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# Randomness, Imperfection, Uncertainty In Science and Arts: Toward Quantum Music

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# ICFO – Quantum Optics Theory

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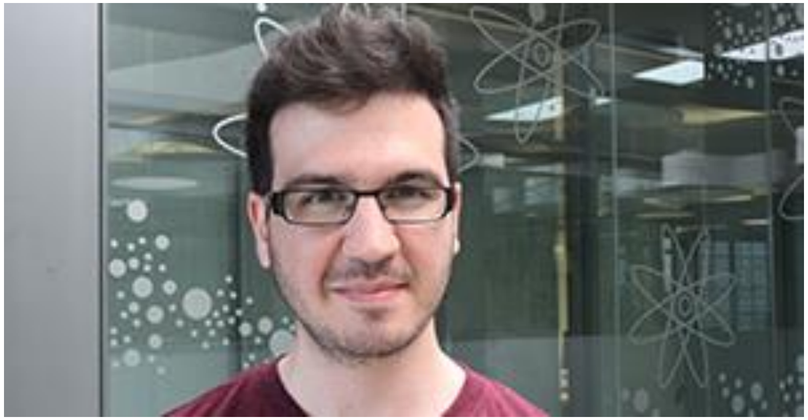

Albert Aloy

Maciek Lewenstein

# Outline

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## Part I

1. Randomness and unpredictability of classical physics+
2. Randomness and unpredictability in music composition:

   Introduction & Initial thought

## Part II

3. Randomness and unpredictability of quantum physics
4. Advanced treatment of Randomness and Unpredictability

   in music : Still deterministic?

## Part III

5. Toward Quantum Music?

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# Part I

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1. Randomness and unpredictability of classical physics

   i) Laplace's determinism

   ii) Complexity of classical many body systems

   iii) Deterministic chaos

2. Randomness and unpredictability in music composition: Introduction & Initial thought

   i) Chance operation: John Cage

   ii) *Musique concrète*: Pierre Schaeffer

   iii) Computer-assisted algorithmic composition: Iannis Xenakis

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## Epistemic and ontic character of probability

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**Def. 1 – Apparent (a.k.a. epistemic) randomness.**

Apparent randomness is the randomness that results exclusively from a lack of full knowledge about the state of the system in consideration. Had we known the initial state of the system exactly, we could have predicted its future evolution exactly. Probabilities and stochastic processes are used here as an *efficient tool* to describe at least a partial knowledge about the system and its features. Apparent randomness implies and requires existence of the, so called, underlying *hidden variable theory*. It is the lack of knowledge of hidden variables that causes apparent randomness. Had we known them, we could have make predictions with certainty.

## Epistemic and ontic character of probability



**Def. 2 – Intrinsic (a.k.a. inherent or ontic) randomness.** Intrinsic randomness is the randomness that persists even if we have the full knowledge about the state of the system in consideration. Even exact knowledge of the initial state does not allow to predict future evolution exactly: we can only make probabilistic predictions. Probabilities and stochastic processes are used here as a *necessary and inevitable tool* to describe our knowledge about the system and its behavior. Of

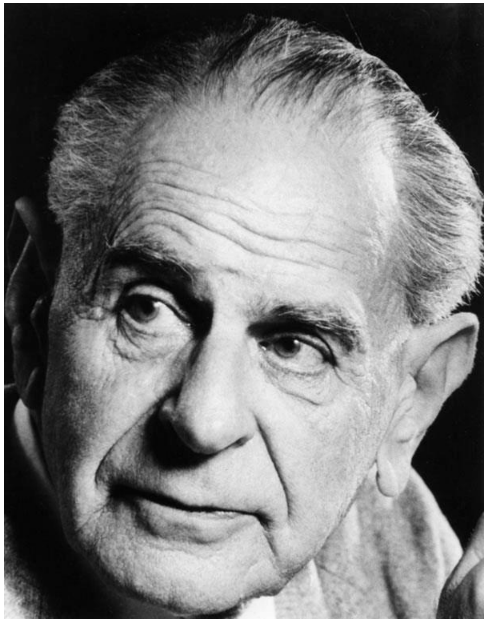
# 1.2 Randomness in classical physics – Determinism?

of determinism that of Pierre Simon de Laplace (Laplace, 1814): '*Une intelligence qui, pour un instant donné, connaîtrait toutes les forces dont la nature est animée, et la situation respective des êtres qui la composent, si d'ailleurs elle était assez vaste pour soumettre ces données à l'analyse, embrasserait dans la même formule les mouvemens des plus grands corps de l'univers et ceux du plus léger atome : rien ne serait incertain pour elle, et l'avenir comme le passé, serait présent á ses yeux.*[5] Two hundred years later Karl Raimund

**Pierre-Simon Laplace (23 de març del 1749, Beaumont-en-Auge, Normandia - 5 de març del 1827, París), fou un brillant matemàtic, astrònom i físic francès.**

# 1.2 Randomness in classical physics

follows: The doctrine of 'scientific' determinism is the doctrine that the state of any closed physical system at any given future instant of time can be predicted, even from within the system, with any specified degree of precision, by deducing the prediction from theories, in conjunction with initial conditions whose required degree of precision can always be calculated (in accordance with the principle of accountability) if the prediction task is given' (Popper, 1982). By contraposition thus, unpredictability implies indeterminism. If we now



*Sir* Karl Raimund Popper, Kt, CH, FRS, FBA (Viena, Imperi austrohongarès, 28 de juliol de 1902 - Londres, Anglaterra, 17 de setembre de 1994) fou un dels filòsofs i sociòlegs més importants del segle XX.

# 1. Randomness in classical physics

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Henri Poincaré

Marian Smoluchowski

initial conditions. In fact such a sensitiveness was pointed as a source of chance by Poincaré[12] and Smoluchowski[13] soon after modern statistical physics was born, but it is hard to argue that this gives to the chance an ontological status. It is, however, worth mentioning that Poincaré was aware that randomness might have not only epistemic character. In the above cited Introduction to his *Calcul des probabilités* he states '*Il faut donc bien que le hasard soit autre chose que le nom que nous donnons à notre ignorance*'[14], ('So it must be well that chance is something other than the name we give our ignorance'[15]).

[16] '...ein ganz wesentliches Merkmal desjenigen, was man im gewöhnlichen Leben oder in unserer Wissenschaft als Zufall bezeichnet ... läßt sich ... kurz in die Worte fassen: *kleine Ursache—große Wirkung*', Smoluchowski (1918) ('...fundamental feature of what one calls chance in everyday life or in science allows a short formulation: *small cause—big effect*').

Smoluchowski M V 1918 Über den Begriff des Zufalls und den Ursprung der Wahrscheinlichkeitsgesetze in der Physik *Naturwissenschaften* 6 253–63

# 1. Randomness and unpredictability of classical physics

i) Laplace's determinism – in practice?

ii) Complexity of classical many body systems

In the macroscopic system there are 10^23 (Avogadro number) of particles… = APPARENT RANDOMNESS

iii) Deterministic chaos

Even few body systems may exhibit strong sensibility to intial conditions (butterfly effect) due to strong nonlinear nature of the motions = APPARENT RANDOMNESS

**Moral: Use approximate description: thermodynamics, statistical physics**

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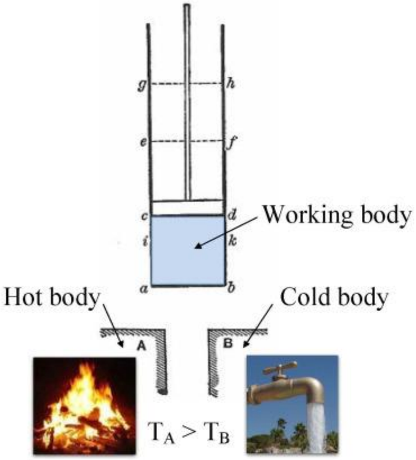
## Thermodynamics – a success story

Thermodynamics is a branch of science concerned with heat and temperature and their relation to energy and work. The behavior of these quantities is governed by the laws of thermodynamics, irrespective of the composition or specific properties of the material or system in question.

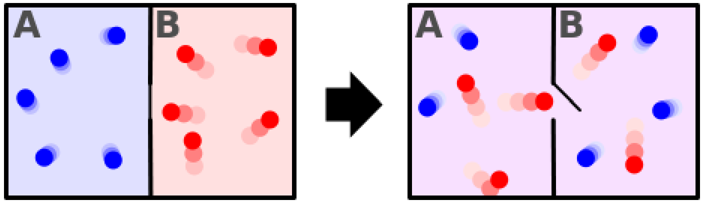
Historically, thermodynamics developed out of a desire to increase the efficiency of early steam engines, particularly through the work of French physicist Nicolas Léonard Sadi Carnot (1824). Rudolf Clausius and Lord Kelvin formalized the second law of thermodynamics and define the concept of entropy.



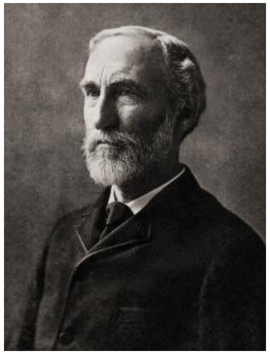
# 1. Randomness in classical physics

## Thermodynamics, statistical mechanics and information theory

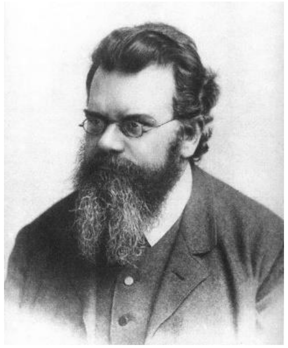
Statistical mechanics is a branch of theoretical physics using probability theory to study the average behaviour of a mechanical system, where the state of the system is "uncertain".




James Clerk Maxwell



Josiah Willard Gibbs



Ludwig Boltzmann

A common use of statistical mechanics is in explaining the thermodynamic behaviour of large systems. Microscopic mechanical laws do not contain concepts such as temperature, heat, or entropy; however, statistical mechanics shows how these concepts arise from the uncertainty about the state of a system.

Classical statistical mechanics "works" also for small systems: Deteministic chaos!!!

# 2. Randomness and unpredictability in music:
## Cage - a chance as a governing principle

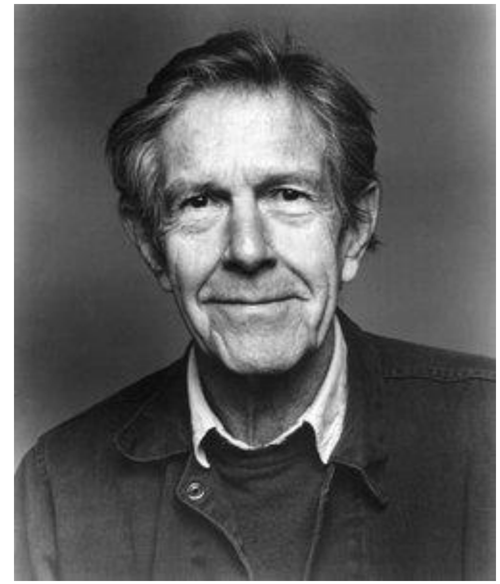
**The role of art is the 'imitation of nature in her mode of operation'**

Music of Changes (1951)

Tania Caroline Chen, piano

- Seeking a balance between rational and irrational
- Bypassing a reliance on his aesthetic judgement
- Westernized adaptation of I-ching and the influence of Buddhist philosophy
- I-ching (100—750BC): complex random number operation to be used in divination

**Chance operations for organizing pre-composed materials**



**John Milton Cage Jr. (1912-1992)**

Aleatoric music, graphic scores, prepared and unconventional instruments, chance and game operations (i.e. 4'33" -1952)

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# 2. Randomness and unpredictability in music:
## *Schaeffer – musique concrete, objet sonore*

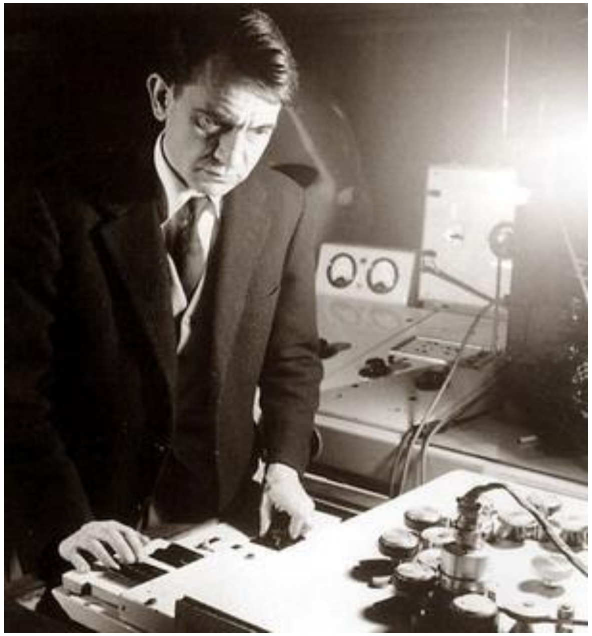
**Musique concrete:**

music made of raw sounds (i.e. thunderstorms, steam-engines) and not produced by traditional acoustic musical instruments; They are captured on tape and manipulated to form sound-structures.

"I have coined the term musique concrète for this commitment to compose with materials taken from 'given' experimental sound in order to emphasize our dependence, no longer on preconceived sound abstractions, but on sound fragments that exist in reality and that are considered as discrete and complete sound objects …"

**The work method is**

- **Empirical**
- **Starts from the concrete, given sounds and moves towards a structure**



**Pierre Schaeffer (1910-1995)**

L'Oiseau Rai (1950)
Fixed medium, 2'58"

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# 2. Randomness and unpredictability in music:
## Xenakis- computer assisted algorithmic composition

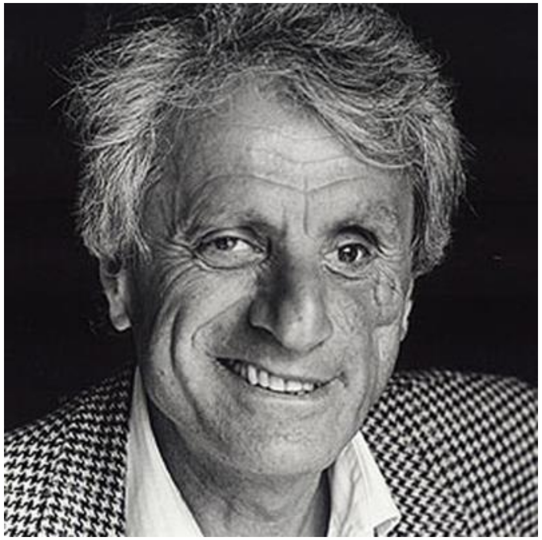
**Algorithmic and stochastic compositions**
i.e. Atrees (1962) Morisma-amorsima (1962)

Using the computer's high-speed computations to calculate various probability theories to aid in compositions.

The program would "deduce" a score from a "list of note densities and probabilistic weights supplied by the programmer, leaving specific decisions to a random number generator"

these scores were performed by live performers on traditional instruments.

**Based on deterministic randomness**



**Iannis Xenakis (1922-2001)**

Composer and architect; mathematics, statistics, and physics applied to music composition (set theory, stochastic processes, game theory); electronic and computer music (UPIC system); integration of architecture into music

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## 3. Randomness and unpredictability of quantum physics

i) Axioms of quantum physics and intrinsic randomness

ii) Essence of quantum physics:

- INTRINSIC randomness
- particle/wave duality; superpositions
- correlations

## 4. Advanced treatment of Randomness and Unpredictability in music : Still deterministic?

i) Chaos game : Alvin Lucier

ii) AI approach

iii) 4'33"

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# 3. Randomness and unpredictability of quantum physics

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The postulates of QM for simple mechanical systems (single or many particle), as given in (Cohen-Tannoudji et al., 1991), read:

- **First Postulate.** At a fixed time $t_0$, the state of a physical system is defined by specifying a wave function $\psi(x; t_0)$, where $x$ represents collection of parameters to specify the state.
- **Second Postulate.** Every measurable physical quantity $Q$ is described by an operator $\hat{Q}$; this operator is called an observable.
- **Third Postulate.** The only possible result of the measurement of a physical quantity $Q$ is one of the eigenvalues of the corresponding observable $\hat{Q}$.
- **Fourth Postulate (non-degenerate case).** When the physical quantity $Q$ is measured on a system in the normalized state $\psi$, the probability $P(q_n)$ of obtaining the non-degenerate eigenvalue $q_n$ of the corresponding observable $\hat{Q}$ is

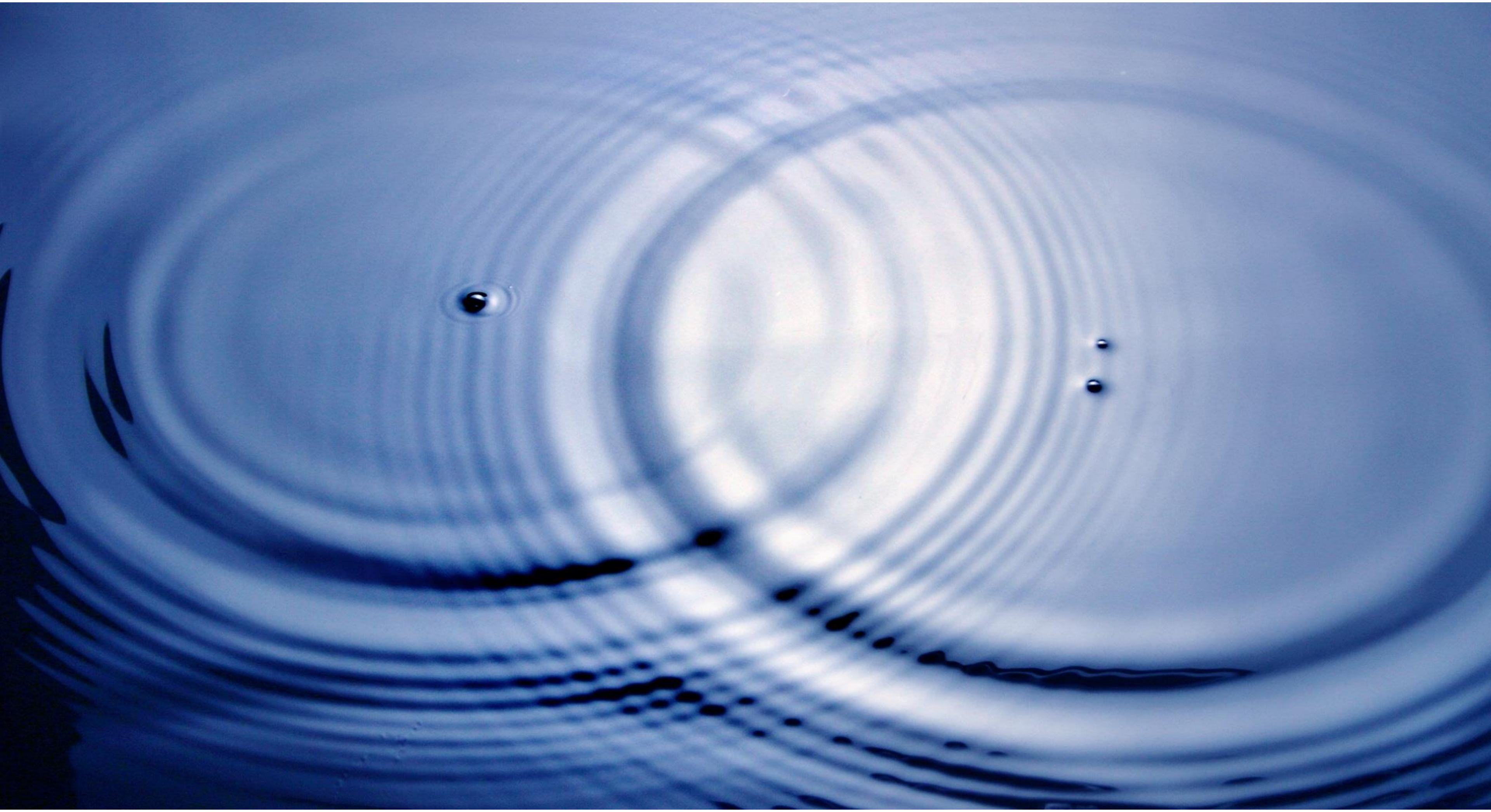
$$P(q_n)=|\langle\phi_n|\psi\rangle|^2$$

- **Fifth Postulate (collapse).** If the measurement of the physical quantity $Q$ on the system in the state $\psi$ gives the result $q_n$, the state of the system immediately after the measurement is $\varphi_n$.
- **Sixth Postulate (time evolution).** The time evolution of the wave function $\psi(x; t)$ is governed by the Schrödinger equation

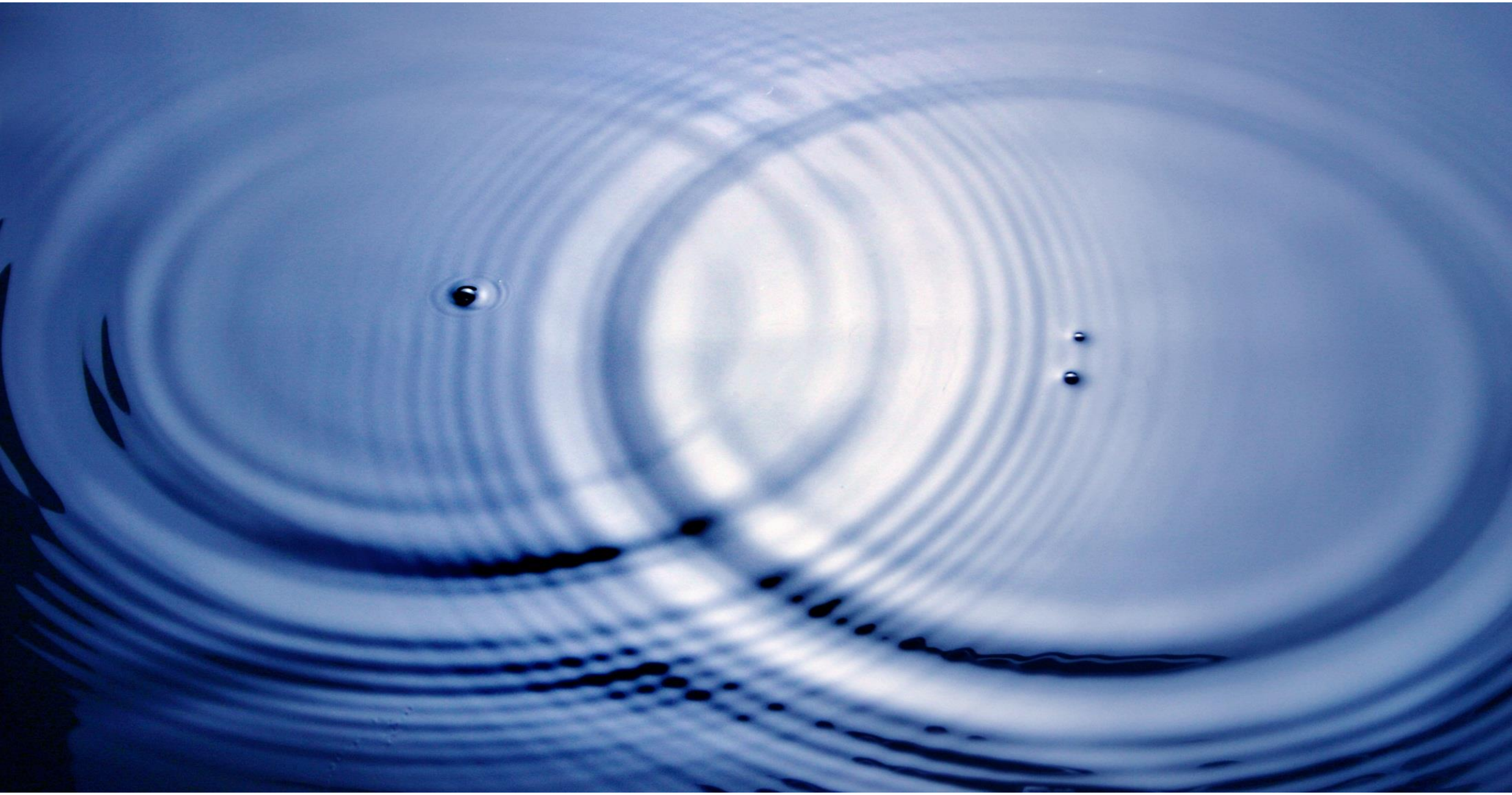
$$i\hbar\frac{\partial\psi}{\partial t} = \hat{H}\psi,$$

  where $\hat{H}$ is the observable associated with the total energy of the system.
- **Seventh Postulate (symmetrization).** When a system includes several identical particles, only certain wave functions can describe its physical states (leads to the concept of bosons and fermions). For electrons (which are fermions), the wave function must change sign whenever the coordinates of two electrons are interchanged. For hydrogen atoms (regarded as composite bosons) the wave function must not change whenever the coordinates of two bosons are interchanged.

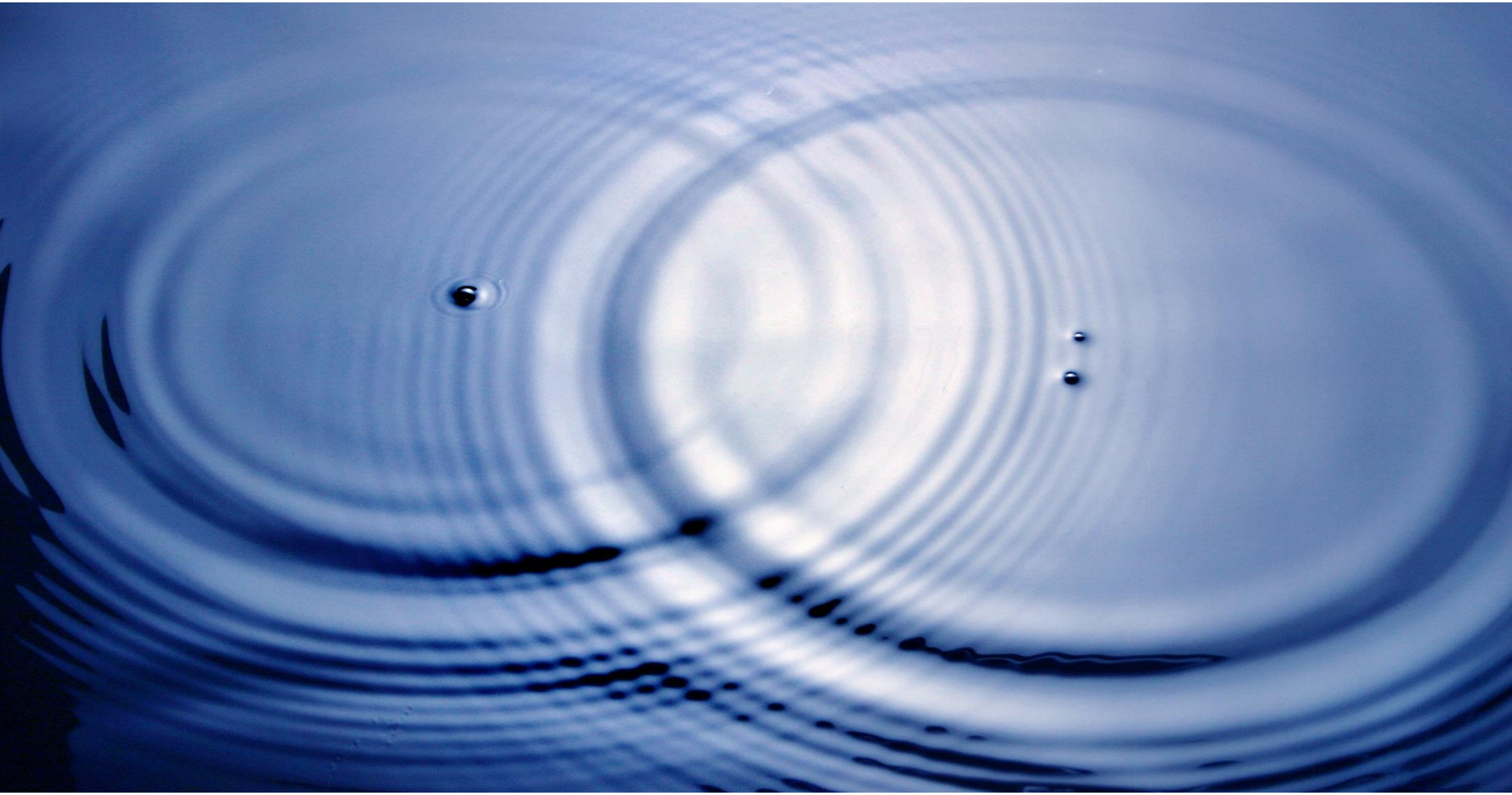
# Essence of quantum physics: Quantum Mechanics = Patricle-Wave Duality



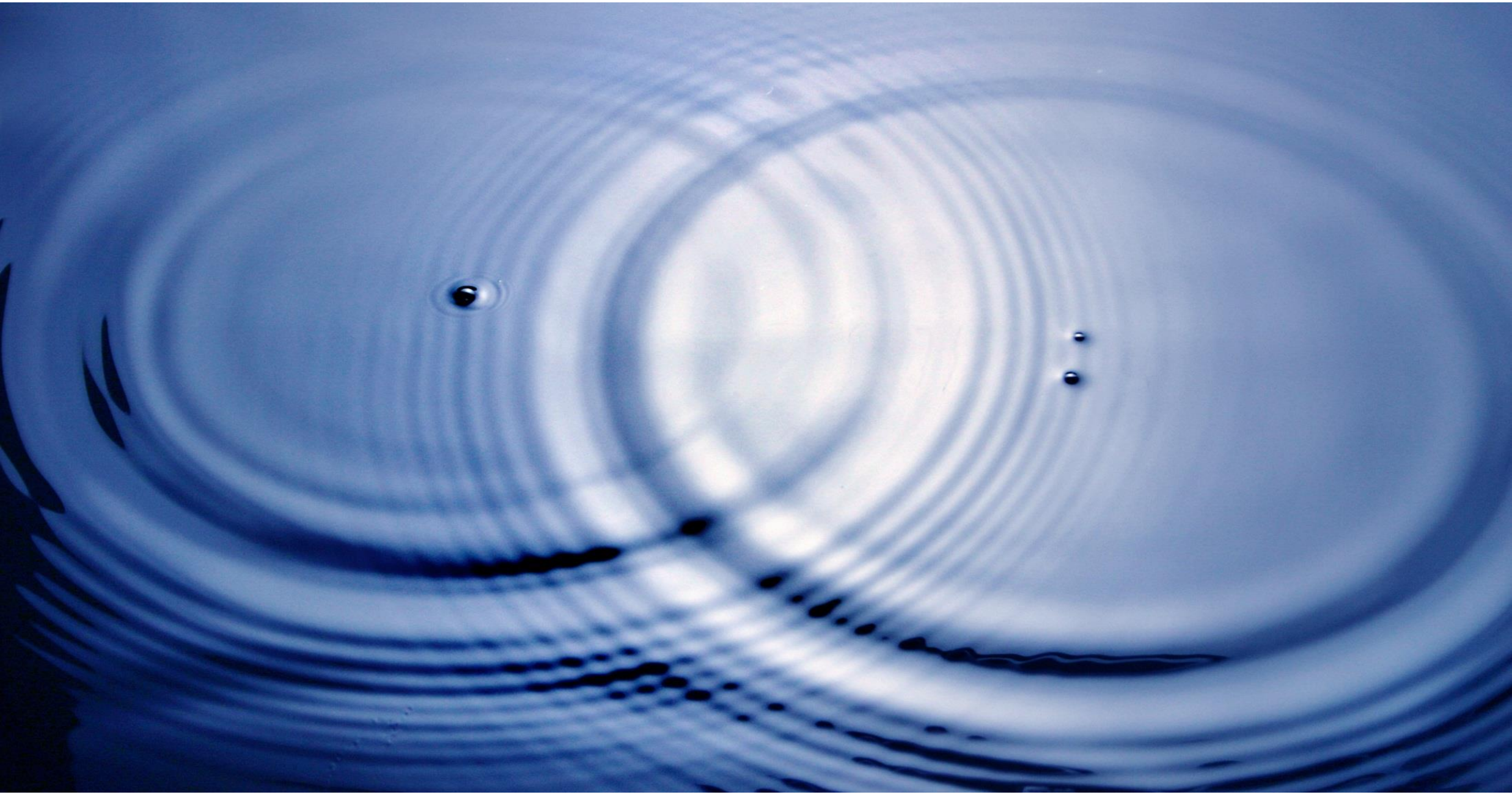
# Essence of quantum physics: Quantum Mechanics= Principle of Superposition and Interference



# Essence of quantum physics: Quantum Mechanics = The measurement affects the measured one



# Essence of quantum physics: Quantum Mechanics = Entangled systems



# 4. Randomness and unpredictability in music: *Lucier – chaos game*

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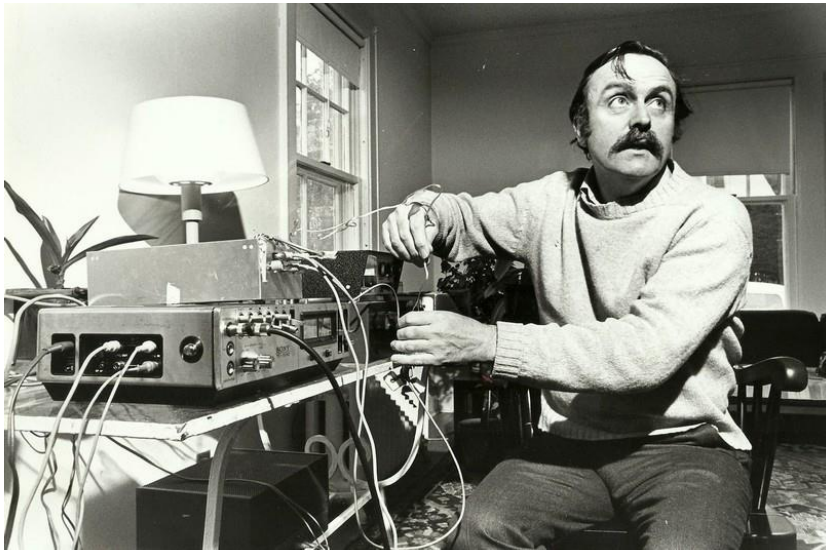
**Chaos theory**
The systems are described as systems of mathematical equations, and display behaviours found in a large number of systems in nature, such as the weather, the mixing of fluids, the phenomenon of turbulence, population cycles, the beating of the human heart, and the lengths of time between water droplets dripping from a leaky faucet" (Alpern, 1995).

**Chaos game:**

**I Am Sitting in a Room (1969)**

Lucier records himself narrating a text, and then plays the recording back into the room, re-recording it. The new recording is then played back and re-recorded, and this process is repeated. Since every enclosed area has a characteristic resonance, the effect is that certain frequencies are gradually emphasized as they resonate in the room, until eventually the words become unintelligible, replaced by the pure resonant harmonies and tones of the room itself.



**Alvin Lucier (1931-)**

Initial

Reiteration no.15

Reiteration no.37

Reiteration no. 59 (final)

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# 4. Randomness and unpredictability in music: AI approach

**Computer assisted compositions**
- **Stochastic** (i.e. Mozart's *Dice Music*, John Cage's *Music for* Changes)
- Greater amount of conceptual complexity can also be introduced to the computations through the computer with **statistical theory** and **Markov chains**
- Applications of **chaos theory** to algorithmic composition

**Artificial intelligence (AI)** systems
- Rule-based systems, based on some pre-defined grammar, with the further capacity of *defining their own grammar*—or, in essence, a capacity to "learn." (i.e. **Experiments in Musical Intelligence (EMI)** by David Cope
- **Genetic programming / Automatic programming**" generates its own musical materials as well as form its own grammar, which then listens to the numerous automatically produced outputs at various stages of the processing to decide which are "fit" or suitable for final output
- **Sound synthesis algorithms**, do not create scores and instead focus on electronic **sound synthesis** or manipulation of recorded sounds (i.e. musique concréte), or on a combination of these activities.
- Combination of both score and electronic sound synthesis in the system's output, controlling both structural content and its own timbral realization.
- **Automatic listening programs** seem to be a new trend and focus: not only does the computer automatically compose, it is also being designed to listen and *respond* to music being performed around it, a field of music that is labelled "live electronics".

**Chance serves only as a tool.**
**The results are deterministic and predictable.**
**To that extent the role of chance is an illusion ~~(quantum randomness)~~**

# 4. Randomness and unpredictability in music:

## Cage: 4'33"

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## 5. Toward quantum music

i) Use of quantum randomness (QRNG)

in organizing sound events

and other parameters

ii) Use of quantum correlations

QUSIDE

Collaborations: Carlos Abellan, José Martínez, David Ciraqui

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# 5. Randomness and unpredictability in music:
## Use of quantum randomness in music: Initial experiment

Previous examples: Allowing randomness to function within the context of a controlled system

Initial experiment:
Use of quantum random number generator to reorganize musical events.

Original excerpt    After treatment

Free improvisation: Jordina Millà Benseny

# Conclusions

Conclusions?

Enjoy science and art and beyond!!!

But, SERIOUSLY PLEASE!!!