What is classical?
What is quantum?

Insights from the Assumptions of Physics program

Gabriele Carcassi
University of Michigan

Assumptions of Physics

UNIVERSITY OF MICHIGAN

International Year of Quantum Science and Technology 2025

International Year of Quantum logo

Date	1 January – 31 December 2025
Type	Exhibitions
Website	quantum2025.org

wikipedia

nature

Quantum mechanics 100 years on: an unfinished revolution

A century ago, physics had its Darwinian moment – a change in perspective that was as consequential for the physical sciences as the theory of evolution by natural selection was for biology.

ScienceNews

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NEWS QUANTUM PHYSICS

Quantum mechanics was born 100 years ago. Physicists are celebrating

The International Year of Quantum marks a century of scientific developments

CERN

A century of quantum mechanics

On 9 July 1925, in a letter to Wolfgang Pauli, Werner Heisenberg revealed his new ideas, which were to revolutionise physics

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A brief ~~hi~~story of quantum mechanics

There were problems with classical physics

Blackbody radiation

Photoelectric effect

Stability of atoms

People futzed around with matrices and waves, to find something new that has some correspondence with classical mechanics

$\Rightarrow$ Quantum mechanics!

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Assumptions of Physics

How to quantize a classical theory

Classical mechanics

$$\frac{df}{dt} = \{f, H\}$$

Quantum mechanics

$$\frac{df}{dt} = \frac{[f, H]}{\imath\hbar}$$

$\Rightarrow$

Quantization!

Dirac's correspondence principle

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Assumptions of Physics

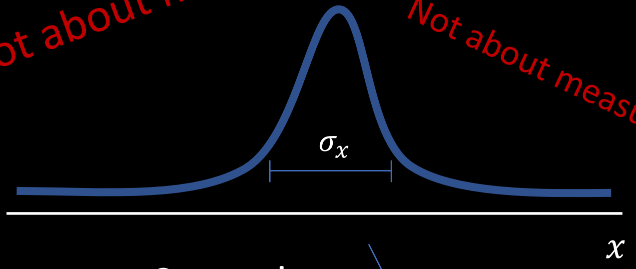
$$\{x, p\} = 1 \qquad \frac{[x,p]}{\imath\hbar} = 1$$

$$\{L_x, L_y\} = L_z \qquad \frac{[L_x,L_y]}{\imath\hbar} = L_z$$

Quantization is a "formal" operation

(i.e. substitute some symbols with some other symbols)

Uncertainty principle



Spread
over position

$$\sigma_x \sigma_p \geq \frac{1}{2} |\langle [x, p] \rangle| = \frac{\hbar}{2}$$

Not about measurement

Not about measurement
Not about measurement
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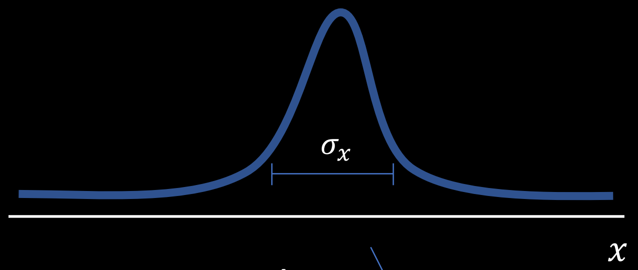
Assumptions of Physics

Indetermination
~~Uncertainty~~ principle



Spread
over position

$$\sigma_x \sigma_p \geq \frac{1}{2} |\langle [x, p] \rangle| = \frac{\hbar}{2}$$

About **preparation**

not measurement!

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Assumptions of Physics

Quantum contextuality

Measurements cannot be thought as revealing pre-existing values

Quantum complementarity

For every quantity we prepare, another quantity is indeterminate

During physical processes

Schrödinger equation

$$\imath\hbar \frac{d}{dt}|\psi\rangle = H|\psi\rangle$$

smooth, deterministic and reversible

During measurements

Projections

$$|\psi\rangle \xrightarrow{p_1} |\phi_1\rangle$$
$$|\psi\rangle \xrightarrow{p_2} |\phi_2\rangle$$
$$|\psi\rangle \xrightarrow{p_3} |\phi_3\rangle$$
$$|\psi\rangle \xrightarrow{p_{\dots}} |\dots\rangle$$

jumpy, non-deterministic, irreversible

Two laws of evolution

Quantum measurement problem

What is quantum mechanics about?

Hidden variables?

Consistent histories?

Interpretations

Many worlds?

Agent information?

Consciousness?

Quantum reconstructions

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Assumptions of Physics

What is the ultimate reason classical mechanics fails, and how is it fixed by quantum mechanics?

Since some of the classical failures are related to thermodynamics, let's look at the relationship between entropy and uncertainty in classical physics

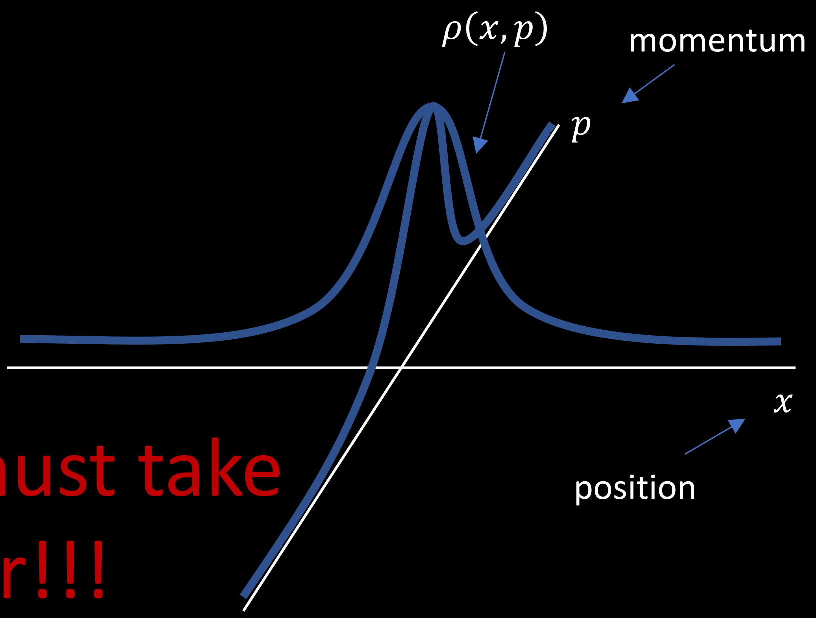
Entropy in classical mechanics

$$S(\rho) = -\int \rho \log \rho \, dx dp$$

Entropy

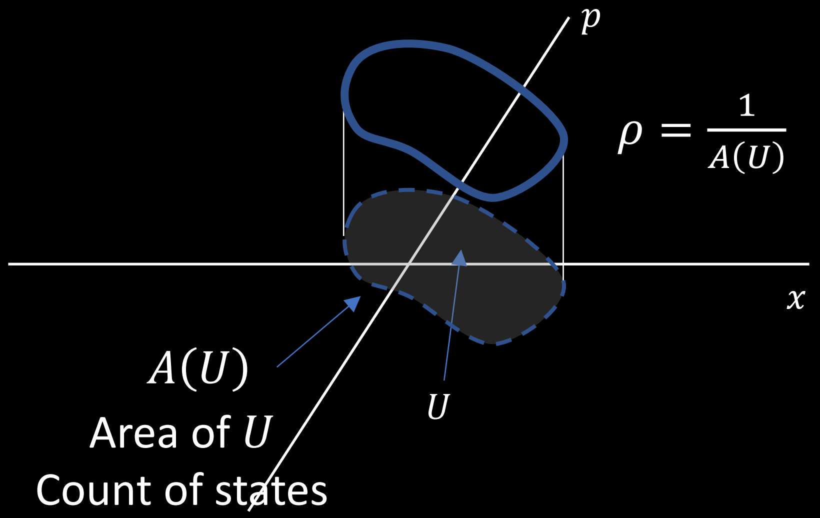
Probability distribution

Logarithm must take pure number!!!



$$S(\rho_U) = \log A(U)$$

Uniform distribution



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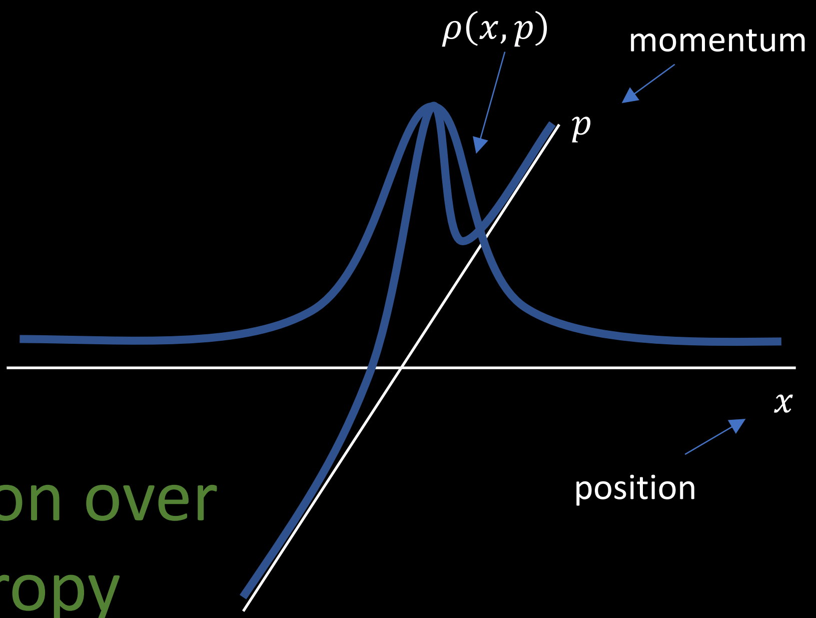
Assumptions of Physics

Entropy in classical mechanics

$$S(\rho) = -\int \rho \log h\rho \, dxdp$$

Entropy

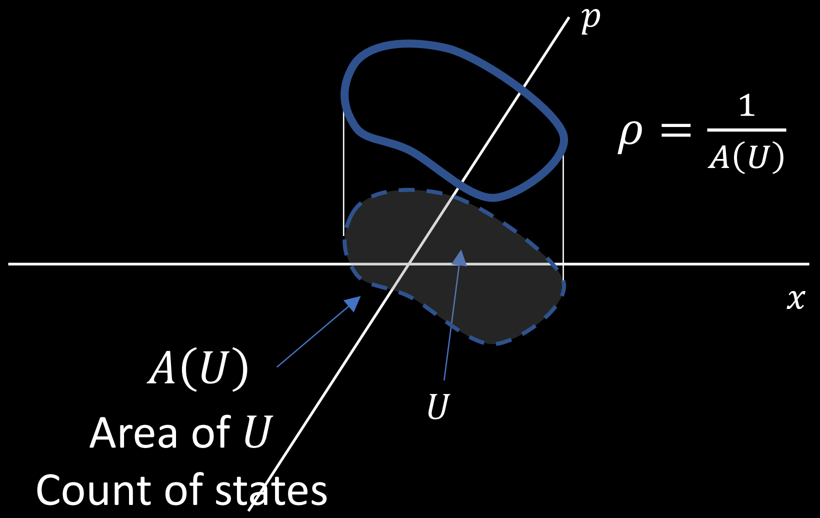
Probability distribution



Uniform distribution over area $h \Rightarrow$ zero entropy

$$S(\rho_U) = \log \frac{A(U)}{h}$$

Uniform distribution



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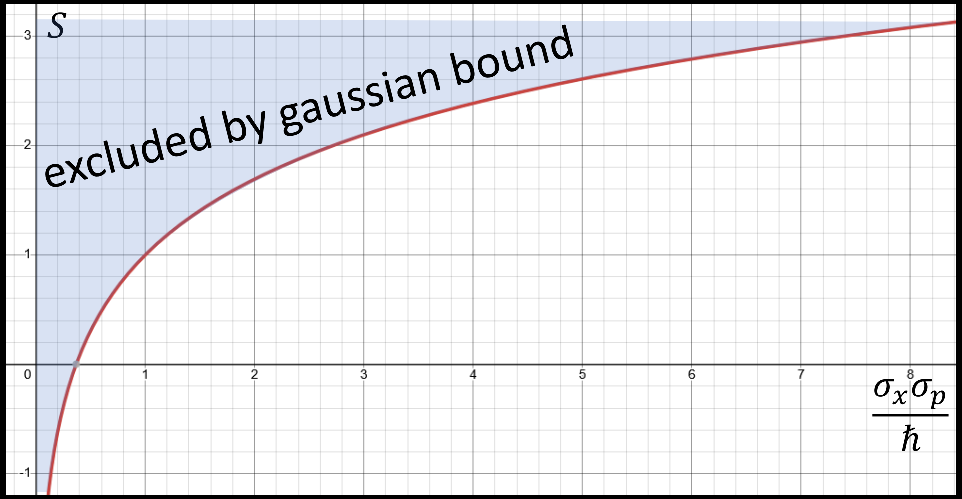
Entropy vs uncertainty

Let's plot one against the other



Gaussian maximizes entropy for a given uncertainty

$$S(\rho) \leq \log 2\pi e \frac{\sigma_x \sigma_p}{h}$$

$$\sigma_x \sigma_p \geq \frac{h}{2\pi e} e^{S(\rho)} = \frac{\hbar}{e} e^{S(\rho)}$$

Entropy puts a lower bound on the uncertainty

Is there a universal lower bound to the entropy?

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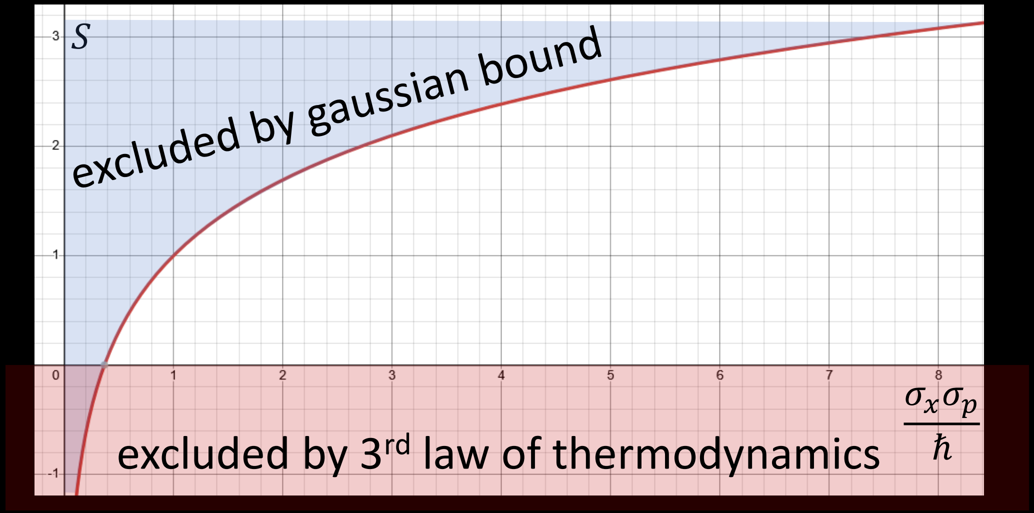
Enter the 3rd law

Every substance has a finite positive entropy, but at the absolute zero of temperature the entropy may become zero, and does so become in the case of perfect crystalline substances.

G. N. Lewis and M. Randall, Thermodynamics and the free energy of chemical substances (McGraw-Hill, 1923)



$$S \geq 0 \quad \Rightarrow \quad \sigma_x \sigma_p \geq \frac{\hbar}{e}$$

Classical ~~uncertainty~~ principle
indetermination

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Assumptions of Physics

Comparing theories

classical

$$\sigma_x \sigma_p \geq \frac{\hbar}{e}$$

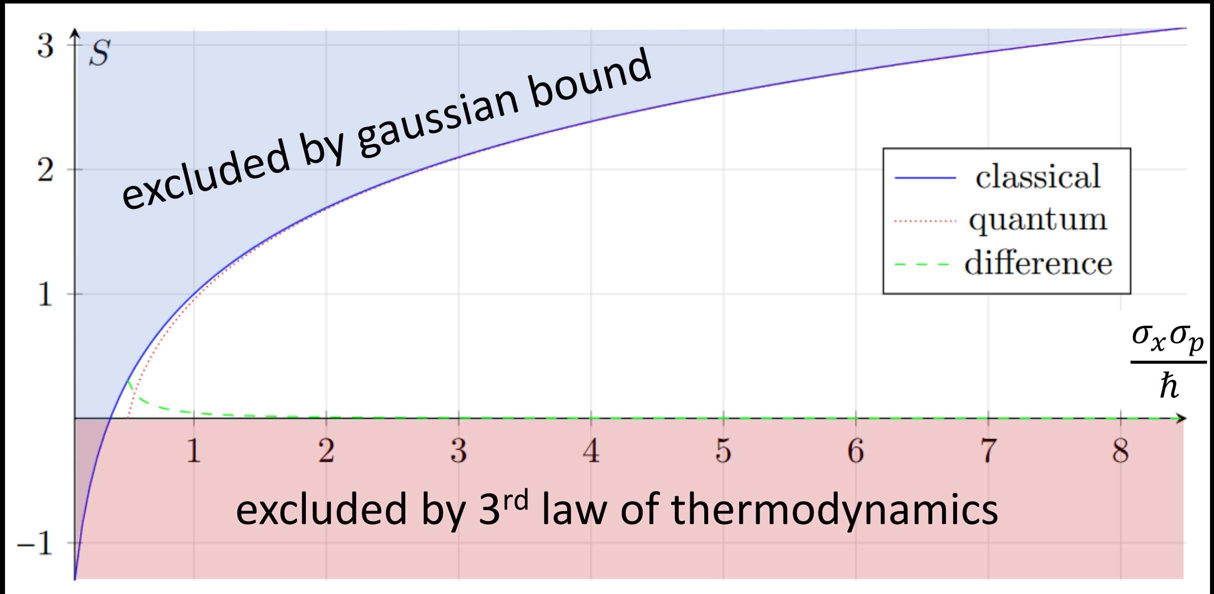
2.71828…

quantum

$$\sigma_x \sigma_p \geq \frac{\hbar}{2}$$

The gaussian bound quickly becomes very similar across theories

Entropy of quantum states is already non-negative



$$S_C = \ln e\sigma$$

$$S_Q = \left(\sigma + \tfrac{1}{2}\right)\ln\left(\sigma + \tfrac{1}{2}\right) - \left(\sigma - \tfrac{1}{2}\right)\ln\left(\sigma - \tfrac{1}{2}\right)$$

Quantum mechanics incorporates the third law
Classical mechanics does not

Conjecture: does quantum mechanics recover classical mechanics at high entropy?

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Classical mechanics as high entropy limit?

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greetings

Manuele Landini <manulando@gmail.com>
To carcassi@umich.edu

Reply | Reply All | Forward

Wed 7/10/2024 6:15 AM

You replied to this message on 7/10/2024 10:00 AM.

Caro Gabriele,

Mi chiamo Manuele Landini e lavoro a Innsbruck (Austria) come senior scientist in un gruppo di fisica atomica sperimentale. Puoi vedere di cosa ci occupiamo sul nostro sito: https://quantummatter.at.

Ho visto un po' dei tuoi video su youtube. Mi sembra un progetto molto ambizioso, ma promettente. Mi farebbe piacere riuscire a spiegare agli studenti in futuro in termini piu' fisici concetti come le sovrapposizioni o il teorema spin-statistica.

Per la storia della metrica, da quel che ho capito hai bisogno di una metrica che non sia basata sull'entropia, visto che vuoi definire una distanza a entropia costante. Ci sono varie opzioni, ma la trace distance Trace distance - Wikipedia funziona perche' ha una propireta' fondamentale che puoi usare. Chiamala: T(rho,sigma)

Se parti da stati puri, si riduce a (1-<psi|phi>)^(1/2). Quindi per massimizzarla, scegli due stati ortogonali (non importa quali). Il massimo e' T_0=1. Una volta che hai questi stati, che hanno entropia 0, li puoi trasformare in stati con entropia finita (in particolare quelli con massima distanza) tramite una trace preserving map M.

Siccome T si contrae, hai che T(M(rho),M(sigma))<=T(rho,sigma). L'uguale vale se la mappa e' unitaria. Cosi' definisci un serie di step in cui la distanza massima decresce T_n+1<T_n, fino ad arrivare a 0 per stati fully mixed.

arXiv > quant-ph > arXiv:2411.00972

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Quantum Physics

[Submitted on 1 Nov 2024 (v1), last revised 3 Dec 2024 (this version, v2)]

Classical mechanics as the high-entropy limit of quantum mechanics

Gabriele Carcassi, Manuele Landini, Christine A. Aidala

We show that classical mechanics can be recovered as the high-entropy limit of quantum mechanics. That is, the high entropy masks quantum effects, and mixed states of high enough entropy can be approximated with classical distributions. The mathematical limit $\hbar \to 0$ can be reinterpreted as setting the zero entropy of pure states to $-\infty$, in the same way that non-relativistic mechanics can be recovered mathematically with $c \to \infty$. Physically, these limits are more appropriately defined as $S \gg 0$ and $v \ll c$. Both limits can then be understood as approximations independently of what circumstances allow those approximations to be valid. Consequently, the limit presented is independent of possible underlying mechanisms and of what interpretation is chosen for both quantum states and entropy.

Comments:	14 pages, 3 figures
Subjects:	**Quantum Physics (quant-ph)**
Cite as:	arXiv:2411.00972 **[quant-ph]**
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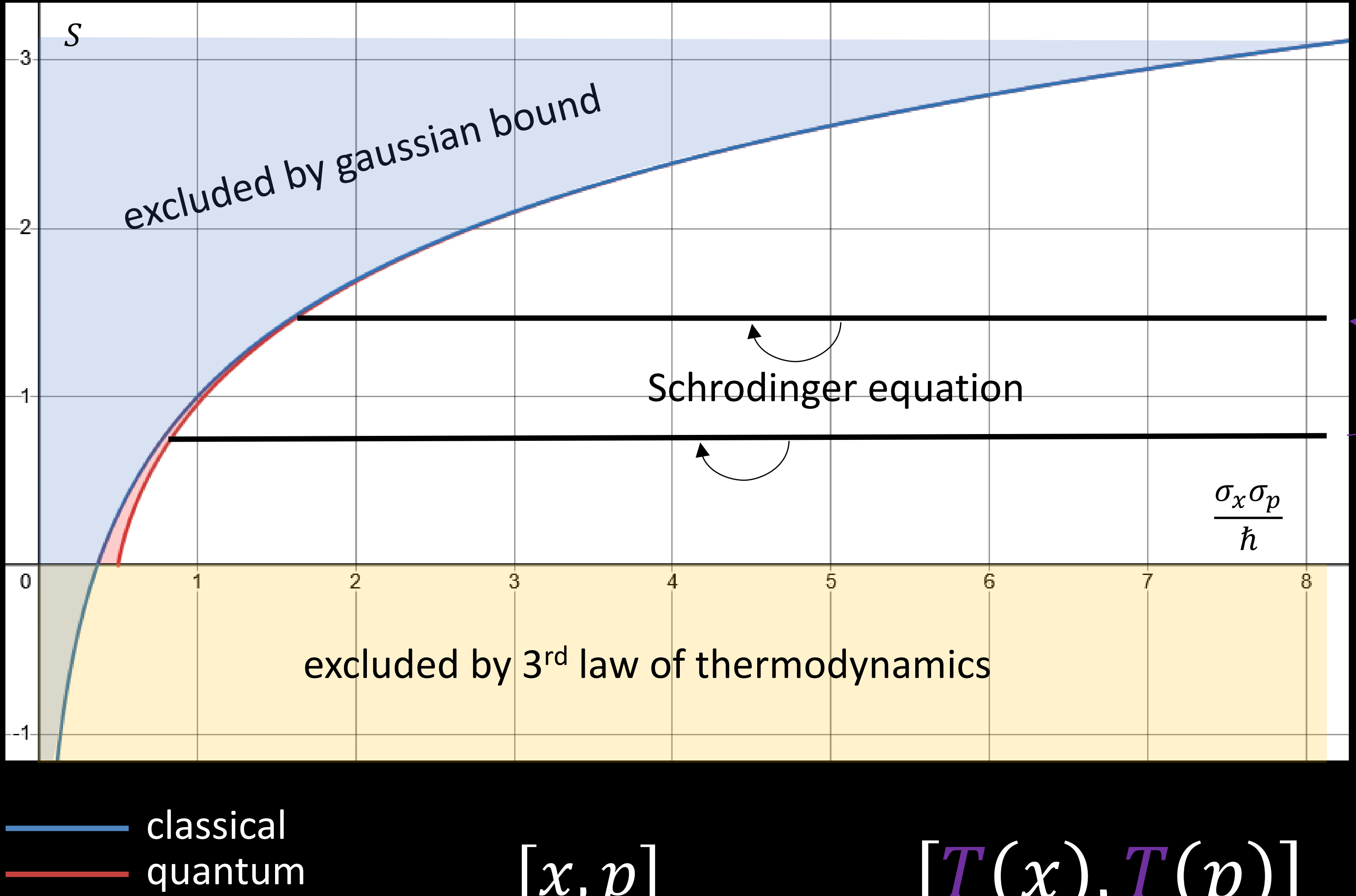
Assumptions of Physics

1. Increase the entropy of all states



T - Entropy increasing map

Spread increase in position and momentum

$$\frac{[x,p]}{\imath\hbar} = 1 \Rightarrow \frac{[T(x), T(p)]}{\imath\hbar} = \lambda$$

$$\sigma_{T(x)}\sigma_{T(p)} \geq \frac{1}{2}|\langle[T(x), T(p)]\rangle| = \frac{\hbar}{2}\lambda$$

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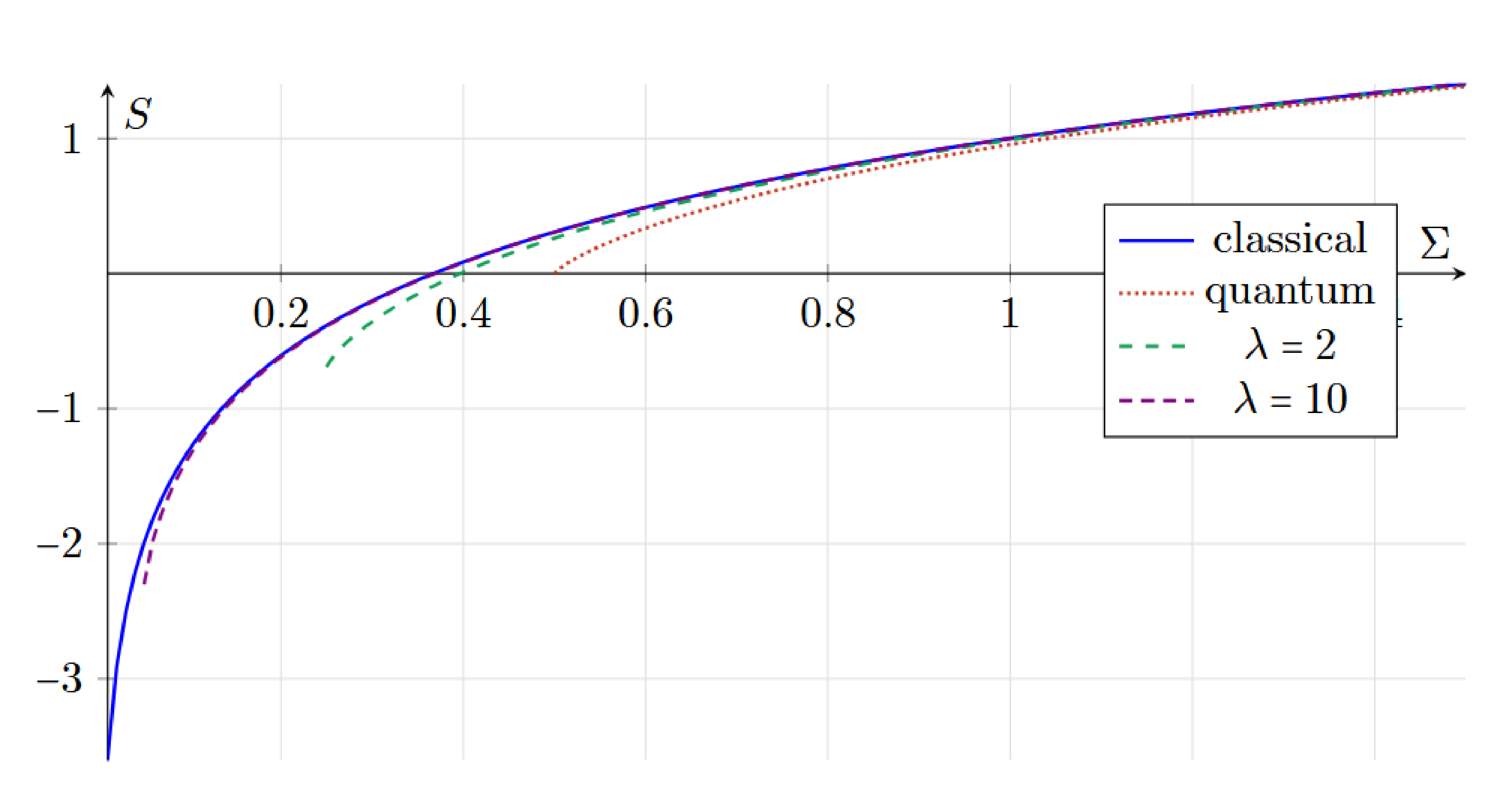
Assumptions of Physics

Mathematical limit

$$\frac{[x,p]}{\imath\hbar} \xrightarrow{\hbar \to 0} \{x,p\}$$

Makes no physical sense!

$\hbar$ is a constant: it doesn't change



2. Decrease the entropy of pure states

$$\frac{[X,P]}{\imath\hbar} = \frac{1}{\lambda} \qquad \frac{[X,P]}{\imath(\hbar/\lambda)} = 1 \xrightarrow[\hbar/\lambda \to 0]{\lambda \to \infty} \{x,p\} = 1$$

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Assumptions of Physics

Low speed
“$c \to \infty$”

Speed

High entropy
“$\hbar \to 0$”

Entropy

Classical Mechanics	Relativistic Mechanics
Quantum Mechanics	Quantum Field Theory

No-mechanism limit
(same as non-relativistic limit)

Quantum to classical

$$\frac{[A,B]}{\imath\hbar} \longrightarrow \{A,B\}$$

High entropy limit

Classical to quantum

$$\{A,B\} \longrightarrow \frac{[A,B]}{\imath\hbar}$$

???

Up to isomorphisms, the Moyal bracket is the unique one-parameter Lie-algebraic deformation of the Poisson bracket

If I asked for a theory that puts a hard lower bound on the entropy, and recovers classical mechanics at high entropy....

there is only one way to do it

Quantum to classical

$$\frac{[A,B]}{\imath\hbar} \longrightarrow \{A,B\}$$

High entropy limit

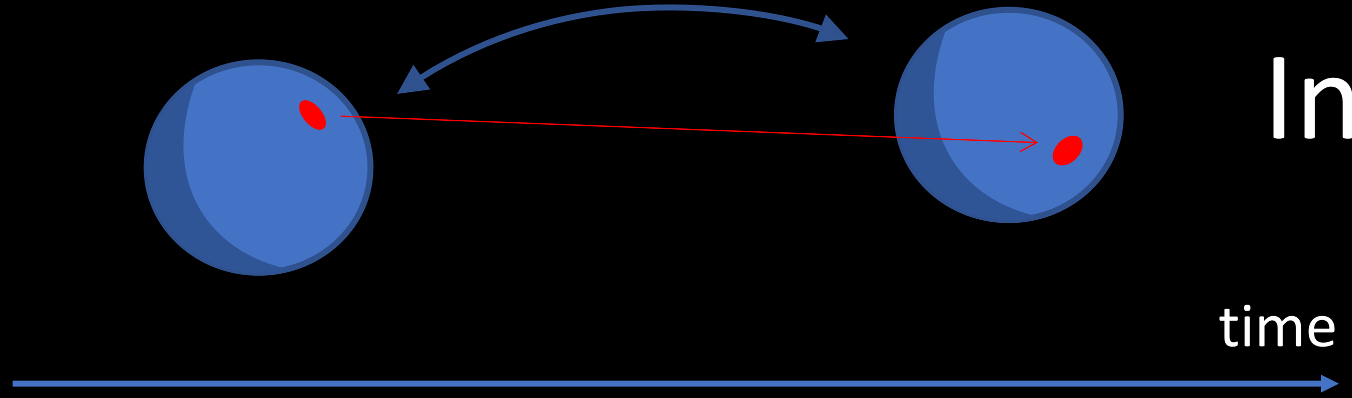
Classical to quantum

$$\{A,B\} \longrightarrow \frac{[A,B]}{\imath\hbar}$$

Entropic lower bound
that recovers classical mechanics

Quantizing a classical theory means putting a lower bound on the entropy

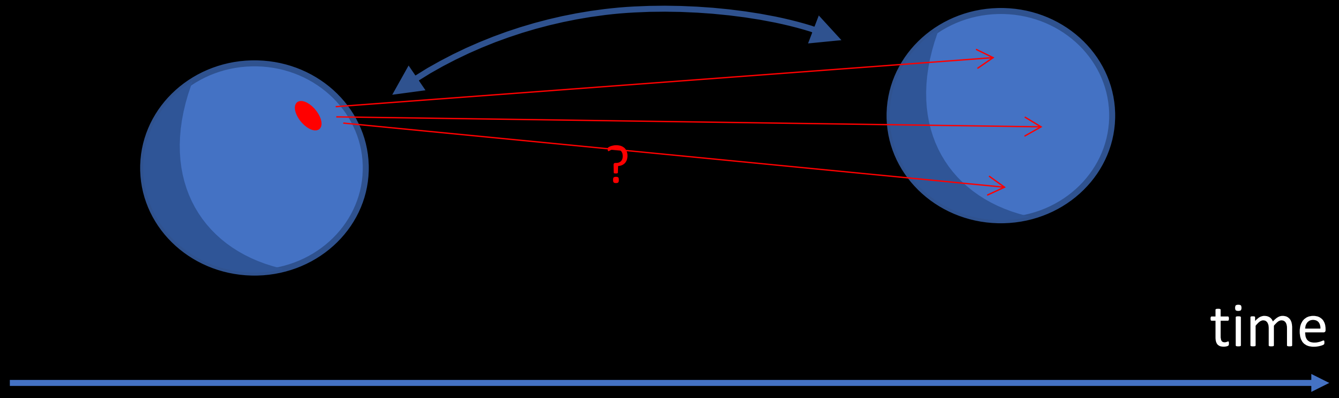
Classical system



Infinitesimally reducible

Internal dynamics
perfectly accessible

Quantum system



Irreducible

Internal dynamics
inaccessible

What is entropy?

Why a lower bound?

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Assumptions of Physics

What is entropy?

You can think of it as disorder

You can think of it as information

You can think of it as lack of information

The Empire Strikes Back, Lucasfilm Ltd

Is or is not.
There is no “you can think of it as.”

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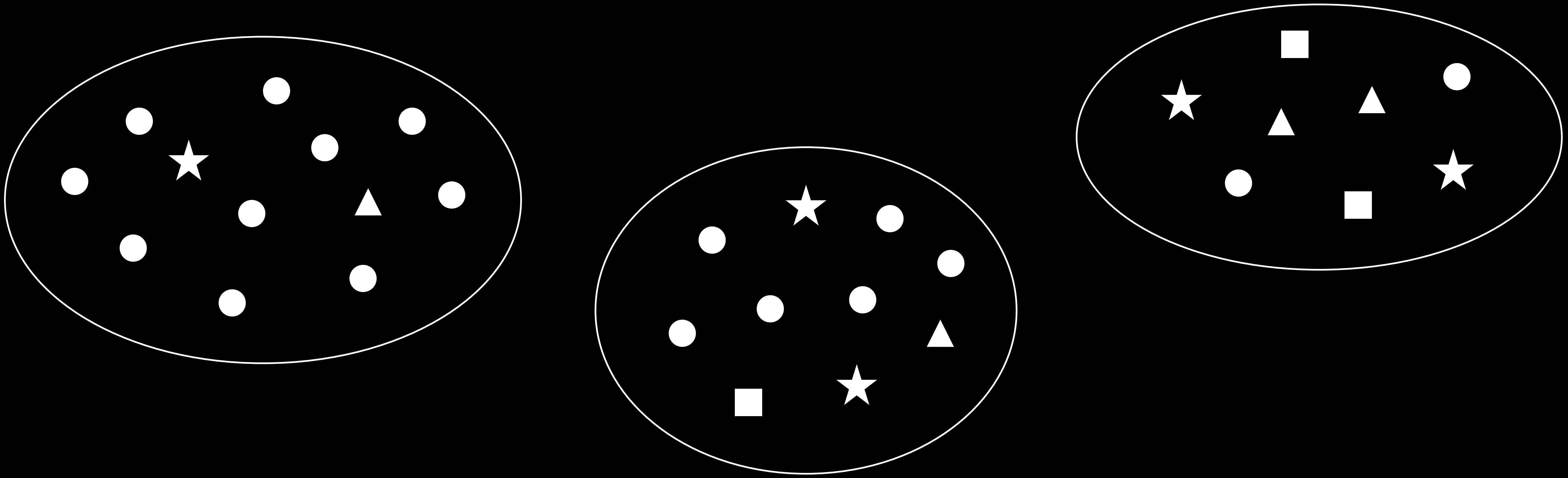
Assumptions of Physics



Suppose you have a (possibly infinite) collection of things

What is the variability of the collection?

How different are the elements within the collection?

Given a discrete distribution p_i
we want an indicator $I(p_i)$ of variability such that:

1. Continuous in p_i
2. Increases if the number of cases increases
3. Linear in probability $\quad I(p_1\hat{p}_i, p_2\bar{p}_j) = I(p_1, p_2) + p_1 I(\hat{p}_i) + p_2 I(\bar{p}_j)$

$\Rightarrow$ Then $I(p_i) = -\sum_i p_i \log p_i$

Proof can be generalized to classical continuum and quantum mechanics

Entropy is variability!

Variability as a better characterization of Shannon entropy

Gabriele Carcassi, Christine A Aidala and Julian Barbour

Published 19 May 2021 • © 2021 European Physical Society

European Journal of Physics, Volume 42, Number 4

Machine learning to detect schedules using spatiotemporal data of behavior: A proof of concept
Marc J. Lanovaz, Varsovia Hernandez, Alejandro León
2025, Journal of the Experimental Analysis of Behavior - Article

Why so slow? Models of parkinsonian bradykinesia
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Entropy is not the property of an element, but of a distribution

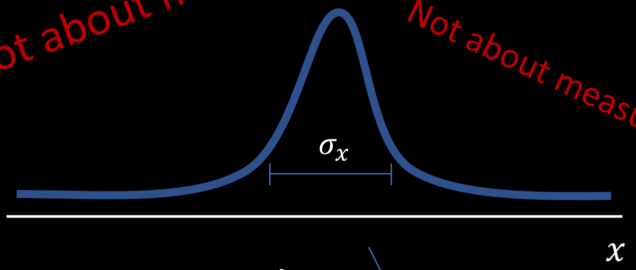
A distribution of what?

A statistical distribution of the molecules of a gas?

A credence distribution of what an agent may think is there?

A probability distribution of the outcomes of a measurement?

Uncertainty principle



Spread
over position

$$\sigma_x \sigma_p \geq \frac{1}{2}|\langle[x,p]\rangle| = \frac{\hbar}{2}$$

Not about measurement

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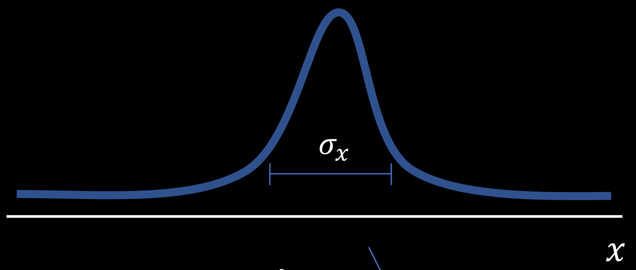
Assumptions of Physics

Indetermination
~~Uncertainty~~ principle



Spread
over position

$$\sigma_x \sigma_p \geq \frac{1}{2} |\langle [x, p] \rangle| = \frac{\hbar}{2}$$

About **preparation**
not measurement!

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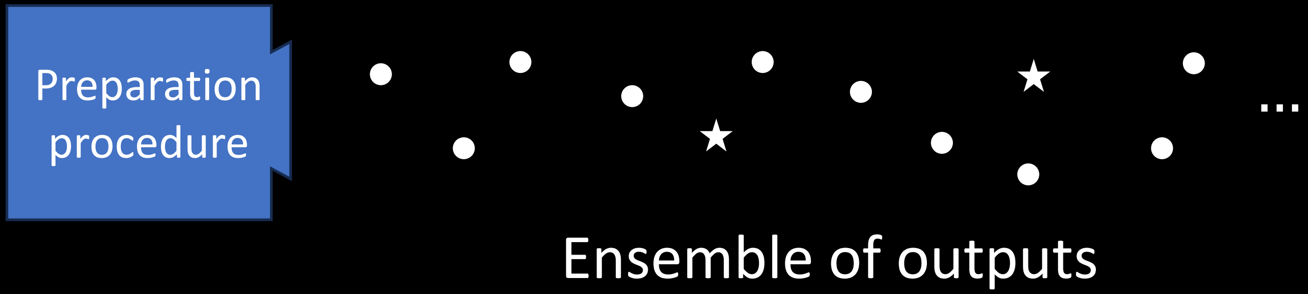
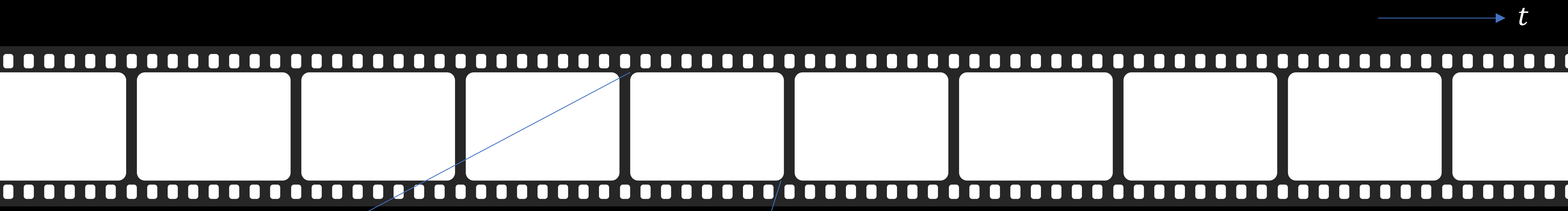
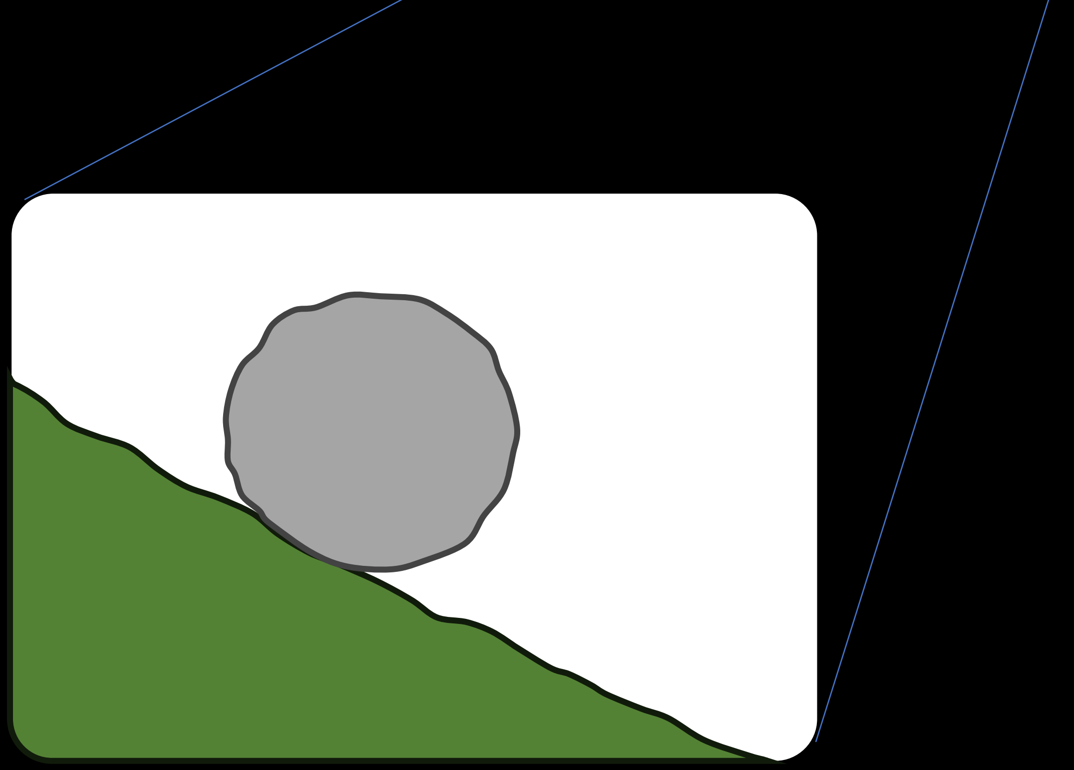
Assumptions of Physics

Entropy is the variability of an ensemble: the collection of all outputs of a reliable preparation procedure

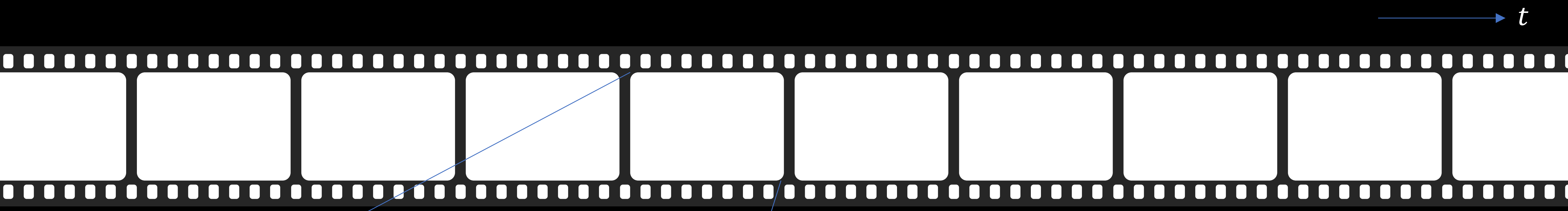


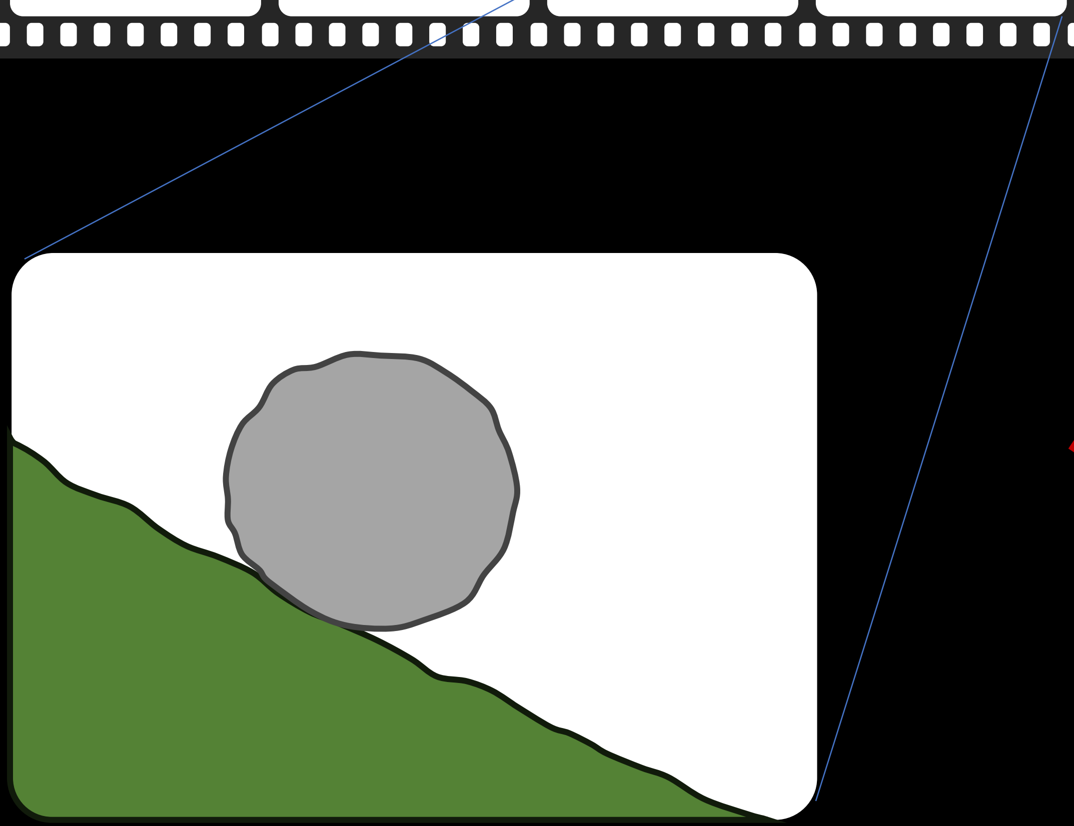




Physics describes the evolution of a particular system like a movie

$$x(t)$$





~~Physics describes the evolution of a particular system like a movie~~

-100 points

$$x(t)$$

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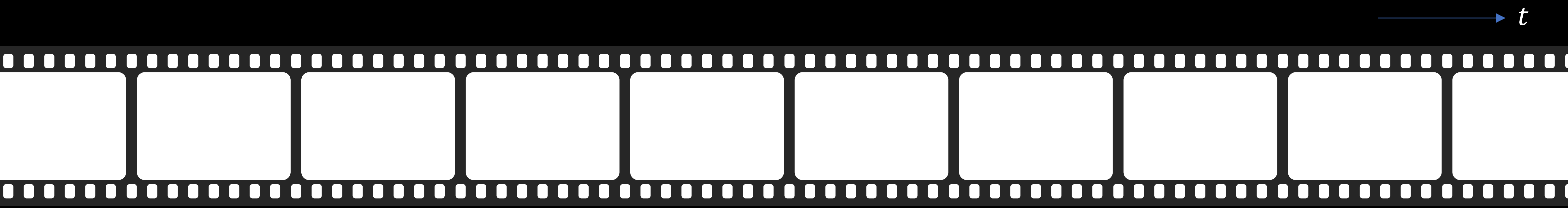
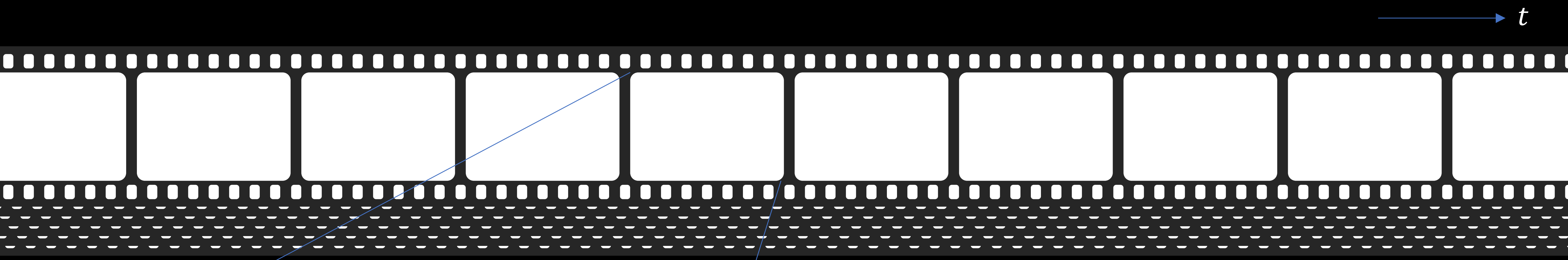
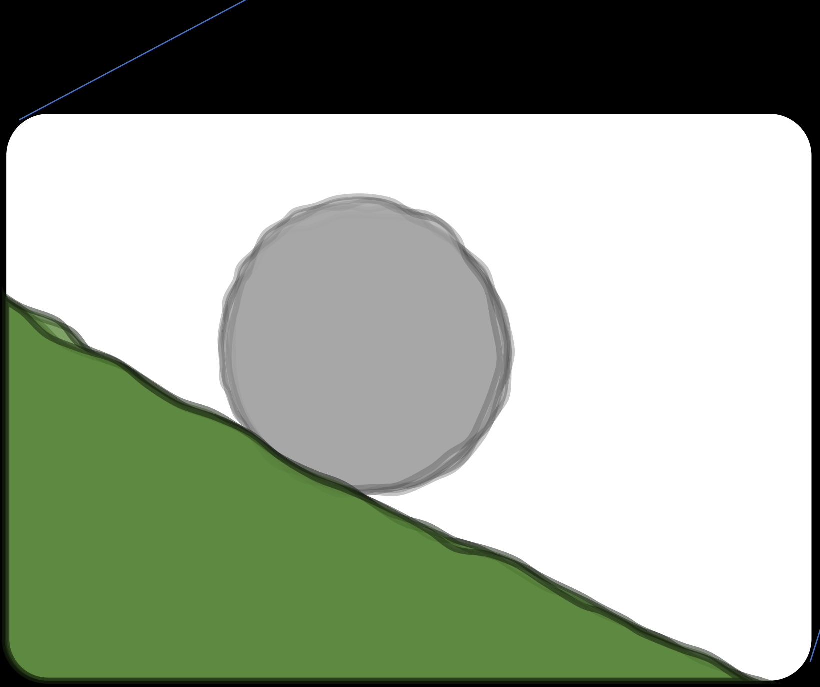


Physics describes the evolution of similarly prepared systems

Every time I do this…

$$x(t)$$





Physics describes the evolution of similarly prepared systems

$$x(t)$$

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Assumptions of Physics

Statistical description of preparations and measurement outcomes

$$x(t)$$

Statistical description of all clocks synchronized at a particular initial event

In physics, we can only study relationships that can be reproduced: relationships between ensembles

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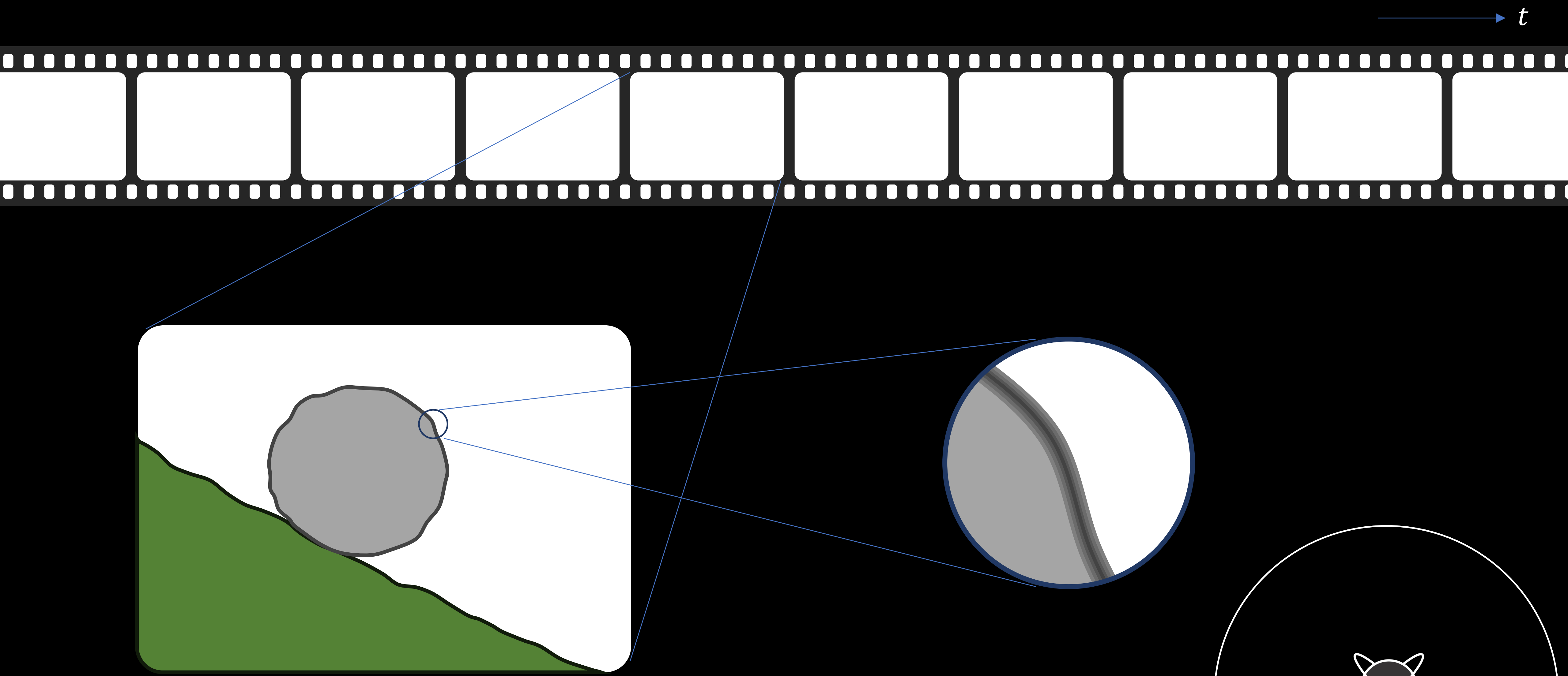
Assumptions of Physics



Even a single measurement is an average over a finite time

To be able to define a probability distribution over heads or tails, you need first to define what heads and tails are

We can do that because we can leave the coin be, and it remains heads or tails

If it kept changing more than 100 times a second, we wouldn't perceive heads or tails: just a blur

wikipedia

wikipedia

The state of a system is what remains "stable" for at least a short amount of time

It's ensembles all the way down

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What is entropy?

Variability within a preparation!

Why a lower bound?

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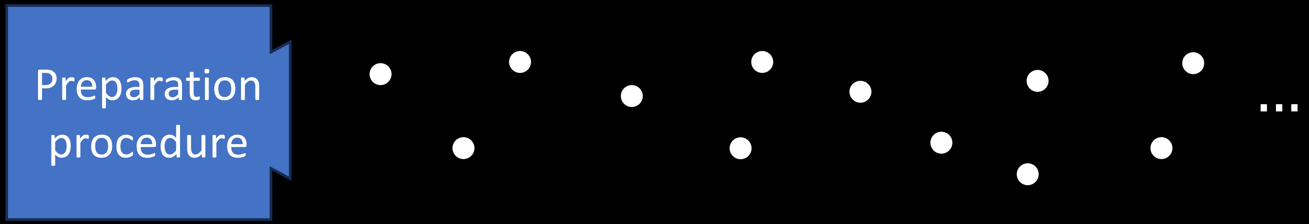
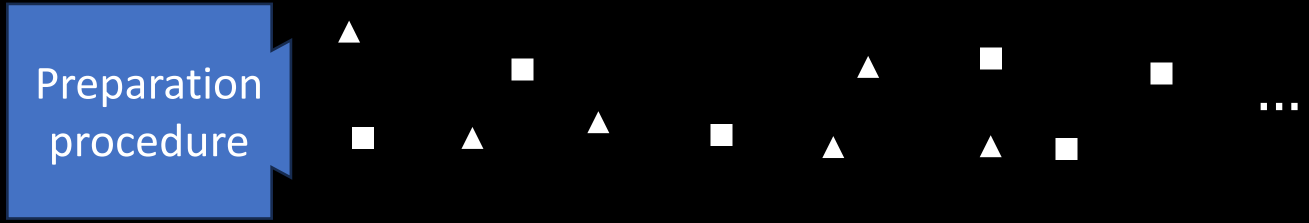
Classical mechanics



Assumes we can have perfect preparations



Concedes that there are no perfect preparations

Quantum mechanics

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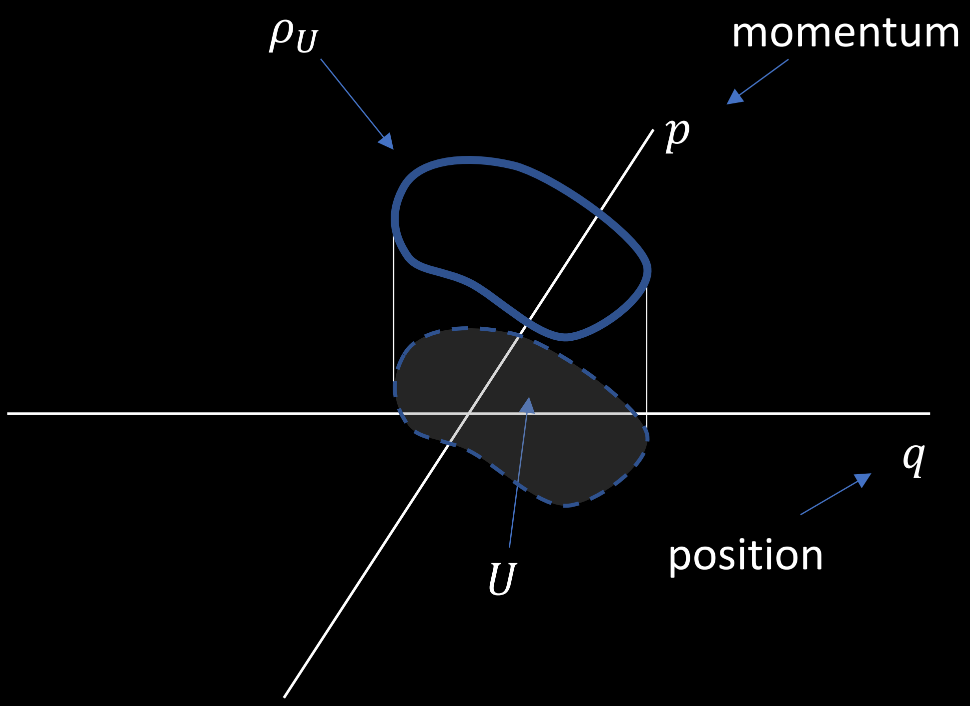
Assumptions of Physics

For classical systems

$$S(\rho_U) = \log \frac{A(U)}{h}$$

Entropy for a uniform distribution over U

Logarithm of the count of states in U



Less than one state!

$$S(\rho_U) < 0 \qquad \frac{A(\rho_U)}{h} < 1$$

What is entropy?

Variability within a preparation!

Why a lower bound?

Our preparations cannot be perfect

Regions with “less than one state” make no sense

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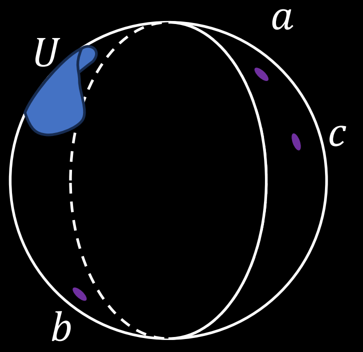
Assumptions of Physics

The problem with counting (on the continuum)

measure

$\mu\left(\text{a set of states}\right) =$ how many states there are in the set



JOHN TEMPLETON FOUNDATION
Inspiring Awe & Wonder

1. Every state counts as one (i.e. $\mu(\{a\}) = 1$)
2. Finite regions have finitely many states (i.e. $\mu(U) < \infty$)
3. Count is additive for disjoint sets (i.e. $\mu(\cup U_i) = \sum \mu(U_i)$)

Incompatible!

Pick two!

On a continuum, a finite region has infinitely many states!

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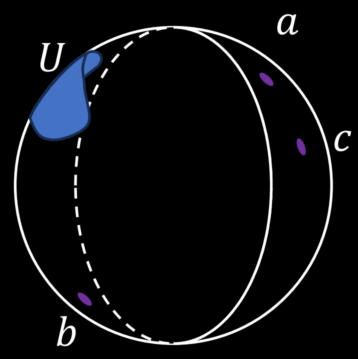
Assumptions of Physics

The problem with counting on the continuum

measure

$\mu\left(\begin{array}{c}\text{a set of}\\ \text{states}\end{array}\right) = \begin{array}{c}\text{how many states}\\ \text{are there in the set}\end{array}$



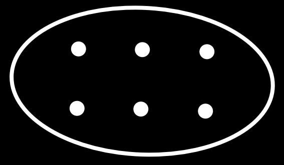
1. Every state counts as one (i.e. $\mu(\{a\}) = 1$)

~~2. Finite regions have finitely many states (i.e. $\mu(U) < \infty$)~~

3. Count is additive for disjoint sets (i.e. $\mu(\cup\, U_i) = \sum \mu(U_i)$)

$\Rightarrow$ Counting measure

What we use in classical discrete case



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Assumptions of Physics

The problem with counting on the continuum

measure

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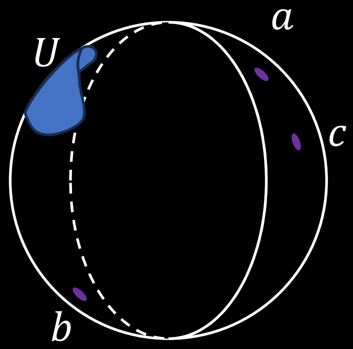

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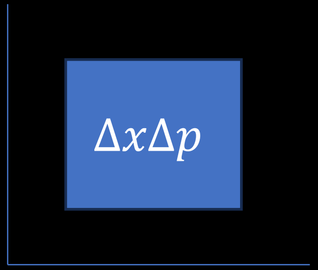
~~1. Every state counts as one (i.e. $\mu(\{a\}) = 1$)~~

2. Finite regions have finitely many states (i.e. $\mu(U) < \infty$)

3. Count is additive for disjoint sets (i.e. $\mu(\cup\, U_i) = \sum \mu(U_i)$)

$\Rightarrow$ Lebesgue measure

What we use in classical continuum case (i.e. classical mechanics)



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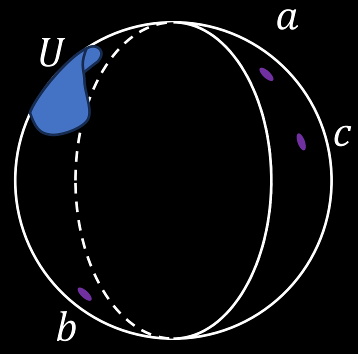
Assumptions of Physics

The problem with counting on the continuum

measure

$$\mu\left(\text{a set of states}\right) = \text{how many states are there in the set}$$



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1. Every state counts as one (i.e. $\mu(\{a\}) = 1$)
2. Finite regions have finitely many states (i.e. $\mu(U) < \infty$)
3. ~~Count is additive for disjoint sets (i.e. $\mu(\cup U_i) = \sum \mu(U_i)$)~~

⇒ "Quantum" measure

What we are implicitly using in quantum mechanics

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Assumptions of Physics

We saw that thinking about entropy makes us understand how classical mechanics fails and gives rise to quantum mechanics

Can we use similar arguments to understand why quantum mechanics and general relativity are incompatible, and how to fix it?

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Assumptions of Physics

General relativity is a field theory

Particle mechanics

Finitely many variables

State defined by
position and momentum:

$$\begin{matrix} x^1 & x^2 & \cdots & x^n \\ p_1 & p_2 & & p_n \end{matrix}$$

Field theory

Continuously (infinitely)
many variables

State defined by
fields at each point:

$$A(x) \quad B(x) \quad \ldots$$

How do we count them?!?

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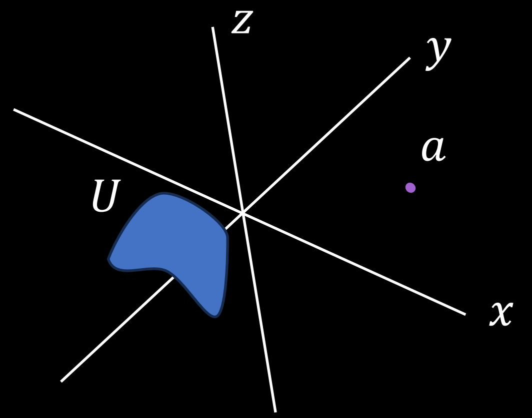
Assumptions of Physics

The problem with counting (on the continuum)

$$\mu\left(\begin{matrix}\text{region of}\\ \text{space}\end{matrix}\right) = \begin{matrix}\text{Volume proportional to}\\ \text{number of variables}\end{matrix}$$



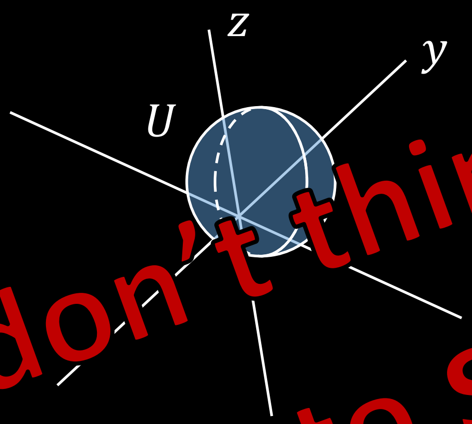
1. Every point has one variable (i.e. $\mu(\{a\}) = 1$)
2. Finite regions have finite volume (i.e. $\mu(U) < \infty$)
3. Count is additive for disjoint sets (i.e. $\mu(\cup U_i) = \sum \mu(U_i)$)

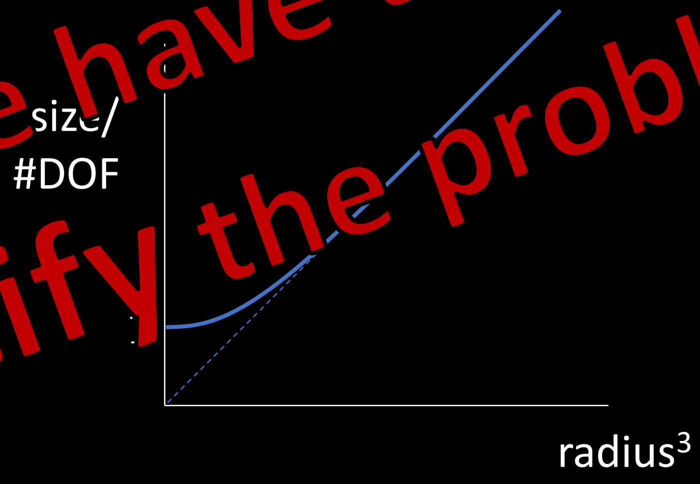
Incompatible!

On a continuum, a finite region has infinitely many points!

Seems that “quantizing space-time” means putting a lower bound on the number of variables (degrees of freedom)

In the same way that a region of state space “with less than one state” makes no sense,
a region of physical space with “less than one degree of freedom” makes no sense





I don’t think we have the right math to specify the problem!

I don’t think we have the right math to solve this problem!

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Assumptions of Physics

~~But we don’t develop theories by writing down assumptions and then derive observable consequences in a sequence of theorems and proofs. In physics, theories almost always start out as loose patchworks of ideas. Cleaning up the mess that physicists generate in theory development, and finding a neat set of assumptions from which the whole theory can be derived is often left to our colleagues in mathematical physics—a branch of mathematics, not of physics.~~

Sabine Hossenfelder – Lost in Math

-100,000 points

Math is not just a tool for calculation: we use it to specify our theories

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Assumptions of Physics

Ultimately, it is up to the physicists to develop a clear physical model

Mathematicians can help find holes… and give options

Clear physical model $\Longleftrightarrow$ clear math

Clarity, meaningfulness, consistency, …
cannot be added after the fact

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Assumptions of Physics

Big systems that work always come from small systems that work, they never come from big systems that don't work

The only way forward is to go back and reconstruct everything from a minimal set of physically meaningful assumptions

Assumptions of Physics

https://assumptionsofphysics.org
For more information, papers, presentations, …

https://www.youtube.com/@gcarcassi
Videos with results and insights from the research

https://assumptionsofphysics.org/foundation https://assumptionsofphysics.org/

Assumptions of Physics

The problem with counting on the continuum

We'd like to say:

1. Every state is a single case (i.e. $\mu(\{\psi\}) = 1$)
2. Finite continuous range carries finite information (i.e. $\mu(U) < \infty$)
3. Count is additive for disjoint sets (i.e. $\mu(\cup U_i) = \sum \mu(U_i)$)

Incompatible!

Pick two!

Discard 1 ⇒ Lebesgue measure

Discard 2 ⇒ counting measure

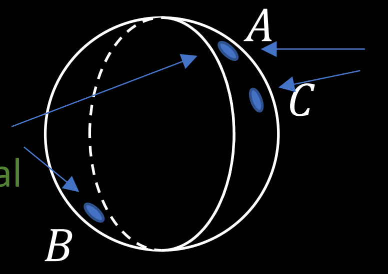
Discard 3 ⇒ "Quantum measure"

$$\mu(U) = 2^{\sup\left(S(\mathrm{hull}(U))\right)}$$

Exponential of the maximum entropy reachable with convex combinations (statistical mixtures) of U (reduces to counting/Liouville measure)

Orthogonal states: different states all else equal

additive



Non-orthogonal states: different states but in different contexts

sub-additive

$\mu(\{A\}) = 2^0 = 1$

$\mu(\{A, B\}) = 2^1 = 2$

$\mu(\{A, C\}) < 2 = \mu(\{A\}) + \mu(\{C\})$

Quantum mechanics ⇒ lower bound on #conf (entropy) on continuous DOF

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Assumptions of Physics

Conjecture: quantum gravity ⇒ lower bound on DOF count

#conf=#DOFs

#conf

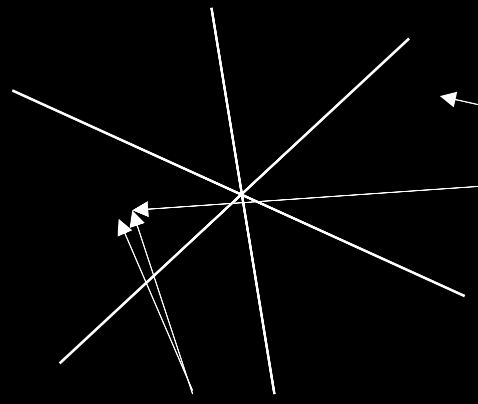
#DOFs

Lower bound on this…

…requires a lower bound on this

Same problem!

1. Every point is a single DOF (i.e. $\mu(\{x\}) = 1$)
2. Finite volume carries finitely many DOFs (i.e. $\mu(U) < \infty$)
3. Count is additive for disjoint regions (i.e. $\mu(\cup U_i) = \sum \mu(U_i)$)



Distant points: independent DOFs

additive

sub-additive

Close points: DOFs not independent

From QM: Lower bound on state count requires a severe revisitation of particle state space

Does lower bound on DOF count require an equally severe revisitation of space-time?

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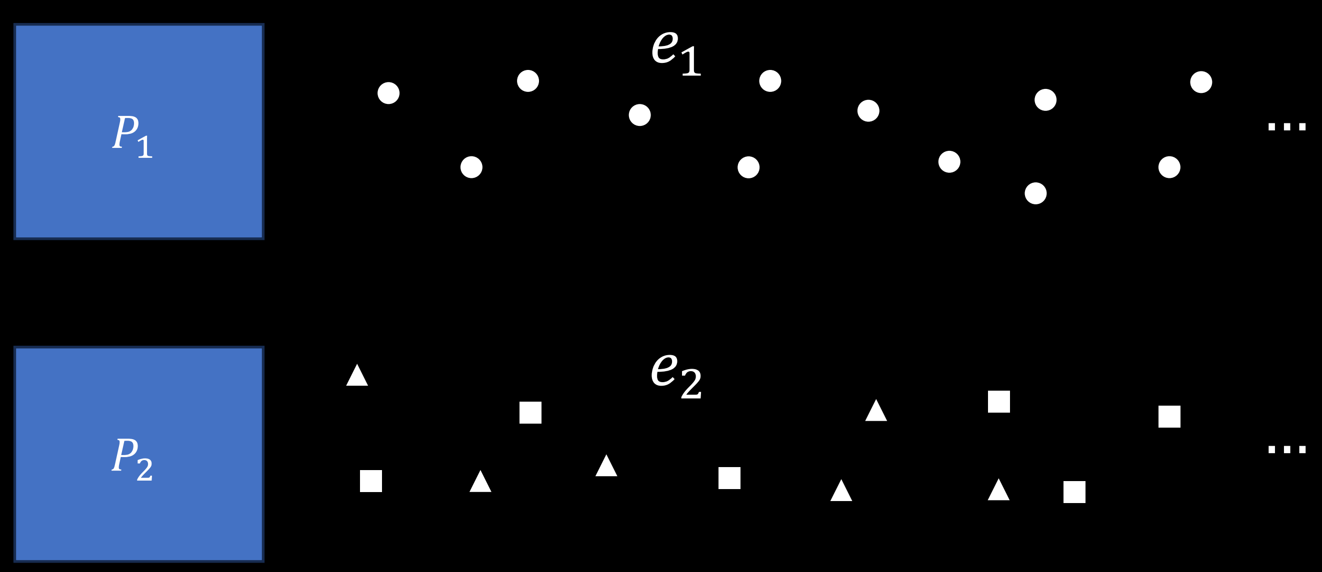
Assumptions of Physics

Preparation

Ensemble



Identically prepared ensemble

There is no variability in the ensemble

Pure ensemble

No process can reduce the variability of the ensemble

There is no a such that $e_2 = pa + \bar{p}b$ for some $p \in (0,1)$ and $b \neq a$

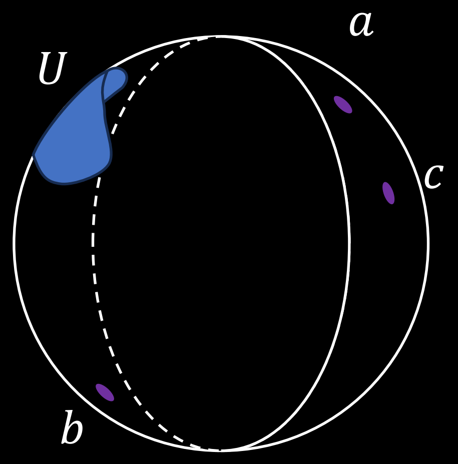
In classical theories, all pure ensembles are identically prepared

No real distinction between ensembles and instances

In non-classical theories, no identically prepared ensembles

Zero entropy does NOT correspond to identically prepared ensembles

The problem with counting on the continuum



$$\mu\left(\text{a set of states}\right) = \text{how many states are there in the set}$$

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Incompatible!

Pick two!

On a continuum, a finite region has infinitely many states!

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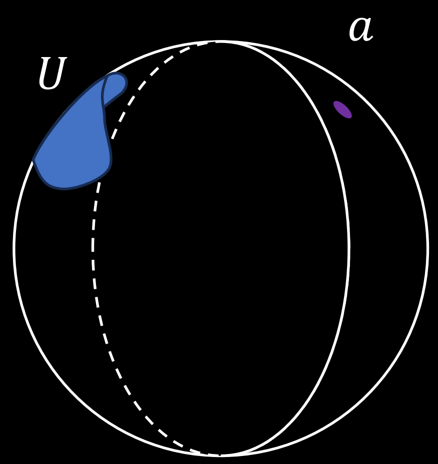
Assumptions of Physics

The problem with counting on the continuum



measure

$$\mu\left(\begin{array}{c}\text{a set of}\\\text{states}\end{array}\right) = \begin{array}{c}\text{how many states}\\\text{are there in the set}\end{array}$$

1. Every state counts as one (i.e. $\mu(\{a\}) = 1$)
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Incompatible!

Pick two!

On a continuum, a finite region
has infinitely many states!

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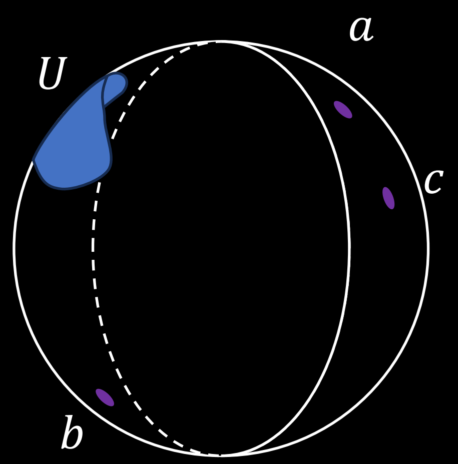
Assumptions of Physics

How does the quantum measure work?



$$\mu(\{a\}) = \mu(\{b\}) = \mu(\{c\}) = 1$$

$$\mu(\{a, b\}) = 2 = \mu(\{a\}) + \mu(\{b\})$$

Additive when states are distinguishable (i.e. mutually exclusive)

$$\mu(\{a, c\}) < 2 = \mu(\{a\}) + \mu(\{c\})$$

Sub-additive when states are not distinguishable (i.e. mutually exclusive)

Non-additivity coincides with non-distinguishability

The measure counts distinguishable (i.e. mutually exclusive) states

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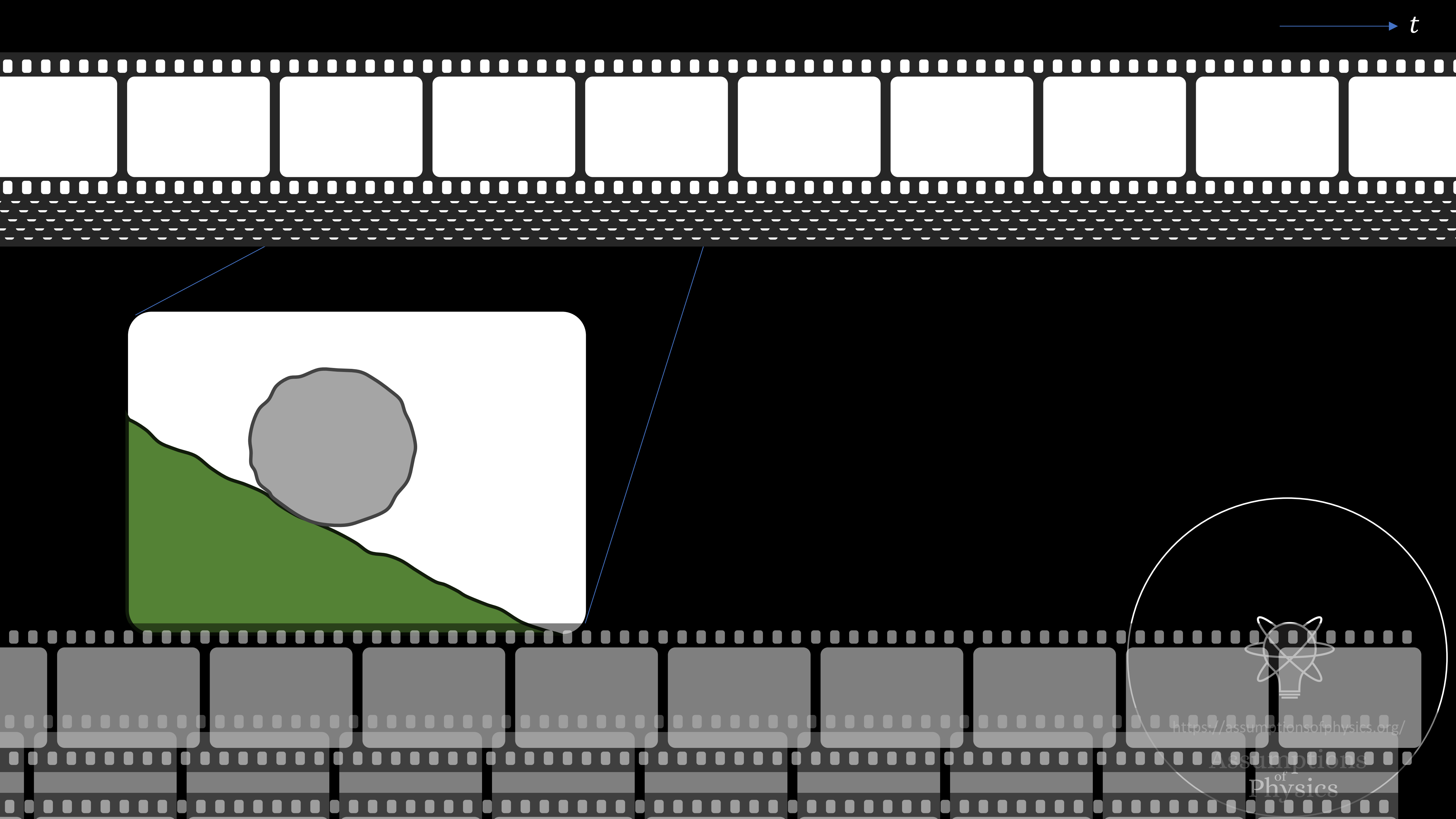
Assumptions of Physics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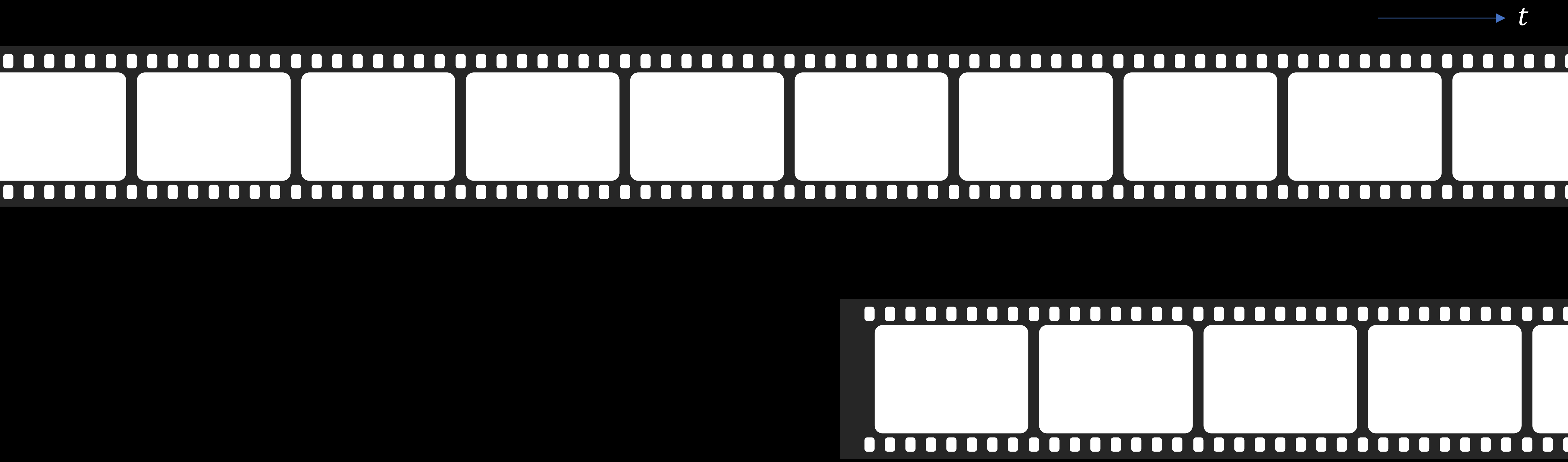
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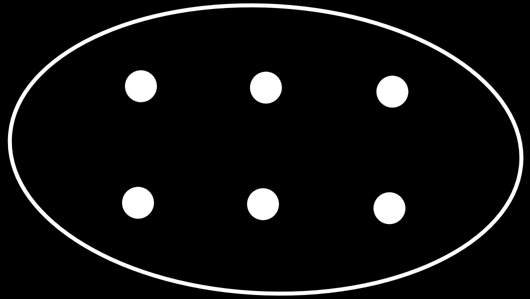
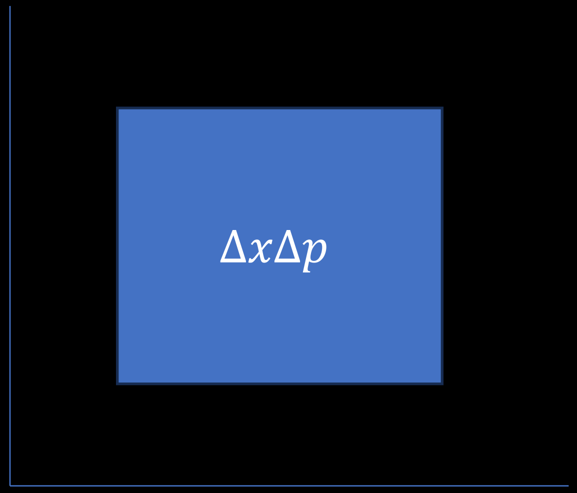
Assumptions of Physics

How should we count states?

For discrete classical systems

You simply count the points





For continuous classical systems

You use areas of position/momentum

For quantum systems?

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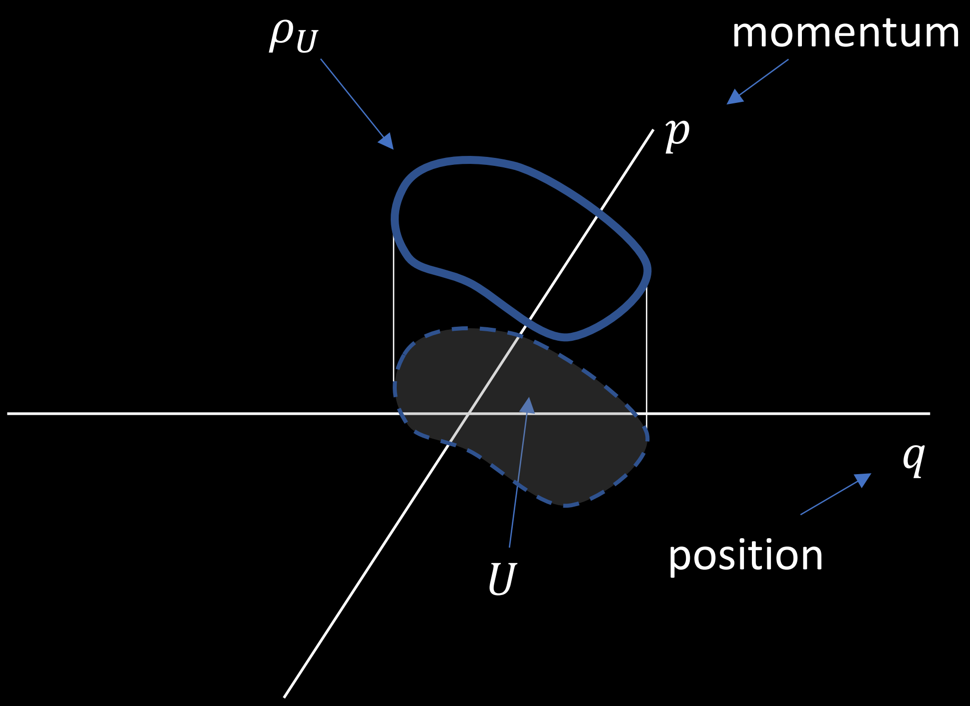
Assumptions of Physics

For classical systems

$$2^{S(\rho_U)} = \mu(U)$$

Exponential of the entropy for a uniform distribution over U

Count of states in U



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Assumptions of Physics

Preparation | Ensemble | Entropy ⟺ Variability within an ensemble

P_1 — e_1 … — $S(e_1)$

One instance is enough to tell e_1 and e_2 apart

Mutually exclusive

more variability

P_2 — e_2 … — $S(e_2)$

Mutually exclusive ⟺ Orthogonal

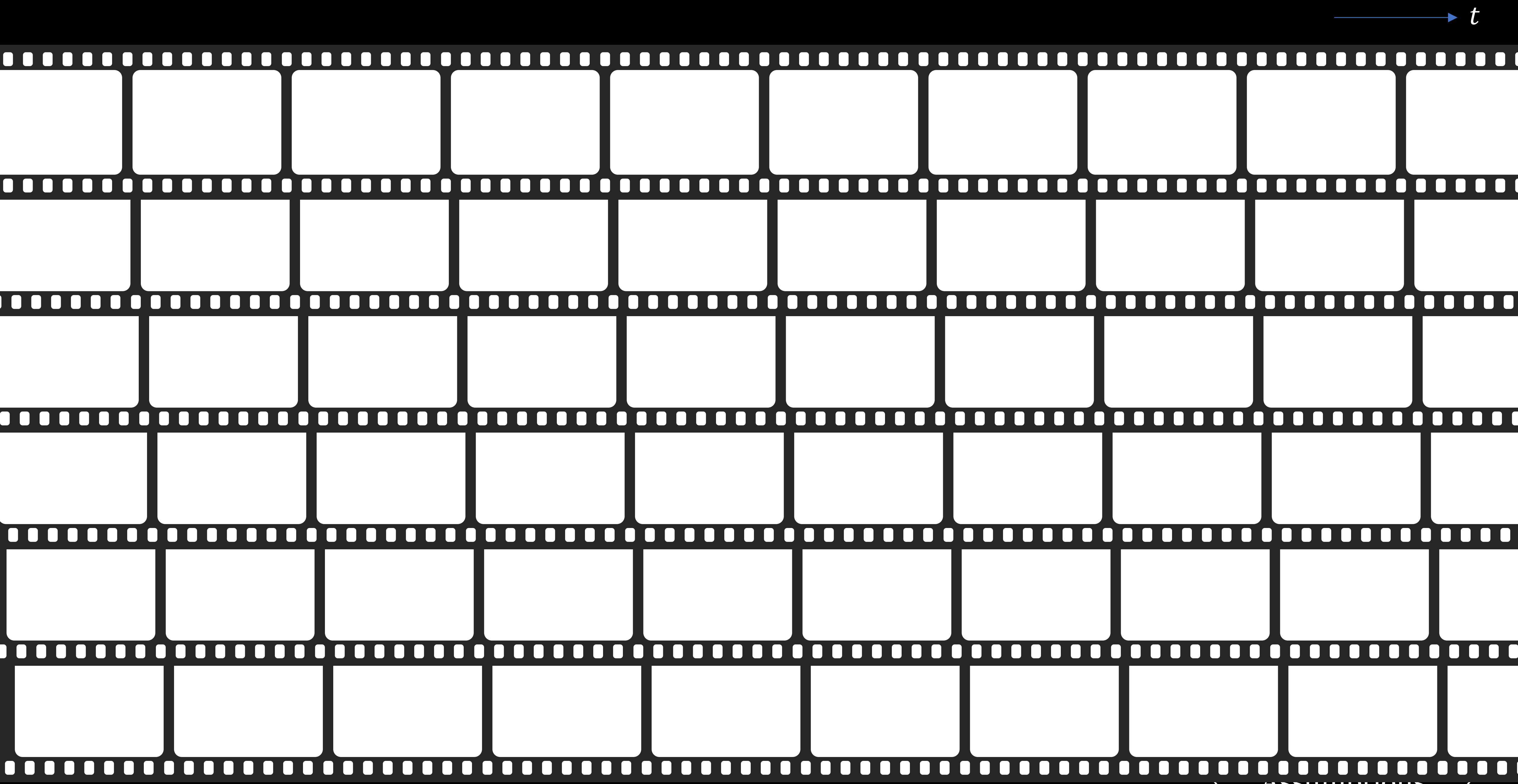
$pP_1 + \bar{p}P_2$ — $pe_1 + (1-p)e_2$

Maximal entropy increase if orthogonal

$$pS(e_1) + \bar{p}S(e_2) \\ + I(p, \bar{p})$$

recovers Shannon entropy

$$I(p, \bar{p}) = -p \log p - \bar{p} \log \bar{p}$$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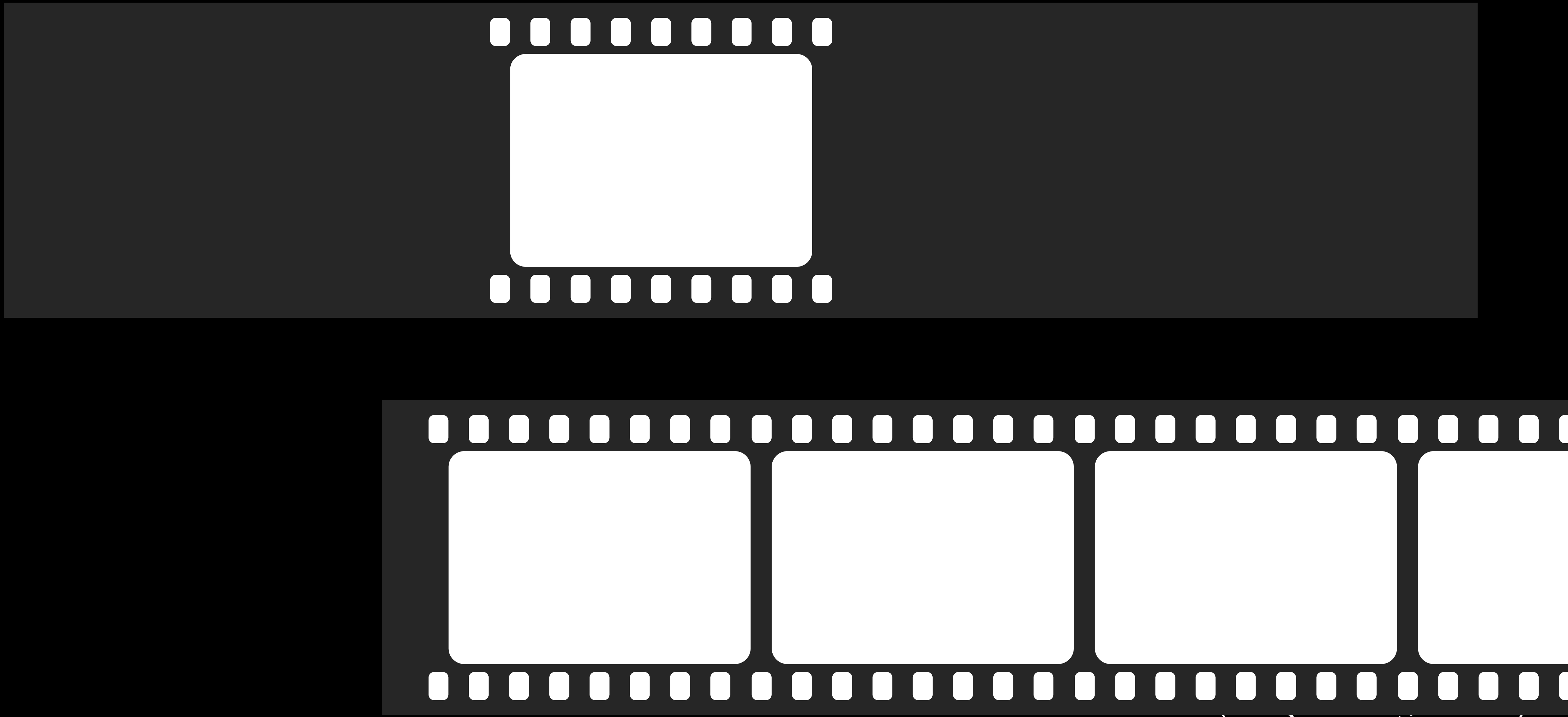

Assumptions of Physics

- We don’t know what it is

- What is a quantum system? What is a classical system?
- Electron/Proton/… all described by same equation. What makes them the same? Contextual. Inner dynamics is decoupled (it does not matter). Irreducibility?
- Can we reorganize all of physics through simple concepts? Most obvious?
- What

- 100 years of QM: fake history, we got some math but we don’t know what it means
- Uncertainty principle, two modes of evolution, contextuality, Dirac’s correspondence principle (quantization)
- Interpretations (hidden variables) and reconstructions don’t work
- Why does classical mechanics fail? Classical uncertainty principle.
- Motivations for the third law. Entropy of nothing. Entropy of one state.
- Classical mechanics recovered at high entropy, quantization is putting a lower bound on the entropy
- Entropy is about ensembles; physics is about ensembles; this is the fundamental mischaracterization of physics (film strip)
- Classical vs quantum: reducibility vs irreducibility; wave particule duality (electron a point particle, state probability distr; or electron a spread out blotch of energy? To tell the difference, needs lower entropy description)
- Back to counting states. 3 out of 2
- Space-time quantization

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Assumptions of Physics