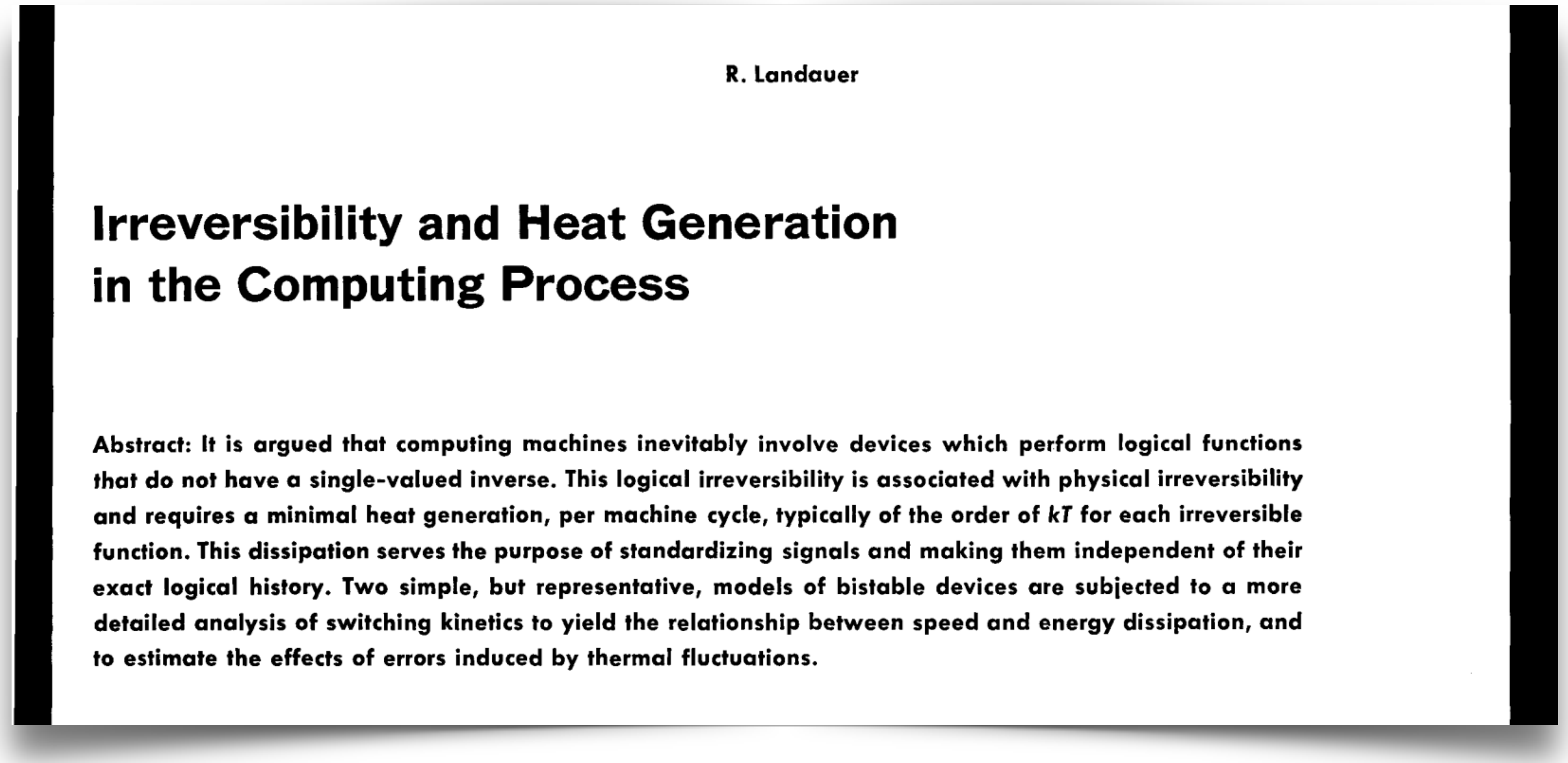
THE MATHEMATICAL THEORY OF COMMUNICATION

CLAUDE E. SHANNON

WARREN WEAVER

Physical Instantiation ?





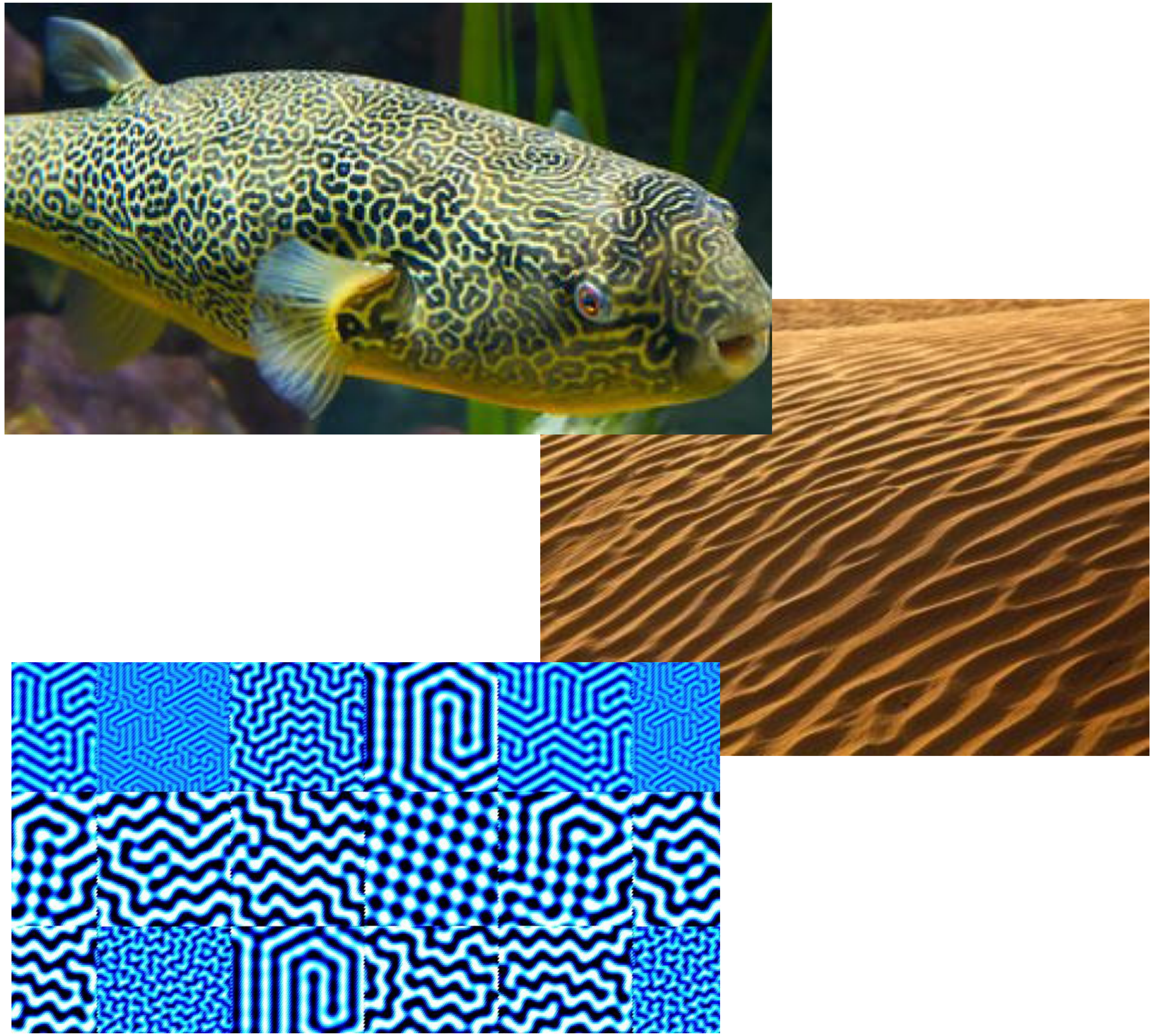
R. Landauer

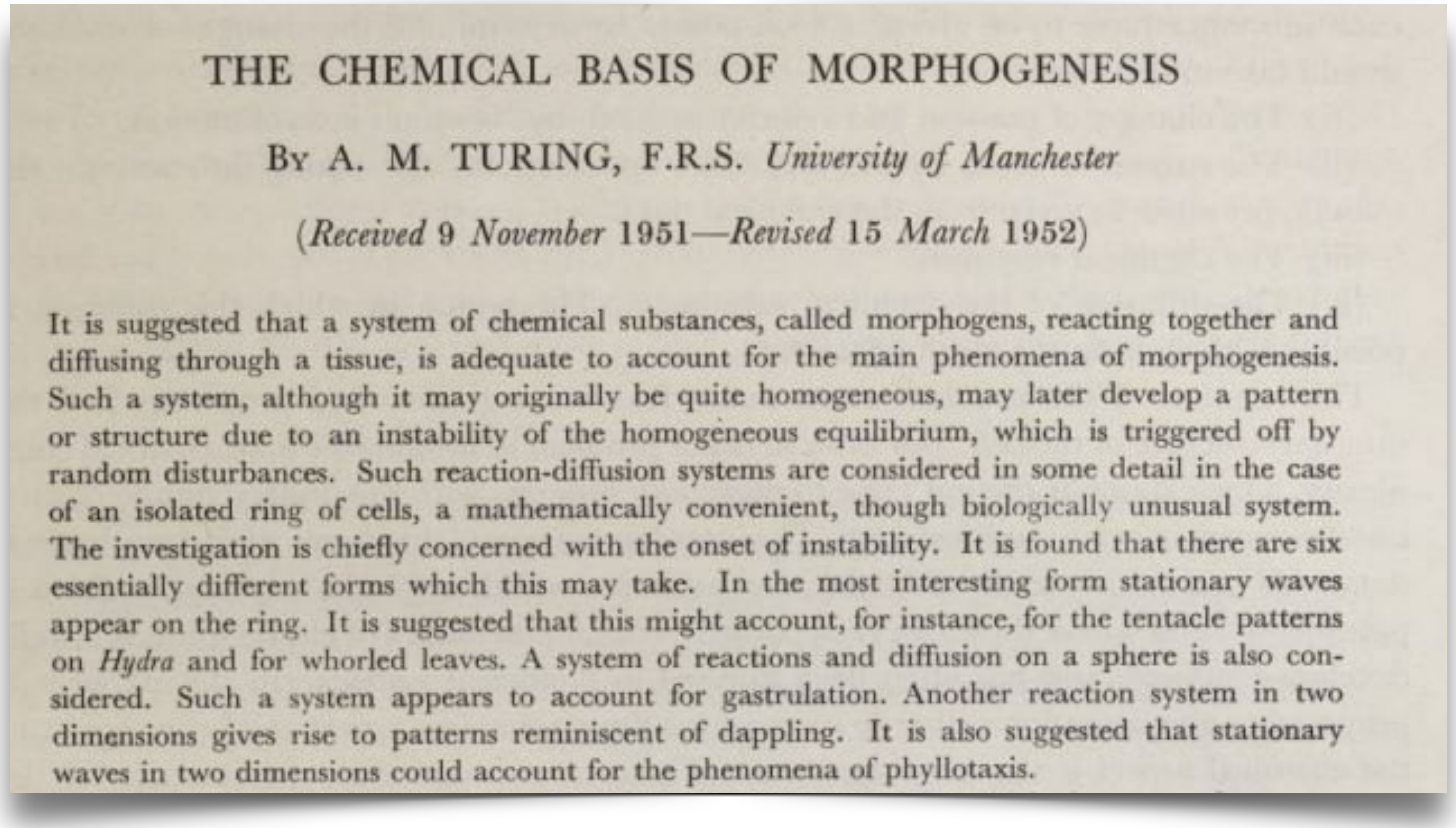
Irreversibility and Heat Generation in the Computing Process

Abstract: It is argued that computing machines inevitably involve devices which perform logical functions that do not have a single-valued inverse. This logical irreversibility is associated with physical irreversibility and requires a minimal heat generation, per machine cycle, typically of the order of *kT* for each irreversible function. This dissipation serves the purpose of standardizing signals and making them independent of their exact logical history. Two simple, but representative, models of bistable devices are subjected to a more detailed analysis of switching kinetics to yield the relationship between speed and energy dissipation, and to estimate the effects of errors induced by thermal fluctuations.

Kissner, Michael & Del Bino, Leonardo & Päsler, Felix & Caruana, Peter & Ghalanos, George. (2024). An All-Optical General-Purpose CPU and Optical Computer Architecture. Journal of Lightwave Technology. PP. 1-15. 10.1109/JLT.2024.3458459.

Emergence of Patterns ?





THE CHEMICAL BASIS OF MORPHOGENESIS

By A. M. TURING, F.R.S. *University of Manchester*

(*Received* 9 *November* 1951—*Revised* 15 *March* 1952)

It is suggested that a system of chemical substances, called morphogens, reacting together and diffusing through a tissue, is adequate to account for the main phenomena of morphogenesis. Such a system, although it may originally be quite homogeneous, may later develop a pattern or structure due to an instability of the homogeneous equilibrium, which is triggered off by random disturbances. Such reaction-diffusion systems are considered in some detail in the case of an isolated ring of cells, a mathematically convenient, though biologically unusual system. The investigation is chiefly concerned with the onset of instability. It is found that there are six essentially different forms which this may take. In the most interesting form stationary waves appear on the ring. It is suggested that this might account, for instance, for the tentacle patterns on *Hydra* and for whorled leaves. A system of reactions and diffusion on a sphere is also considered. Such a system appears to account for gastrulation. Another reaction system in two dimensions gives rise to patterns reminiscent of dappling. It is also suggested that stationary waves in two dimensions could account for the phenomena of phyllotaxis.

Natural information “storage”

Emergence of Behaviors

4 August 1972, Volume 177, Number 4047 **SCIENCE**

More Is Different

Broken symmetry and the nature of the hierarchical structure of science.

P. W. Anderson

The reductionist hypothesis may still be a topic for controversy among philosophers, but among the great majority of active scientists I think it is accepted without question. The workings of our minds and bodies, and of all the animate or inanimate matter of which we have any detailed knowledge, are assumed to be controlled by the same set of fundamental laws, which except under certain extreme conditions we feel we know pretty well.

It seems inevitable to go on uncritically to what appears at first sight to be an obvious corollary of reductionism: that if everything obeys the same fundamental laws, then the only sci-

planation of phenomena in terms of known fundamental laws. As always, distinctions of this kind are not unambiguous, but they are clear in most cases. Solid state physics, plasma physics, and perhaps also biology are extensive. High energy physics and a good part of nuclear physics are intensive. There is always much less intensive research going on than extensive. Once new fundamental laws are discovered, a large and ever increasing activity begins in order to apply the discoveries to hitherto unexplained phenomena. Thus, there are two dimensions to basic research. The frontier of science extends all along a long line from the newest and most modern intensive research, over the extensive research recently spawned by the intensive research of yesterday, to the broad and well developed web of extensive research activities based on intensive

less relevance they seem to have to the very real problems of the rest of science, much less to those of society.

The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other. That is, it seems to me that one may array the sciences roughly linearly in a hierarchy, according to the idea: The elementary entities of science X obey the laws of science Y.

X	Y
solid state or many-body physics	elementary particle physics
chemistry	many-body physics
molecular biology	chemistry
cell biology	molecular biology
•	•
•	•
•	•
psychology	physiology
social sciences	psychology

But this hierarchy does not imply that science X is "just applied Y." At each stage entirely new laws, concepts,

How to do science?

4 August 1972, Volume 177, Number 4047

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Reductionist-constructionist paradigm

↓

Inference paradigm?

Complex Systems: Then and Now

4 August 1972, Volume 177, Number 4047

SCIENCE

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It seems inevitable to go on uncritically to what appears at first sight to be an obvious corollary of reductionism: that if everything obeys the same fundamental laws, then the only scientists who are studying anything really fundamental are those who are working on those laws. In practice, that amounts to some astrophysicists, some elementary particle physicists, some logicians and other mathematicians, and few others. This point of view, which it is the main purpose of this article to oppose, is expressed in a rather well-known passage by Weisskopf (*1*):

> Looking at the development of science in the Twentieth Century one can distinguish two trends, which I will call "intensive" and "extensive" research, lacking a better terminology. In short: intensive research goes for the fundamental laws, extensive research goes for the explanation of phenomena in terms of known fundamental laws. As always, distinctions of this kind are not unambiguous, but they are clear in most cases. Solid state physics, plasma physics, and perhaps also biology are extensive. High energy physics and a good part of nuclear physics are intensive. There is always much less intensive research going on than extensive. Once new fundamental laws are discovered, a large and ever increasing activity begins in order to apply the discoveries to hitherto unexplained phenomena. Thus, there are two dimensions to basic research. The frontier of science extends all along a long line from the newest and most modern intensive research, over the extensive research recently spawned by the intensive research of yesterday, to the broad and well developed web of extensive research activities based on intensive research of past decades.

The effectiveness of this message may be indicated by the fact that I heard it quoted recently by a leader in the field of materials science, who urged the participants at a meeting dedicated to "fundamental problems in condensed matter physics" to accept that there were few or no such problems and that nothing was left but extensive science, which he seemed to equate with device engineering.

The main fallacy in this kind of thinking is that the reductionist hypothesis does not by any means imply a "constructionist" one: The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe. In fact, the more the elementary particle physicists tell us about the nature of the fundamental laws, the less relevance they seem to have to the very real problems of the rest of science, much less to those of society.

The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other. That is, it seems to me that one may array the sciences roughly linearly in a hierarchy, according to the idea: The elementary entities of science X obey the laws of science Y.

X	Y
solid state or many-body physics	elementary particle physics
chemistry	many-body physics
molecular biology	chemistry
cell biology	molecular biology
•	•
•	•
•	•
psychology	physiology
social sciences	psychology

But this hierarchy does not imply that science X is "just applied Y." At each stage entirely new laws, concepts, and generalizations are necessary, requiring inspiration and creativity to just as great a degree as in the previous one. Psychology is not applied biology, nor is biology applied chemistry.

In my own field of many-body physics, we are, perhaps, closer to our fundamental, intensive underpinnings than in any other science in which nontrivial complexities occur, and as a result we have begun to formulate a general theory of just how this shift from quantitative to qualitative differentiation takes place. This formulation, called the theory of "broken symmetry," may be of help in making more generally clear the breakdown of the constructionist converse of reductionism. I will give an elementary and incomplete explanation of these ideas, and then go on to some more general speculative comments about analogies at

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The author is a member of the technical staff of the Bell Telephone Laboratories, Murray Hill, New Jersey 07974, and visiting professor of theoretical physics at Cavendish Laboratory, Cambridge, England. This article is an expanded version of a Regents' Lecture given in 1967 at the University of California, La Jolla.

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1972

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VIEWPOINT

Fifty years of 'More is different'

Steven Strogatz, Sara Walker, Julia M. Yeomans, Corina Tarnita, Elsa Arcaute, Manlio De Domenico, Oriol Artime and Kwang-Il Goh

August 1972 saw the publication of Philip Anderson's essay 'More is different'. In it, he crystallized the idea of emergence, arguing that "at each level of complexity entirely new properties appear" — that is, although, for example, chemistry is subject to the laws of physics, we cannot infer the field of chemistry from our knowledge of physics. Fifty years on from this landmark publication, eight scientists describe the most interesting phenomena that emerge in their fields.

Steven Strogatz: More than the sum

In 1665, while confined to his room with "a slight indisposition", Christiaan Huygens noticed that two pendulum clocks he had recently built were keeping perfect time together. When one clock's pendulum swung to the right, the other's swung to the left, exactly 180 degrees out of phase. When Huygens tried disturbing their oscillations, he found to his astonishment that the board from which both clocks were suspended began to jiggle. That jiggling gradually nudged the pendulums back into antiphase synchrony. In letters to his correspondents, he described this "odd sympathy" of clocks as "marvelous".

Huygens's work launched the study of synchronization, a phenomenon that pervades the natural and technological world, from congregations of fireflies that flash in unison to arrays of superconducting Josephson junctions. Yet although more than 350 years have passed since Huygens's observations, we still don't fully understand the sympathy of pendulum clocks mathematically.

The main obstacle is that synchronization is a nonlinear phenomenon, which makes the governing equations impossible to solve explicitly. On top of that, the equations include non-smooth, impulsive effects, stemming from the sudden jolts imparted by the clocks' escapement mechanisms.

In this way, the sympathy of clocks exemplifies what Philip Anderson discussed in 'More is different'[1]. Even though we know the laws for individual pendulum clocks, that isn't enough to tell us how two or more of them will behave together.

Sara Walker: Broken symmetry

In the study of life's origin, one cannot avoid emergence. Life itself is an emergent property: a cell is alive, but its parts are not. To adopt Anderson's words, the ability to reduce life to simple fundamental parts does not imply the ability to start from those parts and reconstruct life. Indeed, attempts to solve the origin of life have not yet succeeded, even though we have detailed knowledge of molecular biology.

What are we missing? The answer is ordering in time — life is historically contingent. Darwin spoke of "endless forms most beautiful" in contradistinction to Newton's fixed law of gravity[2] for good reason: only in living things do we see path-dependence and mixing of histories to generate new forms; each evolutionary innovation builds on those that came before, and often these innovations interact across time, with more ancient forms interacting with more modern ones.

Anderson argued that broken symmetries underlie emergence. The broken symmetry of time is most obvious in looking at life's parts. Even macromolecules like proteins, DNA and RNA are still part of 'life' if not alive: they do not emerge in the Universe without an evolutionary process selecting machinery to assemble them[3]. This ordering in time is driven by life's "information-bearing crystallinity", as Anderson put it. Each innovation, whether a mutation in a genome or in human language, yields affordances for future events in a manner different from the directionality in time illuminated in the second law of thermodynamics. If we are to explain the emergence of life, we need to understand how information breaks symmetry in time.

Julia M. Yeomans: Self-assembly and control mechanisms

Living systems are highly complex machines: cells need to assemble molecular structures that can use chemical energy to perform the complex tasks needed for life processes. The challenges of creating artificial cells underline the intricacy of the emergent self-assembly and control mechanisms that enable life to function.

For example, cells need a way to internally transport cargo. They achieve this using a continually evolving network of tracks consisting of polymeric filaments that grow and disassemble, on which motor proteins carry their loads. In another example, bacteria swim using a rotary motor to turn their flagella at speeds of about 500 revolutions per minute. The motor is an organized array of specialized proteins, about 45 nm in diameter. These form a rotor, driven by a proton flux, which spins relative to the cell within a stator which is anchored to the cell wall. And an embryo is transformed from a small ball of cells to a grown animal by a sequence of steps that involve movements and division of localized groups of cells. Each step must be programmed to occur at specific places and times.

How are these examples of self-assembly and morphogenesis mediated? Living systems operate out of thermodynamic equilibrium. Hence they are increasingly being described using the ideas of active matter physics, which treats materials where each particle continually uses energy to move. Studies of self-assembly in active systems may give insight into the extent to which there are underlying, generic principles at work in biological design, which can then be used to help fabricate efficient microscopic machines.

Corina Tarnita: Emerging patterns

Unparalleled architectural feats, division of labour, agriculture and animal husbandry —

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Complex Systems Topics Overview

Alan Turing

Structure

Spontaneous pattern formation?

How to detect and define?

Emergence of “something new”

Complexity

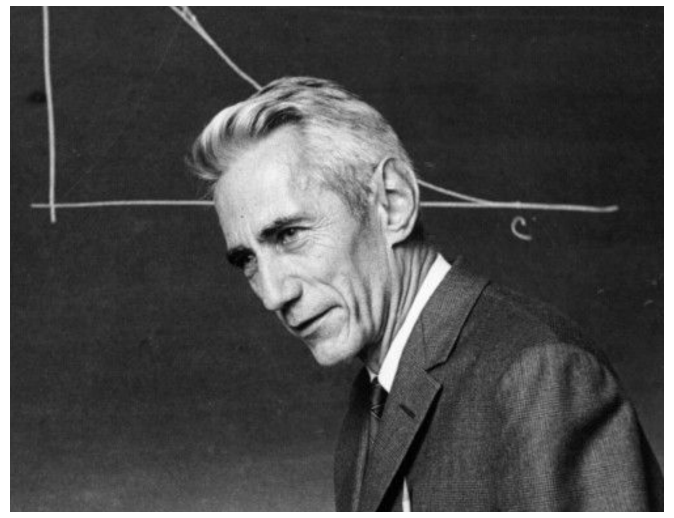
How to quantify? Build models?

Hierarchical structures?

In natural systems?

Thermodynamics of information processing?

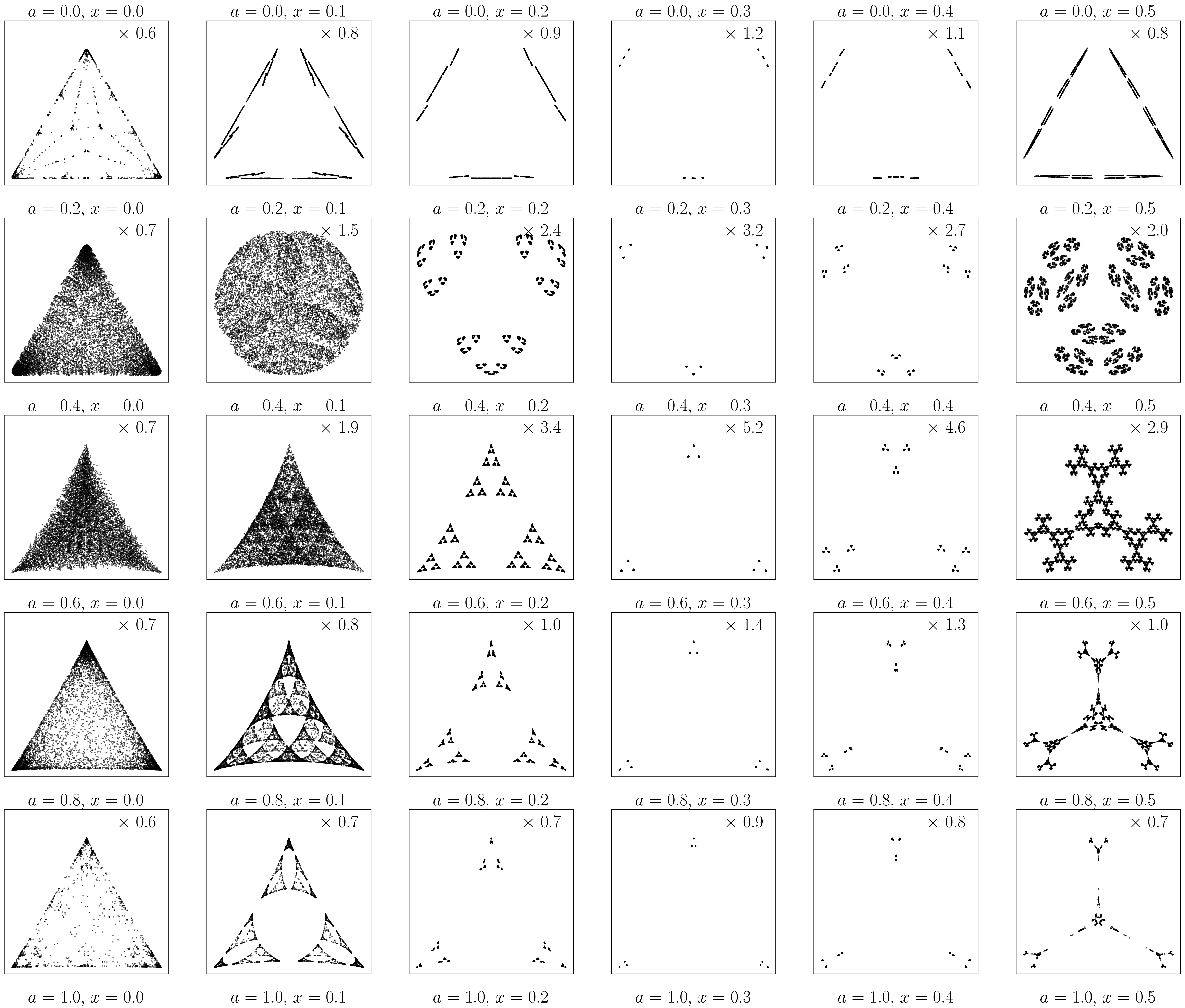
Information



Claude Shannon

Dissertation: Divergent Complexity

Characterizing the complexity of optimal models



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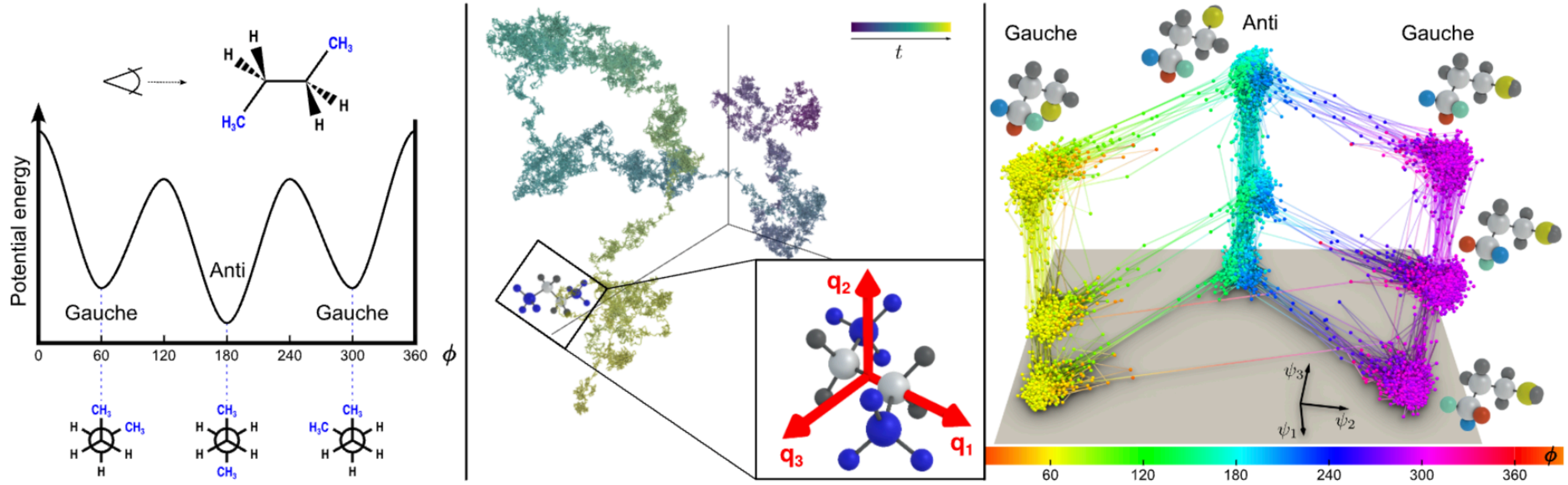
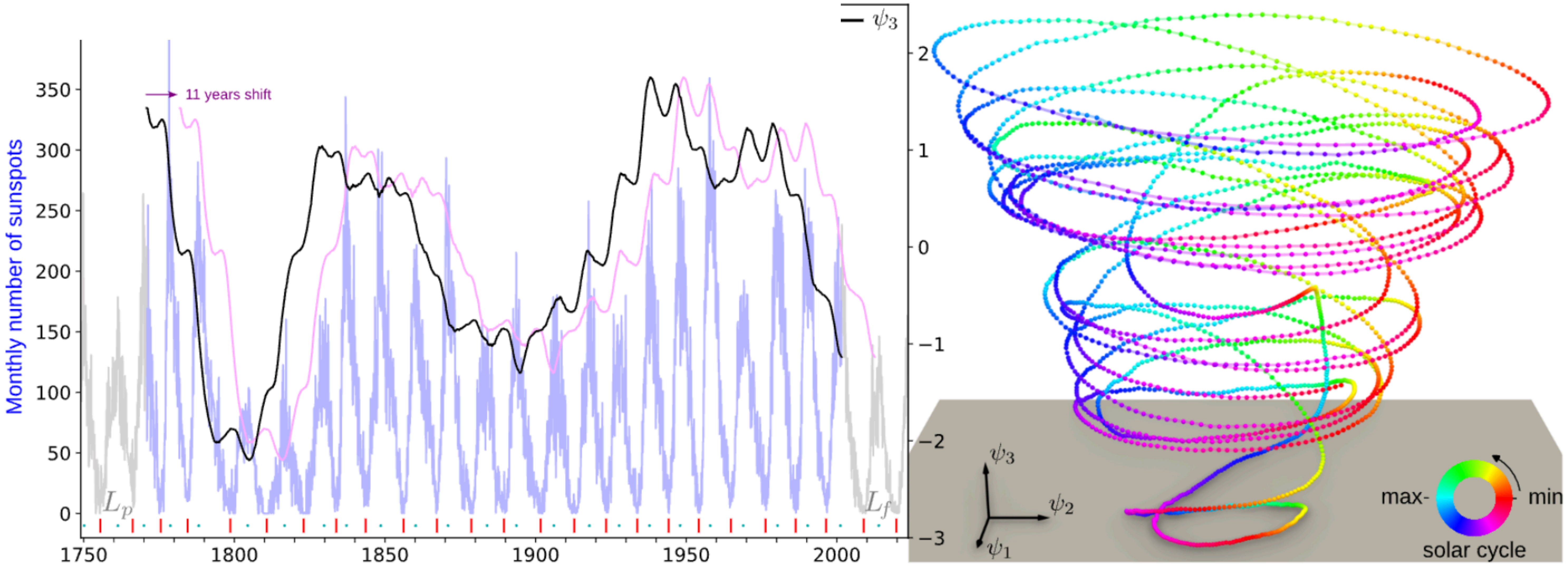
My Research: Structure Discovery





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Questions ?