Module II: Computations in the Physical World, Lecture II.c

Chi-Ning Chou @ 2022 January Mini-Course "What is Computation? From Turing Machines to Black Holes and Neurons"

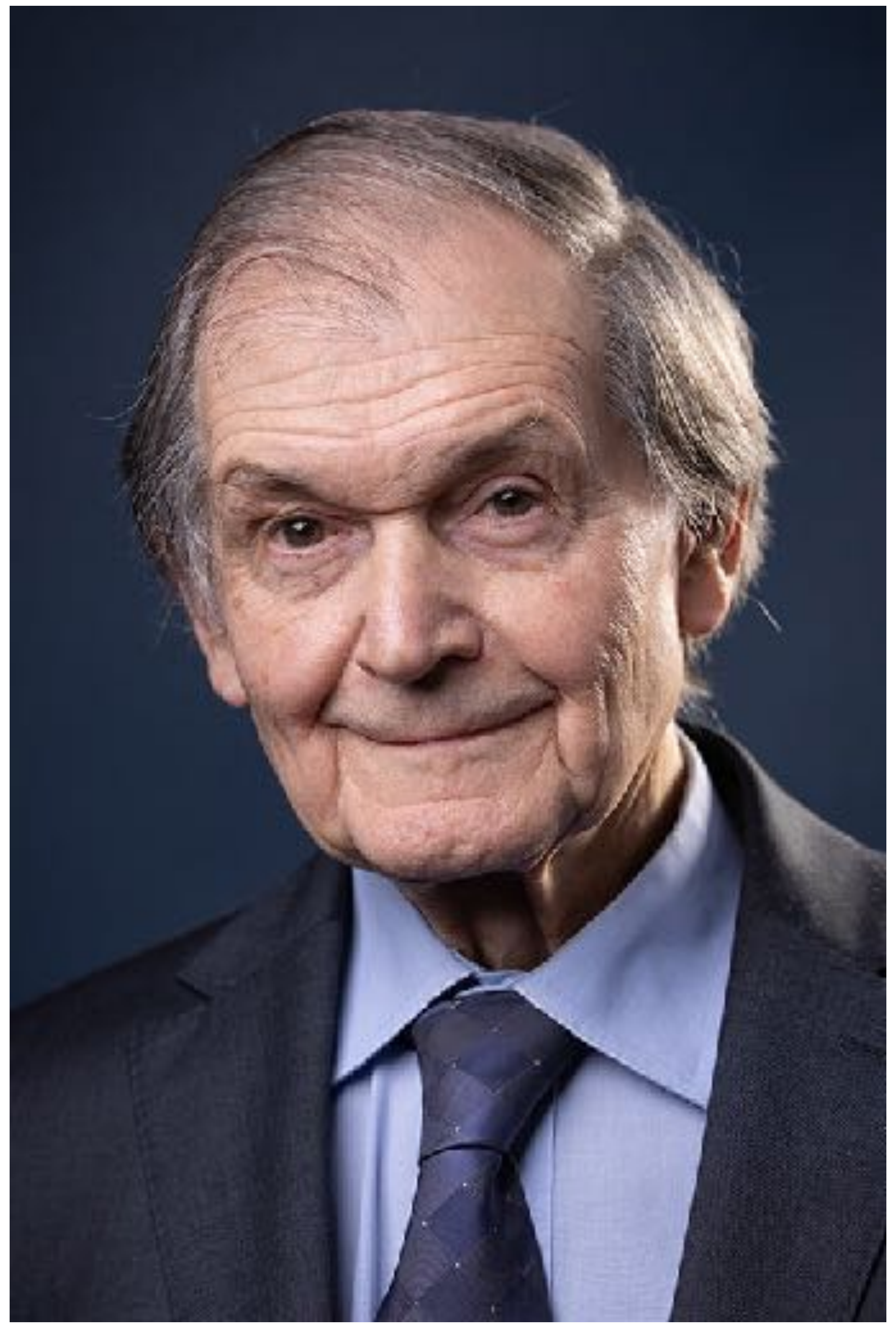
The Road to Reality: New Insights from Computation?

Module II: Computations in the Physical World

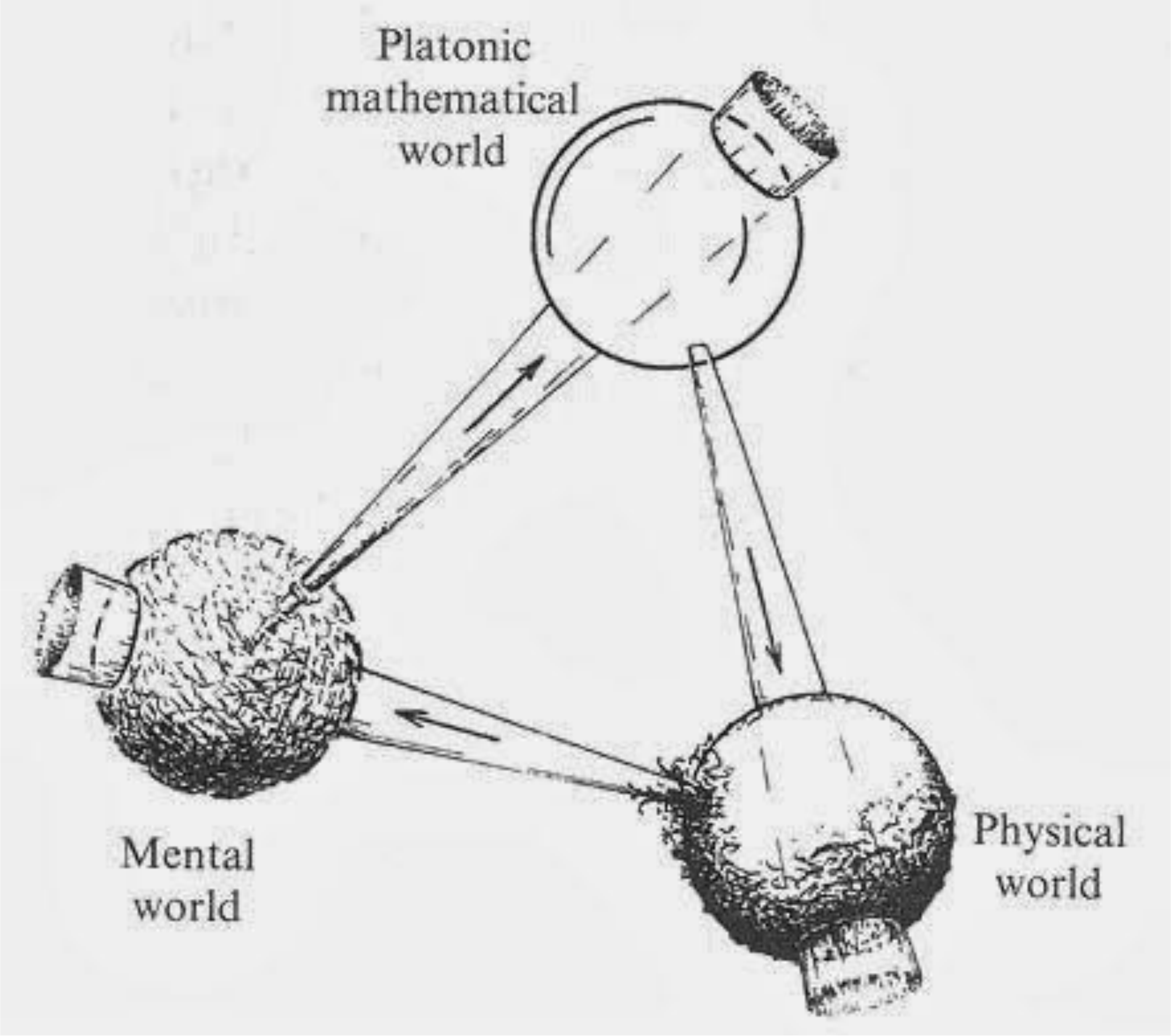
"Science is a differential equation. Religion is a boundary condition."

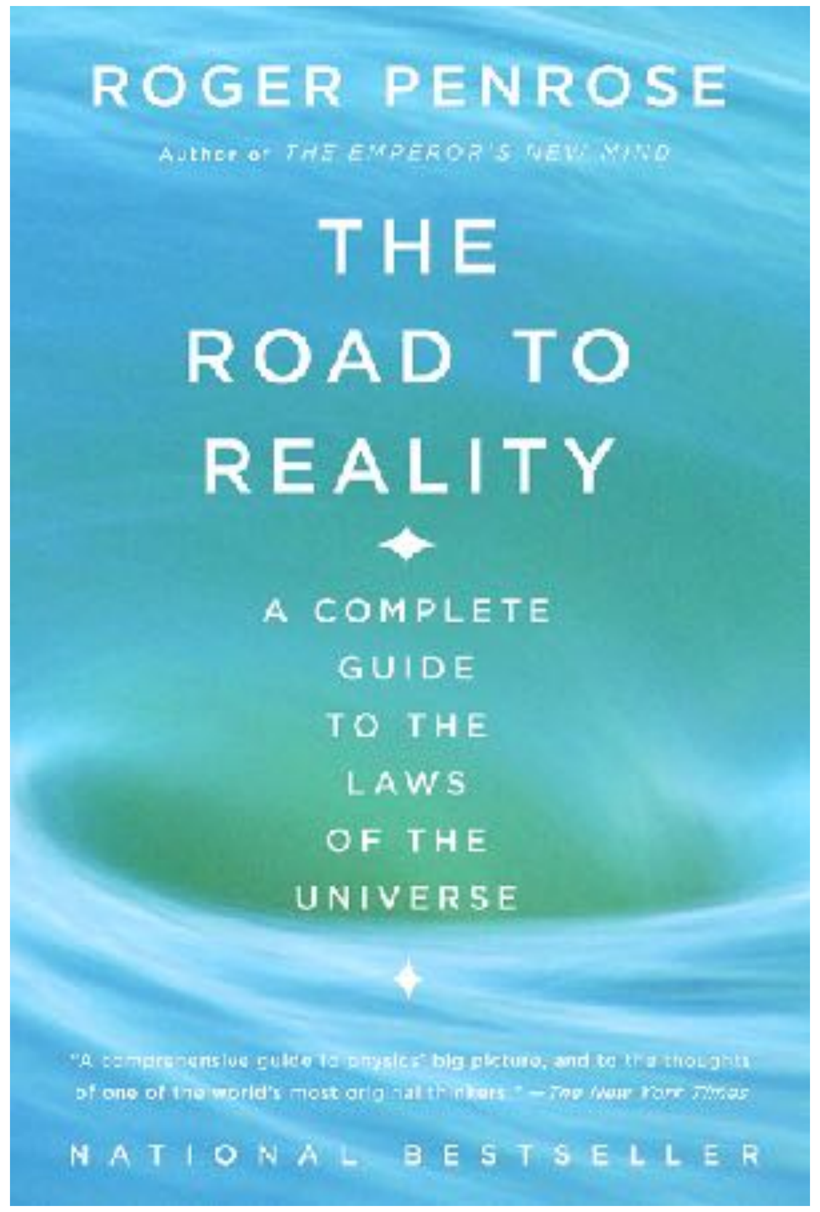
– Alan Turing

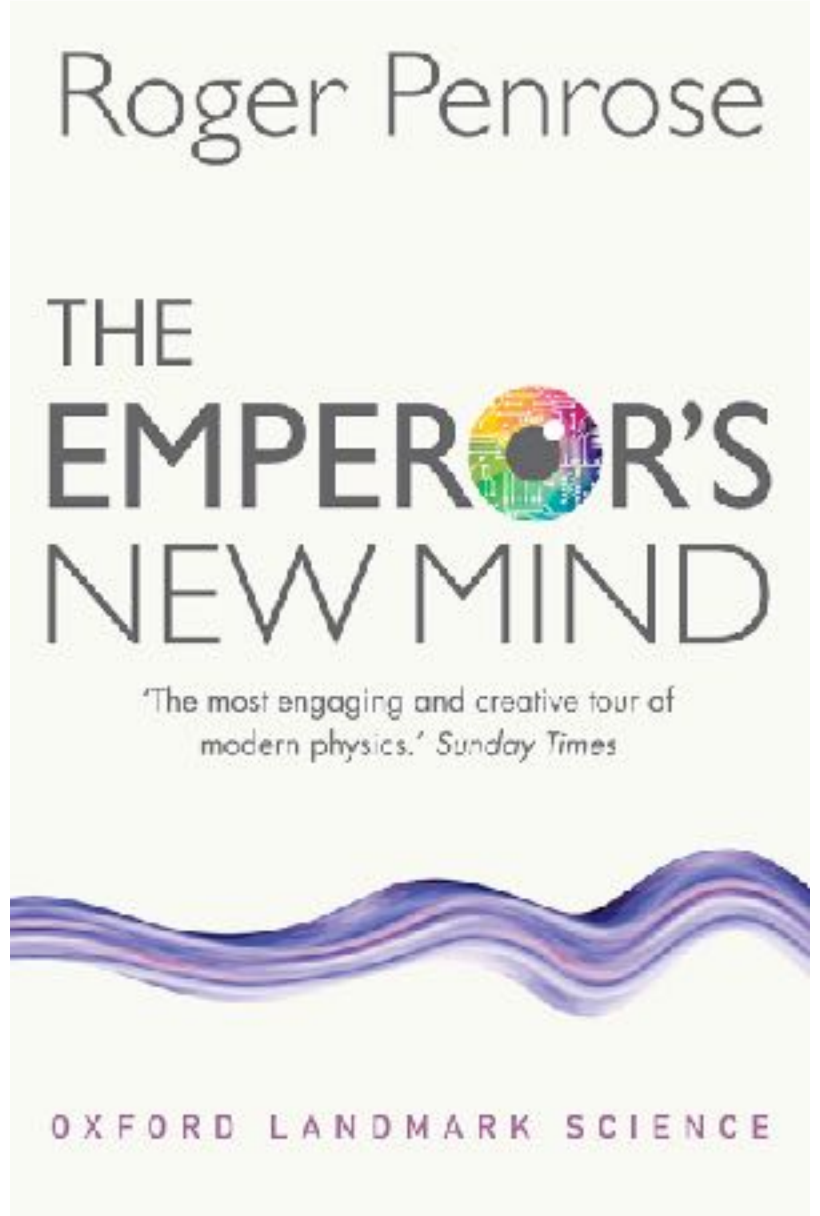
Penrose's Three Worlds



Roger Penrose
1931-present







What’s the limitation of computation in the physical world?

Physics ⟳ Computation

How fundamental does computation play a role in the physical world?

Discrete vs. Continuous

Justin

> If we agree that Physical World is doing Computation, we mostly use real or complex numbers for describing physical variables. However, Turing Machine is mapping integers to integers. How can Turing Machine capture all "Computation" if Physical World is doing Computation using real or complex numbers?

Digital

vs.

Analog

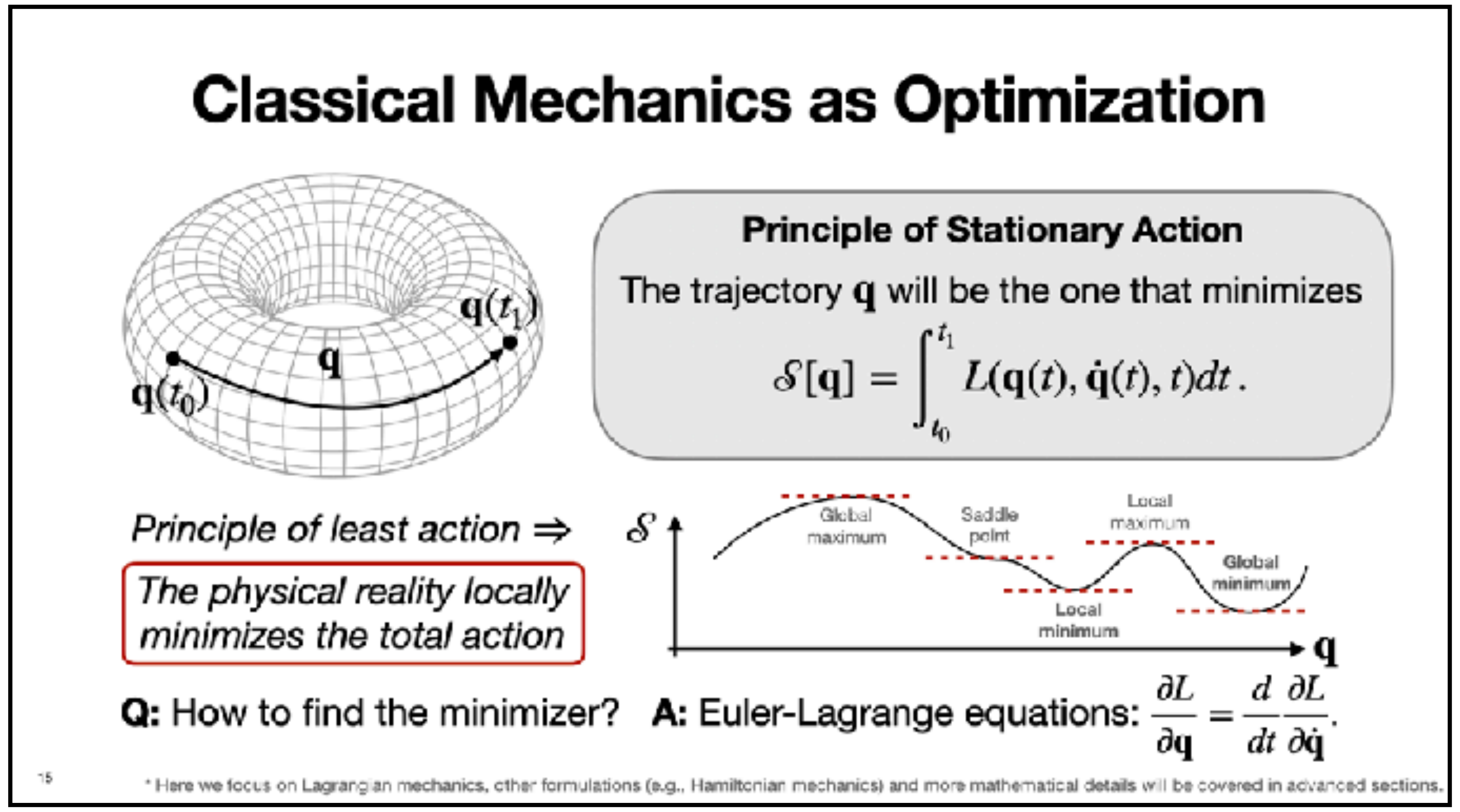
Real-Valued Computational Models (E.g., BSS machine)

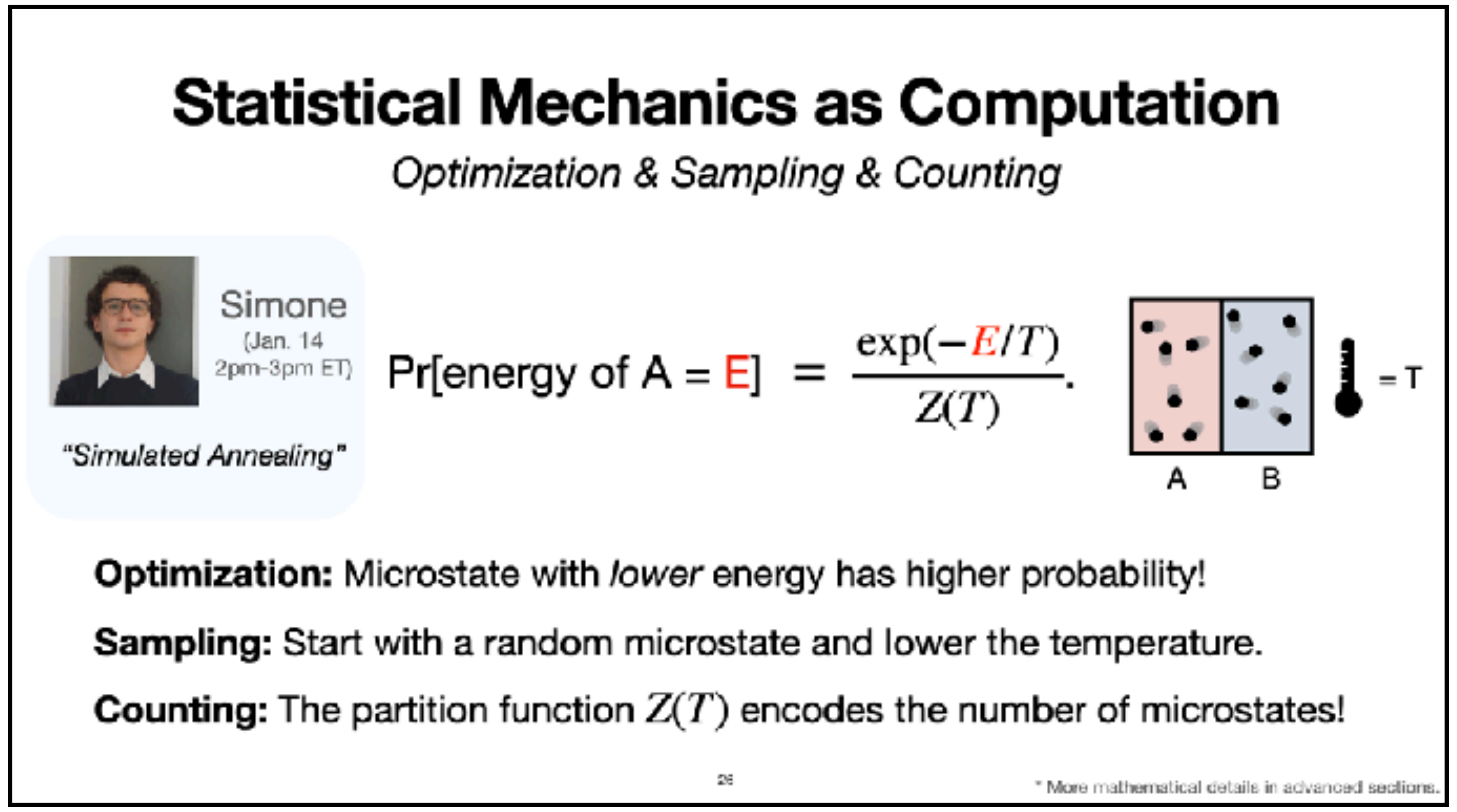
Though the physical world might be continuous, the measurements are discrete (i.e., Planck scale)!?

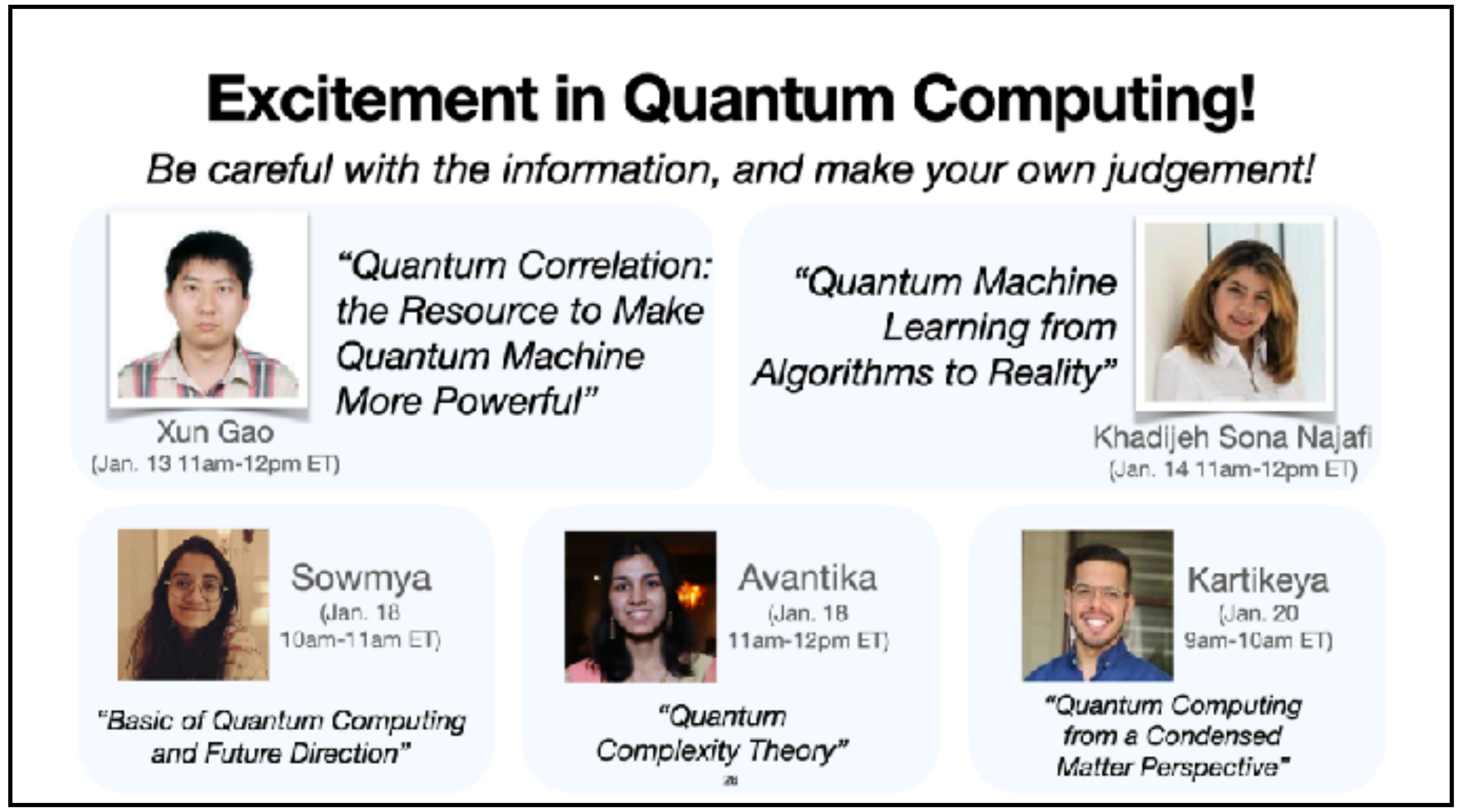
* A nice video explaining the difference between digital and analog computation.

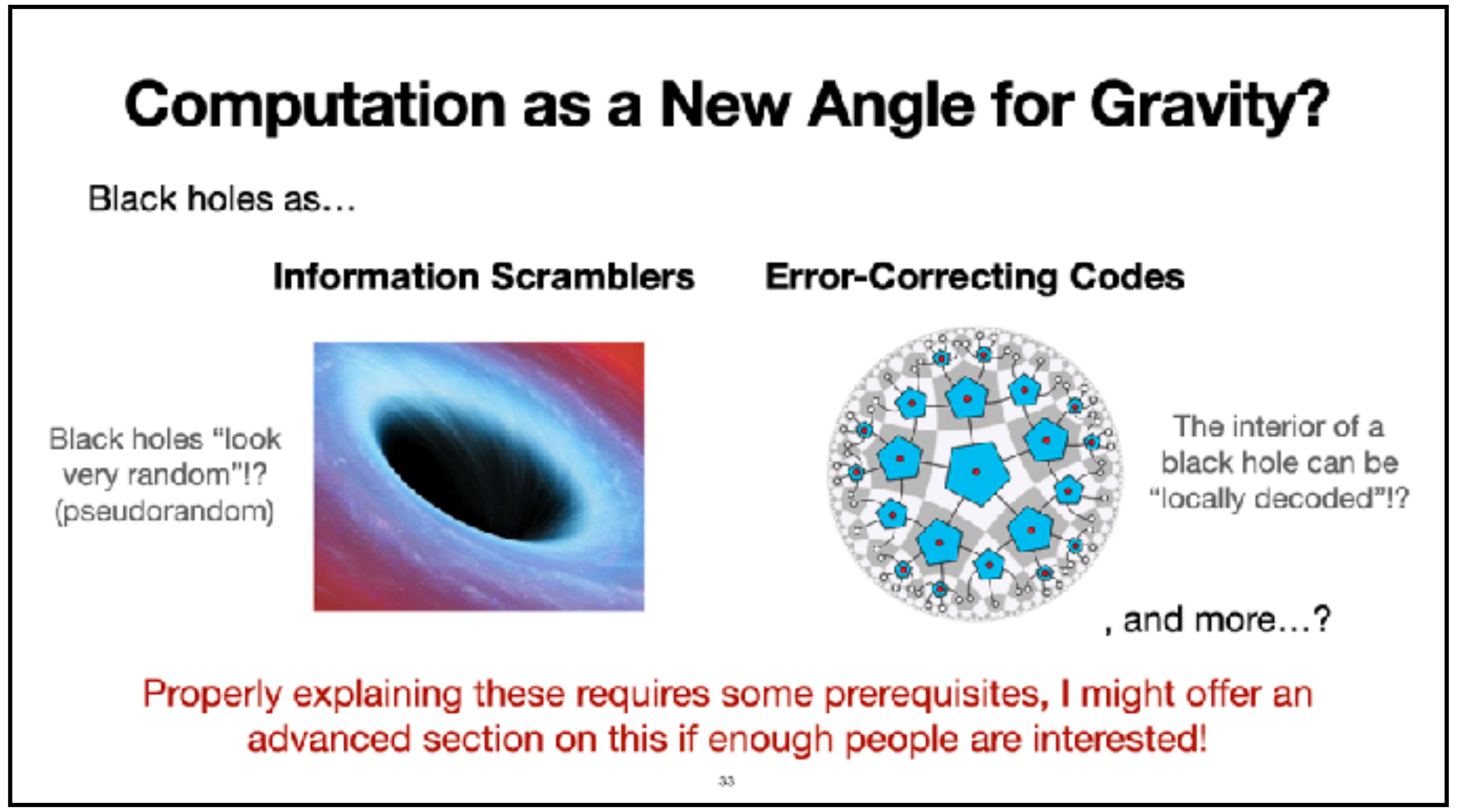
How fundamental does computation play a role in the physical world?

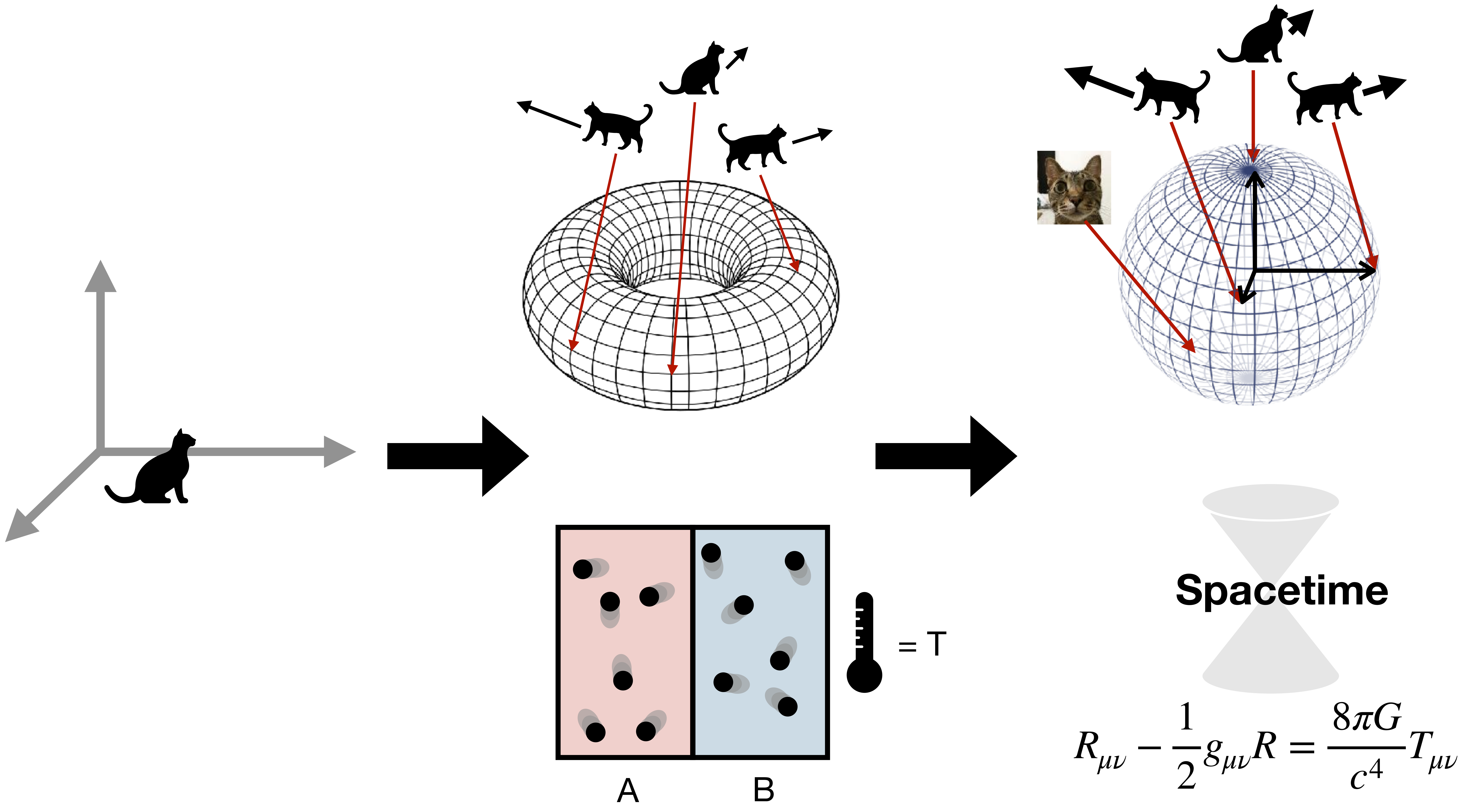
Computation in the Physical World










A
B
= T
Spacetime
$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}$

How Does a Physical System Compute?

Step 1: Encode the problem into the system

Step 2: Let the system evolve (unleash the power)

Step 3: Readout the output

How fundamental computation is in the physical world?

Consider the following thought experiment…

Q1: Does everything perform a certain computation? Or, does everything perform any computation? Is computation independent to particles, fields, forces, spacetime, etc.?

Q2: If all or some of the above were true, what does this mean? What's the difference between computation done by a physical system compared to the intuitive idea of "mechanical procedure"? What can the lens of computation bring to physics?

Type your thoughts in zoom chat!

Pancomputationalism (PC)

Unlimited PC	Limited PC	Ontic PC
Everything can do every computation.	Everything can do some computation.	The universe is a computing system.

My personal view:

- The issue of encoding problem.
- The statements seem to be vacuous, i.e., not much new insights yet?

We need to be more concrete and dig into it further!

* We will also elaborate on different of concrete computation in Lecture III.c.

What Insights Can Computation Give Us?

As physicists discover the importance of entropy, momentum, energy, etc.…

What aspects of computation are analyzable and insightful?

Maybe computational complexity could be a good candidate?

But it seems that complexity theorists cannot solve their own problems…

Maybe restricting ourselves to physically-relevant computations/algorithms can open the door!? E.g., in statistical physics, people do have exactly solvable models for certain realistic cases.

What’s the limitation of computation in the physical world?

Physical Church-Turing Thesis

Mathematical Church-Turing Thesis

All computable functions/numbers can be computed by a Turing machine.

Physical Church-Turing Thesis

All feasible computation in the physical world can be done by a Turing machine.

Extended Church-Turing Thesis

All feasible computation in the physical world can be done by a Turing machine efficiently.

Stronger

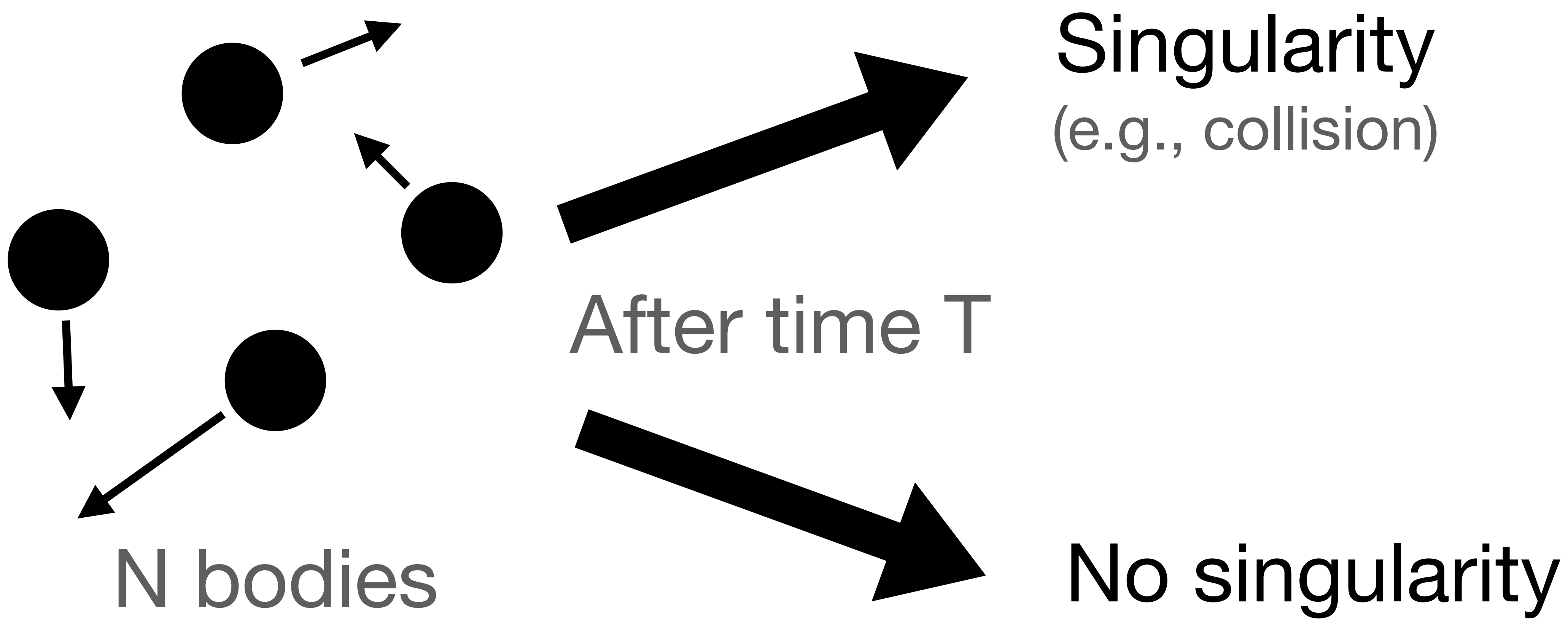
Can Turing Machine Simulate Classical Mechanics?

Extended Church-Turing Thesis

All feasible computation in the physical world can be done by a Turing machine efficiently.

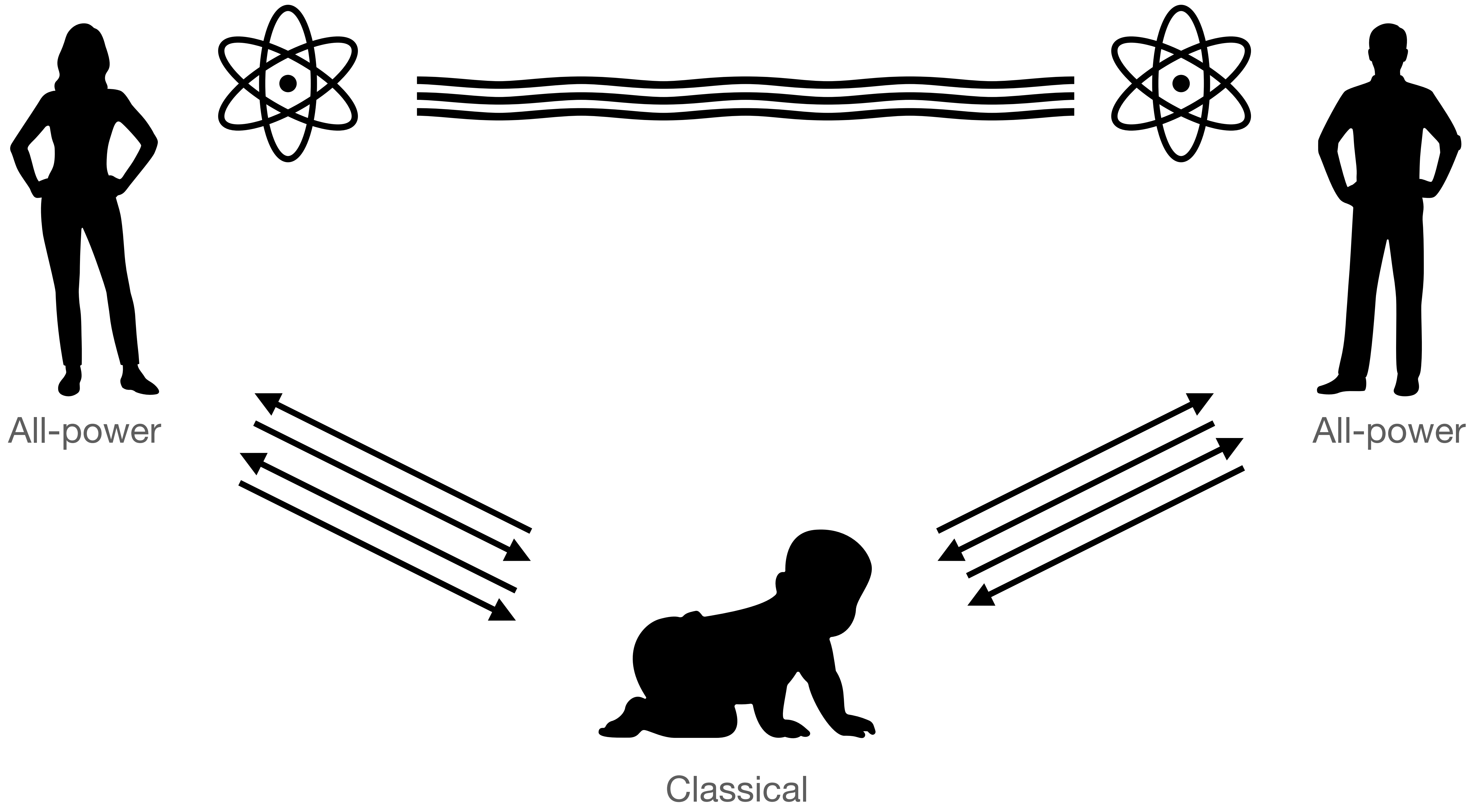
Q: Can we identify some computational problems in classical mechanics that cannot be efficiently computed by a Turing machine?

Andrew Chi-Chih Yao



* Yao credited the original idea to [Smith 1993].

MIP*=RE



They can solve the Halting Problem in polynomial time!

How to interpret their results in the physical world?

* An article by quanta magazine for general audience.
* A blog post by Henry Yuen, one of the authors, for more technical readers.

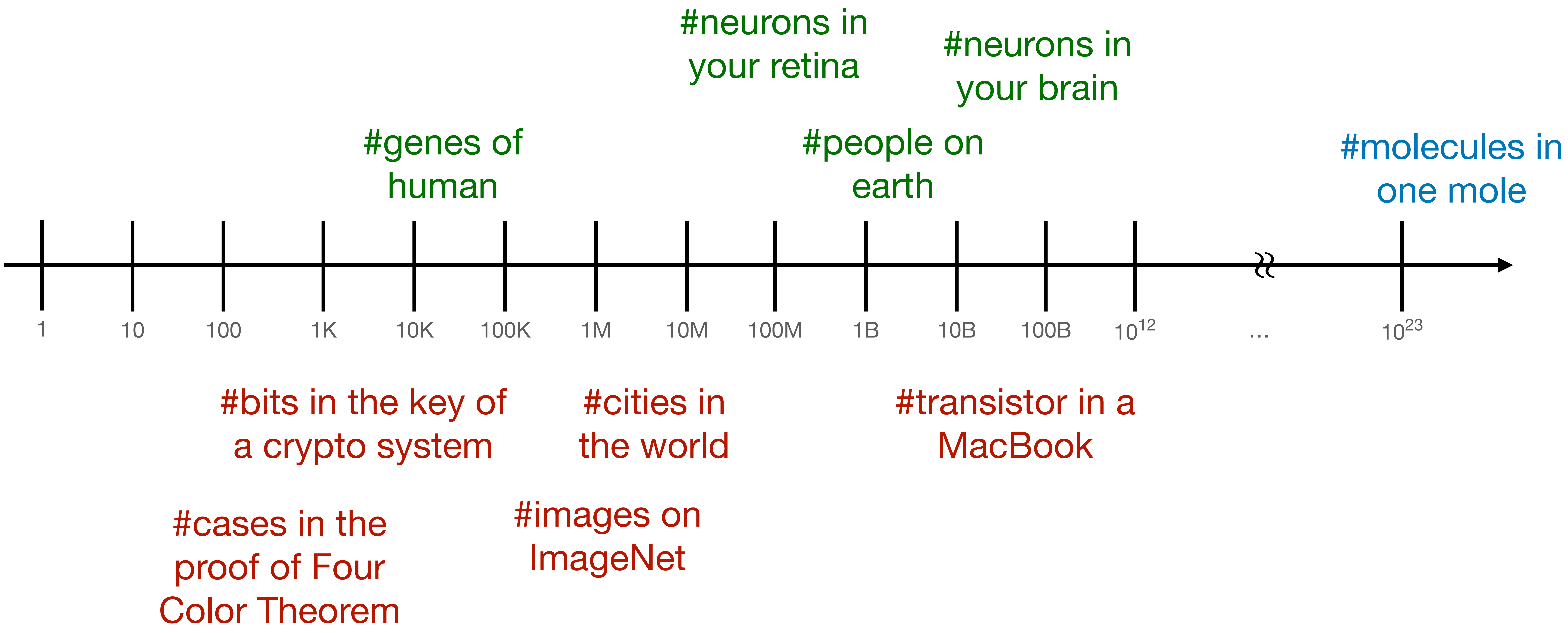
Limitations of Computation in the Physical World

Q3: How to interpret results like Shor's algorithm and MIP*=RE where the theoretical computational models haven't been implemented or even might not be able to be built?

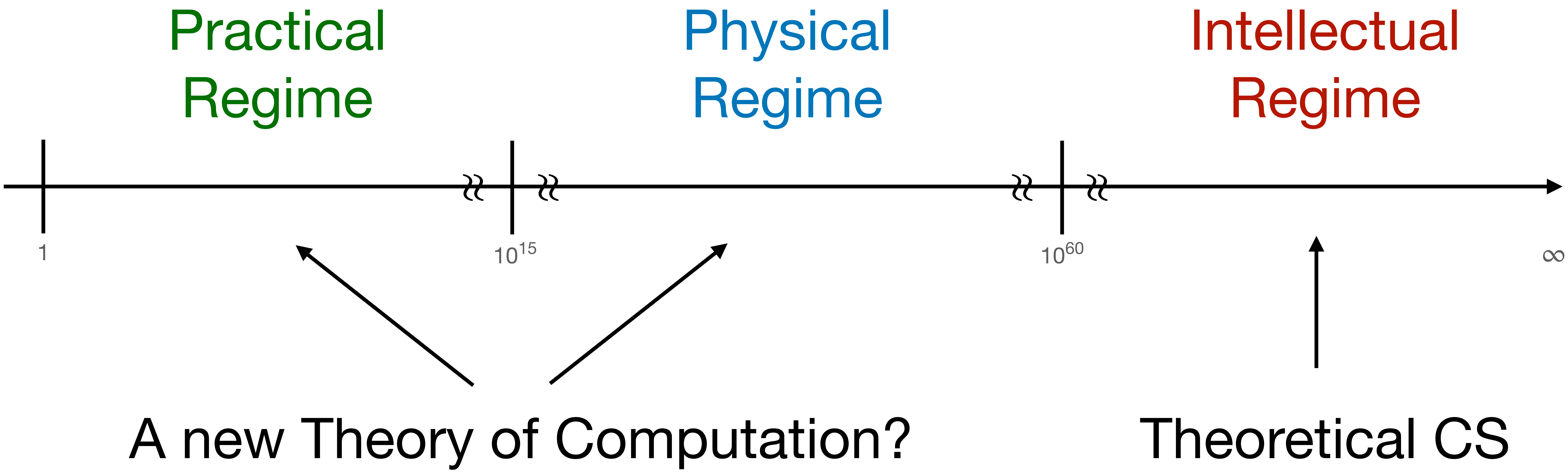
Q4: Infinity plays an important role in both theoretical physics and theoretical computer science. The former has a great success due to the fact that the order of atoms is indeed quite large (e.g., 10^{20}). However, the size of the computation problems we encounter in the real world could potentially be much smaller. What's your opinion on taking infinity/asymptotic into account when studying the computation in the physical world?

Type your thoughts in zoom chat!

Finiteness Matters!?



Three Regimes?



Summary

Questions of This Lecture

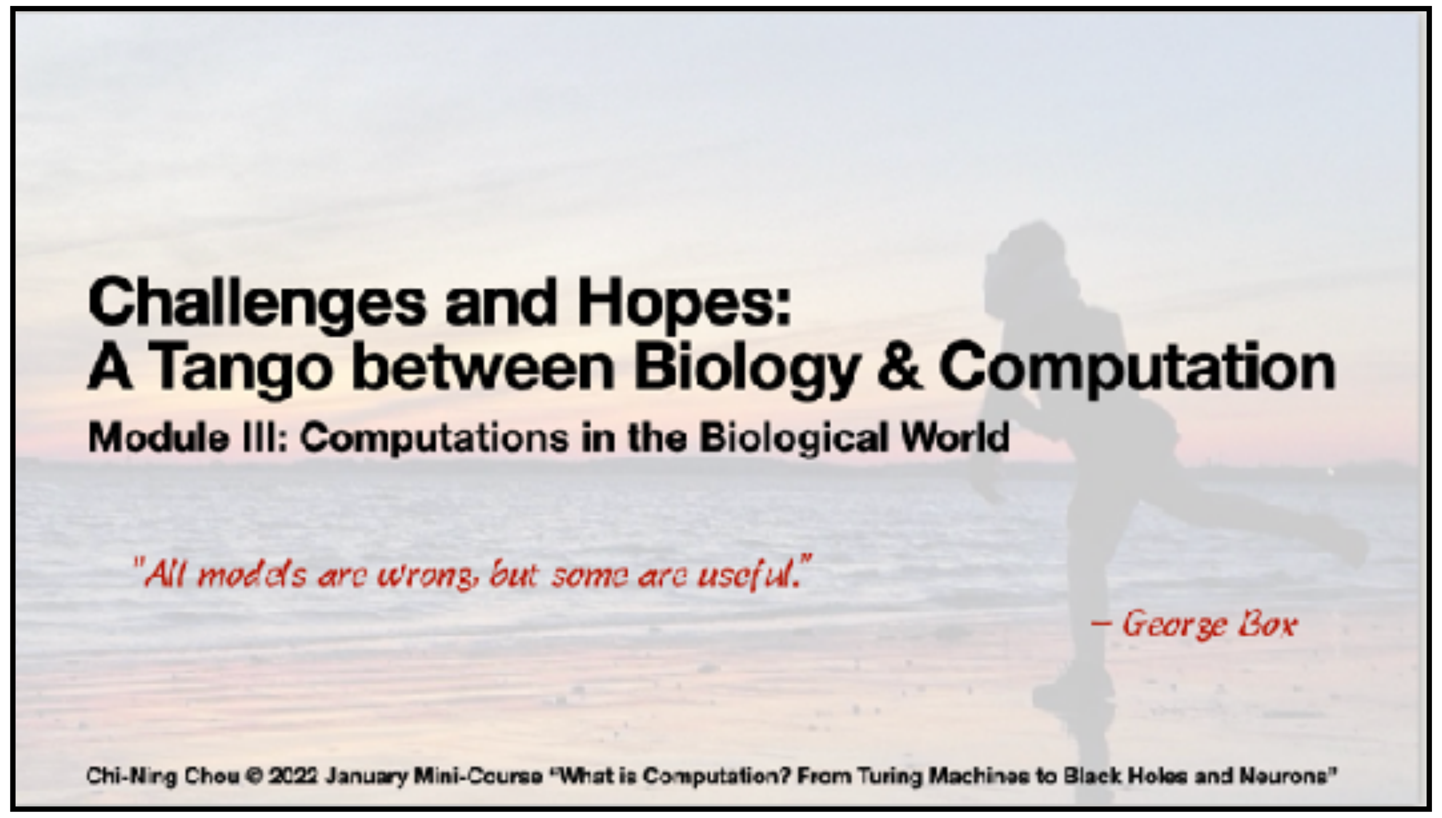
Q1: Does everything perform certain computation? Or, does everything perform any computation? Does computation prior to particles, fields, forces, spacetime, …?

Q2: If some of the above were true, what does this mean? What's the difference between computation done by a physical system compared to the intuitive idea of "mechanical procedure"? What can the lens of computation bring to physics?

Q3: How to interpret results like Shor's algorithm and MIP*=RE where the theoretical computational models haven't been implemented or even might not be able to be built?

Q4: Infinity plays an important role in both theoretical physics and theoretical computer science. The former has a great success due to the fact that the order of atoms is indeed quite large (e.g., 10^{20}). However, the size of the computation problems we encounter in the real world could potentially be much smaller. What's your opinion on taking infinity/asymptotic into account when studying the computation in the physical world?

Next



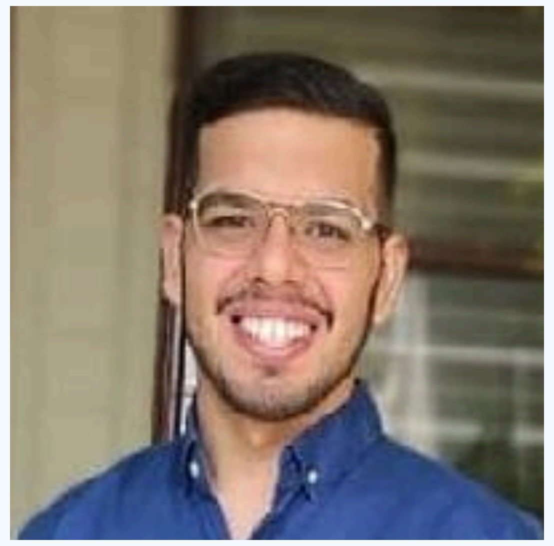
Lecture III.c
(Jan. 20 10am-10:50am ET)

"A Road to Totality: Between Art and Computation"

Zhiqian Wang
(Jan. 19 11am-12pm ET)

Salvador
(Jan. 20 1pm-2pm ET)

"Computing with Chemistry: Turing Machines, Graph Colouring, and DNA"



Kartikeya
(Jan. 20 9am-10am ET)

"Quantum Computing from a Condensed Matter Perspective"

Chi-Ning
(Jan. 21 9am-10am ET)

"When Black Holes Meet Computational Complexity"

References

Articles:

- Yao, Andrew Chi-Chih. “Classical physics and the Church–Turing thesis.” Journal of the ACM (JACM) 50.1 (2003): 100-105, link.
- Piccinini, Gualtiero and Corey Maley, “Computation in Physical Systems”, The Stanford Encyclopedia of Philosophy (Summer 2021 Edition), Edward N. Zalta (ed.), link.

Introductory Books:

- Feynman, Richard P., Tony Hey, and Robin W. Allen. Feynman lectures on computation. CRC Press, 2018, link.
- Penrose, Roger. The road to reality: A complete guide to the laws of the universe. Random house, 2005, link.
- Mezard, Marc, and Andrea Montanari. Information, physics, and computation. Oxford University Press, 2009, link.

Advanced Books:

- Mézard, Marc, Giorgio Parisi, and Miguel Angel Virasoro. Spin glass theory and beyond: An Introduction to the Replica Method and Its Applications. Vol. 9. World Scientific Publishing Company, 1987, link.
- Sakurai, Jun John, and Eugene D. Commins. “Modern quantum mechanics, revised edition.” (1995): 93-95, link.