From Quantum Computing to Computers of Generation Omega (a brief overview of Fall 2020 class CS 5354/CS 4365)

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1. We Need Faster Computers

- Modern computers are much faster than in the past.
- However, there are still many practical problems for which they are too slow.
- E.g., it is possible to predict, with high probability, where a tornado will go in the next 15 minutes.
- However, even on modern high performance computers, this computation will require several hours.
- This is too late for this result to be useful.

2. What Physical Processes Can We Use to Speed up Computations

- We have been unable to achieve a drastic speedup by using the traditionally used physical processes.
- So, a natural idea is to analyze whether using other physical processes can help.
- This analysis is the main topic of this class.

3. How Can We Find Physical Processes that Can Help to Speed up Computations?

- A natural idea is to find processes whose future behavior are computationally difficult to predict; indeed:
  - if this behavior was not difficult to predict,
  - then we would be able to replace the use of these processes with the corresponding computations;
  - thus, we would get a traditional computer that uses almost the same computation time;
  - however, we want a drastic increase in computational speed.
- We want to decide which physical processes are appropriate for computation speed-up.
- So, we need to analyze the computational complexity of different physical phenomena.

4. This Leads to Computational Complexity: the 1st Topic of this Class

- We want to perform computational complexity analysis of different physical phenomena.
- To be able to do it, we will first recall the main definitions of computational complexity:
  - worst-case time complexity,
  - average time complexity,
  - feasible algorithms,
  - P and NP, and
  - NP-hard problems.
- After that, we will start analyzing computational complexity of different physical phenomena.

5. Types of Physical Processes

- Depending on what we can determine – we can divide physical processes into three main types.
- For some processes, we know the models that predict the results.
- For some processes, the results are partly unpredictable.
- For these processes, we can predict some characteristics – e.g., probabilities of different outcomes.
- Some processes are completely "lawless".
- For such processes, any predicting model will eventually turn out to be wrong.
- We will analyze if and how processes of each type can be used to speed up computations.

6. Processes for Which We Know the Models that Predict the Results

- Most such processes are described by partial differential equations.
- In these equations, the time derivative of all the quantities $x(t)$ depends on their current values.
- Usually, the dependence of the time derivative $v(t)$ on the current values is computationally feasible.
- So, to predict the value $x(t+h)$ for small $h > 0$, we can simply compute $x(t) + h \cdot v(t)$.
- Thus, such processes cannot lead to a drastic computational speedup.

7. Processes for Which the Results are Partly Unpredictable, but for Which We Can Predict Some Characteristics – e.g., Probabilities Of Different Outcomes: Main Example

- There are such process – e.g., radioactive decay.
- These processes are described by quantum mechanics.
- In quantum mechanics:
  - in addition to differential equations that describe a *smooth* change in the system's state,
  - we also have *abrupt* – and *probabilistic* – changes corresponding to measurements.
- And measurements are ubiquitous, since they are the only way by which we can gain information.

8. Quantum Processes Can Indeed Speed up Computations

- For quantum systems, prediction indeed turns out to be NP-hard.
- Not surprisingly, several schemes have been discovered for using quantum processes to speed up computations.

9. Quantum Computing Can Help in Solving All Practical Problems

- From the general viewpoint, these schemes cover all possible applications of computers.
- Indeed, from this general viewpoint, what do we want?
- We want to understand how the world works, predict what will happen.
- This is, crudely speaking, what science is about.
- For example, we want to understand where the tornado will turn.
- We also want to understand how can we improve the situation.
- This is, crudely speaking, what engineering is about.

10. Quantum Computing Can Help (cont-d)

- For example, how can be make tornadoes change their course?
- How can we make houses less vulnerable to tornadoes?
- Finally, we want to communicate – or not – with others.
- So we need to develop techniques for communication only with the intended folks.

11. Quantum Computing is Useful in Solving the Main Problems of Science And Engineering

- In the general prediction problem, we need to find a model that fits all the observations.
- In a usual engineering problem, we need to find a design and/or a control that satisfies a given specification.
- In most of these problems:
  - once we have a model, a design, or a control,
  - it is computationally feasible to check whether this model, design, etc. satisfies the given specs.
- It is searching for a satisfactory model, design, etc. which is computationally intensive.
- To speed up such problem, we can use Grover's quantum search algorithm.

12. Quantum Computing and Grover's Algorithm: the 2nd Topic of This Class

- In class, we will review the basic ideas of quantum computing.
- Then, we will explain the main ideas behind Grover's algorithm.

13. Need for Optimization

- In some cases:
  - we do not just want to find not just *a* model, a design, or a control,
  - but rather the *best* model, design, and control.
- It turns out that Grover's algorithm can speed up the solution of optimization problems as well.
- Quantum optimization will be the 3rd topic of this class.

14. Quantum Computing and Communications

- Due to its efficiency, quantum computing can break down the existing encryption algorithms such as RSA.
- Good news is that by using quantum effects, we can develop an unbreakable quantum cryptography scheme.
- RSA algorithm, its quantum-related vulnerability, and quantum cryptography will be the 4th class topic.

15. Randomness in General

- Intuitively, a random sequence is a sequence that cannot be easily computed.
- This leads to a formal definition of randomness via Kolmogorov complexity in Algor. Information Theory.
- Not surprisingly, the corresponding notions are difficult to compute.
- E.g., Kolmogorov complexity is not algorithmically computable.
- According to modern physics, random processes do occur in real life.
- So, the use of random processes may lead to yet another way to speed up computations.
- Kolmogorov complexity, randomness, and their computablity will be the 5th class topic.

16. Completely "Lawless" Processes

- Many physicists believe that:
  - no matter how complex theories we propose,
  - there will always be some new phenomena that would require us to modify these theories.
- In computational terms, this means that the sequence of observations is not computable.
- Not surprisingly, this idea leads to the possibility of speeding up computations.
- Study of such "lawless" sequences will form a (relatively short) 6th topic of this class.

17. Processes about Which We Do Not Know Much but that Show Promise

- Another possibility is to look for processes which are promising, i.e., processes which:
  - are surprisingly faster
  - than they should be.
- A biological example of such a process will be given.
- This will be an even shorter 7th topic of this class.

18. Another Possibility: Using Physical Processes with Unusual Space And Time

- Up to now, we considered processes within the usual concepts of physical space and physical time.
- However, many physical theories are based on changing the usual concepts of space and time.
- Many of these changes can lead to speed up of computations.
- We can use the fact that, according to relativity theory, time slows down:
  - for fast particles
  - or in the presence of a strong gravitational field, for example, near the black hole.

19. Unusual Space-Time Models (cont-d)

- We can use the fact that in curved space-time, volume changes.
- So we may be able to fit more processors working in parallel and thus, speed up computations.
- We can use possible acausal processes.
- We can use models in which space and time are discrete.
- Discrete computations are usually more difficult than continuous ones.
- So if we have a real-life discrete system, this can potentially speed up computations.
- Studying how different space-time models can speed up computations will be the last topic of this class.