Lecture 1: From the Universe to the Qubit
Why Quantum Information Science?

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What does nature allow information to do?

Four Questions for Today

By the end of this lecture, you should be able to explain four ideas in your own words:

- What does the word *quantum* mean?
- Why does physics matter to computer science and information?
- Why do we need a field called Quantum Information Science?
- Why is a quantum computer actually called *quantum*?

We will begin with something familiar: the computer in front of you.

1. Start With the Computer in Your Hand

Think about your phone or laptop. It can display videos, run programs, store photographs, communicate across the Internet, and perform billions of operations.

As computer scientists, we normally describe these activities using programs, algorithms, processors, memory, and networks.

Suppose we execute

```
print("Hello, world!")
```

To us, this is one line of code.

But the computer must physically make something happen.

The program is translated into lower-level instructions. Those instructions are executed using logic gates. Logic gates are built from transistors. Transistors are made from physical materials. Those materials are made from atoms and electrons.

We can imagine the path as

$$\text{Software} \rightarrow \text{Instructions} \rightarrow \text{Logic Gates} \rightarrow \text{Transistors} \rightarrow \text{Atoms and Electrons.}$$

Something that begins as an abstract instruction eventually becomes a physical process.

This gives us our first important idea:

Every computation ultimately happens in a physical system.

Computer science normally allows us to ignore those physical details. A programmer does not need to think about individual electrons when writing Python.

But the physical layer is still there.

That leads to an important question:

If the physical rules underneath the computer are different from what we normally experience, can computation also be different?

This question leads us toward quantum computing.

2. The Everyday World and the Quantum World

Our everyday experience gives us a very useful picture of how objects behave.

A baseball has a location. A car follows a path. A door is open or closed. A light switch is on or off.

If nobody looks at a baseball for five seconds, we do not expect it to lose its location.

These ideas are described extremely well by **classical physics**.

Classical physics is not “wrong physics.” It remains an excellent description of the world at the scales we normally experience.

But scientists discovered that atoms, electrons, and light cannot always be described using the same everyday picture.

At microscopic scales, experiments revealed behavior that classical physics could not fully explain.

Scientists therefore needed a new theory.

That theory is called

Quantum Mechanics.

Quantum mechanics gives us the rules used to describe physical systems when quantum effects matter.

A useful distinction is therefore

Classical Physics and Quantum Mechanics.

Classical physics describes everyday behavior extremely well.

Quantum mechanics gives us the deeper rules needed to explain atoms, electrons, light, and many other physical systems.

3. Why Did Scientists Need Quantum Mechanics?

Scientists did not create quantum mechanics simply because they wanted a strange new theory.

Experiments forced them to reconsider how nature works.

Consider two examples.

Example 1: Atoms produce particular colors. When atoms are given energy, they can emit light.

But they do not emit every possible color equally.

Different atoms produce particular patterns of colors, called **spectral lines**.

It was almost as if atoms were saying:

“Only certain energies are allowed.”

Classical physics could not fully explain this behavior.

Example 2: Electrons can produce interference. Imagine firing electrons toward a barrier containing two narrow openings. Behind the barrier is a screen that records where each electron arrives.

Each electron appears at one particular location on the screen.

That sounds particle-like.

But after many electrons arrive, the overall pattern can show **interference**, a behavior we normally associate with waves.

Even when electrons are sent one at a time, the interference pattern can gradually appear.

An electron therefore does not behave exactly like a tiny classical ball.

Nor is it simply an ordinary classical wave.

It is a **quantum object**.

These experiments taught physicists something important:

Nature does not always follow our everyday intuition.

Quantum mechanics was developed because it successfully describes what experiments actually show.

4. What Does "Quantum" Actually Mean?

Today the word *quantum* appears everywhere:

quantum computing, quantum communication, quantum sensing, quantum networks.

It can therefore sound as though "quantum" simply means small, strange, powerful, or futuristic.
That is not what the word means.
Historically, a *quantum* refers to an amount or quantity.
One important discovery was that some physical quantities can take only particular allowed values.
This is called **quantization**.

Ramp versus staircase. Imagine walking up a smooth ramp.
You can stop at almost any height.
Now imagine walking up a staircase.
You can stand on Step 1, Step 2, or Step 3.
The allowed heights come in levels.
Some properties of quantum systems behave somewhat like the staircase.
For example, an electron bound inside an atom can have particular allowed energy levels,

$$E_1, \qquad E_2, \qquad E_3, \qquad \dots$$

rather than every possible energy in between.
That is one example of quantization.
But there is an important warning:

Quantum mechanics does not simply mean "everything comes in steps."

Quantum mechanics also includes ideas such as

superposition, interference, entanglement, and measurement.

We will learn each of these ideas gradually.
For this course, the simplest meaning to remember is

"Quantum" means that the system must be described using the rules of quantum mechanics.

5. What Is a State?

Before discussing a *quantum state*, we need to understand the word *state*.
A traffic light can be

red, yellow, green.

A door can be

open or closed.

A classical bit can be

0 or 1.

In each case, the state describes the condition of the system that matters to us.
The same basic idea appears in physics.
A **state** is a description of a physical system that allows us to reason about how the system behaves and what we may observe.
Quantum mechanics gives us special rules for describing **quantum states**.
Those rules are different from the rules we use for ordinary classical states.
That difference is what eventually gives us quantum information.

6. Information Is Physical

Now return to computing.

The basic unit of classical information is a **bit**.

A bit has two logical values:

$$0 \quad \text{or} \quad 1.$$

But a bit is an abstract idea.

To store a bit inside a real computer, something physical must represent it.

A device might use two voltage ranges, two amounts of electrical charge, two magnetic states, or some other physical distinction.

Similarly, suppose we want to store the letter

$$A.$$

On the screen, the letter is represented using pixels.

Inside memory, it is represented using physical states of electronic devices.

During wireless communication, it is carried by electromagnetic signals.

In optical fiber, information can be carried using light.

The physical representation changes, but the information can remain the same.

This leads to one of the most important ideas in this course:

Information is abstract, but storing, processing, and communicating information require physical systems.

This idea is often shortened to

Information is physical.

And once information is physical, the laws of physics matter.

That gives us the bridge from physics to information science.

7. Why Do We Need Quantum Information Science?

A natural question now appears.

If information is stored in physical systems, what happens when those physical systems obey quantum mechanics?

This is the central question of **Quantum Information Science**, or **QIS**.

A simple definition is

Quantum Information Science studies information when the systems carrying that information obey quantum mechanics.

Why is this useful?

Quantum mechanics gives us ways of representing, transforming, sharing, and measuring information that are different from ordinary classical information.

We can organize QIS around four goals.

1. Understand. Nature itself is quantum mechanical.

Atoms, molecules, chemical reactions, and materials depend on quantum behavior.

Some quantum systems are extremely difficult to simulate using classical computers.

One motivation for quantum technology is therefore

use controlled quantum systems to understand other quantum systems.

2. Compute. Quantum mechanics gives us a different way to represent and transform information.
Computer scientists can therefore ask:

Can a different physical model of information give us different algorithms?

For some problems, the answer is yes.
This gives us **quantum computing**.

3. Communicate. Quantum states can also be transmitted between systems.
Their behavior enables new ideas in communication, networking, and cryptography.
Quantum computing also affects cybersecurity because sufficiently powerful quantum computers would threaten some widely used public-key cryptographic systems.

4. Measure. Quantum systems can be extremely sensitive to changes in their surroundings.
That sensitivity can be used to build very precise sensors for quantities such as time, magnetic fields, acceleration, and rotation.
These four goals are worth remembering:

Understand. Compute. Communicate. Measure.

Quantum computing is therefore only one part of Quantum Information Science.

8. Why Is a Quantum Computer Actually Quantum?

We can now answer an important question.
An ordinary laptop is made from atoms and electrons.
Those atoms and electrons obey quantum mechanics.
So why do we not call every laptop a quantum computer?
Because ordinary computers are designed so that the information we use behaves **classically**.
We want a bit storing 0 to behave reliably like 0.
We want a bit storing 1 to behave reliably like 1.
We want information to be easy to read, copy, store, and process.
The complicated quantum behavior of the underlying matter is mostly hidden from the programmer.
A quantum computer takes a different approach.
Instead of hiding useful quantum behavior, it tries to

preserve it, control it, and use it for computation.

A quantum computer is therefore called quantum because

its computational information is deliberately represented and manipulated using quantum states.

The relationship is

$$\boxed{\text{Quantum Mechanics}} \rightarrow \boxed{\text{Quantum Information}} \rightarrow \boxed{\text{Quantum Computing}}.$$

Quantum mechanics provides the physical rules.
Quantum information studies information under those rules.
Quantum computing uses those rules to perform computation.

9. From a Bit to a Qubit

The basic unit of classical information is the bit:

$$0 \qquad \text{or} \qquad 1.$$

The basic unit of quantum information is the **quantum bit**, or **qubit**.
A qubit has two basic reference states:

$$|0\rangle \qquad \text{and} \qquad |1\rangle.$$

These symbols are pronounced "ket zero" and "ket one."
We will learn this notation carefully in the next lecture.
A qubit can also have a state written as

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle.$$

This is called a **superposition**.
The numbers α and β are called **amplitudes**.
For now, you do not need to calculate with them.
You only need to remember that amplitudes help determine both measurement probabilities and interference.
The most important question is this:

Is a qubit in superposition simply a classical bit whose value we do not know?

No.
Suppose I flip a normal coin and cover it with my hand.
You do not know whether it is heads or tails.
But the coin already has a definite classical result.
Your uncertainty does not make the coin quantum.
A quantum superposition is different.
It is a genuine quantum state, and its amplitudes can later interfere with one another.
That difference becomes extremely important in quantum algorithms.

10. Measurement: How a Quantum State Gives Us an Answer

Suppose a classical program contains

```
x = 5
print(x)
```

Reading the value of x normally does not change x.
Quantum measurement is different.
Measurement is a physical interaction with the quantum system.
If we measure a qubit in the computational basis, the result we observe is classical:

$$0 \qquad \text{or} \qquad 1.$$

The probabilities of those results depend on the qubit's state.
If the qubit was in a superposition before measurement, the measurement does not simply print the full superposition for us.
We receive one classical outcome.
This creates a very important question:

If measurement eventually gives only a classical result, how can quantum computation be useful?

The answer begins with **interference**.

11. Interference: Shaping the Final Answer

Think about water waves.

When two waves meet, they can reinforce one another.

They can also partially cancel one another.

Sound waves behave similarly.

Quantum amplitudes can also interfere.

This matters because a quantum computation can create amplitudes associated with different possible outcomes.

But simply creating many possibilities is not enough.

When we measure the system, we do not receive every possible answer.

A useful quantum algorithm must control the state before measurement so that

useful outcomes are reinforced

and

unhelpful outcomes are reduced or canceled.

A useful sentence to remember is

Superposition creates possibilities; interference shapes the outcome.

This is why the common statement

"A quantum computer simply tries every answer at once"

is misleading.

Having many possibilities is not enough.

The computation must arrange those possibilities so that measurement is likely to give useful information.

12. Entanglement: When Quantum Systems Must Be Described Together

There is one more important quantum idea we should meet today.

Suppose I put one red card in one envelope and one blue card in another.

I send one envelope to El Paso and the other to New York.

If you open the El Paso envelope and find the red card, you immediately know that the New York envelope contains the blue card.

The results are correlated.

But there is nothing quantum about this.

The colors were already placed inside the envelopes.

Quantum systems can have a different kind of relationship called **entanglement**.

For example, two qubits can share the state

$$\frac{|00\rangle + |11\rangle}{\sqrt{2}}.$$

Do not worry about the mathematics yet.

The important idea is that the two qubits share a **joint quantum state**.

The system must be described as a whole rather than simply imagining that each qubit carries its own independent classical answer.

This gives us another useful statement:

Entanglement is a specifically quantum relationship between systems.

Entanglement does not allow us to send arbitrary messages faster than light.

We will study its meaning much more carefully later in the course.

13. Why Might Quantum Computing Matter?

Quantum computers are interesting because changing how information is represented and processed can change what algorithms are possible.

But quantum computers are not automatically better than classical computers.

They are useful only when a problem can take advantage of quantum computation.

Three examples are especially important.

Simulating quantum systems. Molecules, materials, and chemical reactions are quantum mechanical.

Representing complicated quantum systems on classical computers can become extremely difficult.

Quantum computers may provide more natural ways to simulate some of these systems.

Cryptography. Much of modern cybersecurity depends on mathematical problems that are difficult for known classical algorithms.

Shor's algorithm shows that a sufficiently capable quantum computer could efficiently solve mathematical problems underlying several important public-key cryptographic systems.

This does **not** mean that quantum computers break all encryption.

It means that some cryptographic systems must be replaced with designs that remain secure even when attackers have quantum computers.

This is the motivation for **post-quantum cryptography**.

Search. Suppose we need to search through N possible items with no useful structure.

A classical search may require work proportional to roughly

$$N.$$

Grover's quantum search algorithm requires roughly

$$\sqrt{N}$$

queries.

That is an important improvement.

But it is not an exponential improvement, and it does not mean every search problem suddenly becomes easy.

This leads to an important rule:

Quantum computers compute differently; they are not faster at everything.

Classical computers will remain essential.

Future systems may combine different kinds of processors:

$$\text{CPU} + \text{GPU} + \text{Quantum Processor}.$$

14. Why Is Quantum Computing So Difficult?

The quantum behavior we want to use is difficult to preserve.

Quantum systems interact with their surroundings.

Heat, electromagnetic noise, imperfect control, and other unwanted interactions can disturb the quantum state.

The loss of useful quantum behavior through interaction with the environment is associated with a process called **decoherence**.

Quantum operations are also imperfect.

Measurements can contain errors.

This means that building useful quantum computers requires extremely careful control.

Researchers must develop better hardware, better control methods, better algorithms, better error correction, and better software.

This is also why the number of qubits alone does not tell us how useful a quantum computer is.

The quality of those qubits and operations matters.

Different technologies can be used to create qubits, including superconducting circuits, trapped ions, photons, neutral atoms, and spins.

The important point is

A qubit is an information concept, not one particular physical object.

Different physical systems can be engineered to behave as qubits.

15. Why Do Computer Scientists Belong in QIS?

Quantum technologies are not only physics problems.

Useful quantum systems also require

algorithms, software, compilers, architectures, networks, security, verification, and error correction.

Someone must design quantum algorithms.

Someone must translate algorithms into quantum circuits.

Someone must optimize those circuits for real hardware.

Someone must build programming tools.

Someone must secure quantum and post-quantum systems.

Someone must determine whether a claimed quantum advantage is real.

These are computer science problems.

You do not need to become a physicist to study Quantum Information Science.

But you do need to understand enough quantum mechanics to know the rules governing the information you want to process.

That is what we will learn in this course.

Five Misconceptions to Avoid

- **"Quantum simply means very small."**
  No. Quantum refers to behavior governed by quantum mechanics. Size alone is not the definition.
- **"A qubit is just a random bit."**
  No. Classical uncertainty and quantum superposition are fundamentally different.
- **"A qubit is simply both 0 and 1 at the same time."**
  This phrase is an oversimplification. A qubit can be in a superposition described by amplitudes associated with $|0\rangle$ and $|1\rangle$.
- **"A quantum computer tries every answer and gives us all of them."**
  No. Measurement gives a classical result. Quantum algorithms use interference to make useful results more likely.
- **"Quantum computers are faster than classical computers."**
  Not in general. Quantum computers provide advantages for particular problems and algorithms.

The Big Picture

We can now reconstruct the entire lecture in one chain.

We began with a computer:

$$\text{Software} \to \text{Hardware} \to \text{Transistors} \to \text{Atoms and Electrons.}$$

This taught us that

computation is physical.

Experiments with atoms, electrons, and light showed that classical physics was not enough.
That led to

$$\boxed{\text{Quantum Mechanics}}.$$

Quantum mechanics describes how quantum physical systems behave.
But information must be stored in physical systems.
Therefore, quantum physics also affects what information can do.
That leads to

$$\boxed{\text{Quantum Information}}.$$

And once we deliberately process that quantum information to perform computation, we obtain

$$\boxed{\text{Quantum Computing}}.$$

The full story is therefore

$$\boxed{\text{Physical Laws}} \to \boxed{\text{Physical States}} \to \boxed{\text{Information}} \to \boxed{\text{Computation}}.$$

For quantum systems,

$$\boxed{\text{Quantum Mechanics}} \to \boxed{\text{Quantum States}} \to \boxed{\text{Quantum Information}} \to \boxed{\text{Quantum Computing}}.$$

This leads to the central question of the course:

If the physics changes, can computation change?

Quantum Information Science shows us that it can.

Check Your Understanding

Try answering these questions without looking back at the notes.

- Why does computation ultimately depend on physics?
- Why did scientists need quantum mechanics if classical physics already worked well?
- What does it mean for a physical property to be quantized?
- Why does “quantum” mean more than “everything is discrete”?
- What does the statement “information is physical” mean?
- Why is an ordinary laptop not called a quantum computer?
- Why do we need Quantum Information Science?
- What four words summarize the major goals of QIS?
- How is a quantum superposition different from not knowing the value of a classical bit?
- Why is interference important in quantum computing?
- Why is “a quantum computer tries every answer at once” misleading?
- What is the basic idea behind entanglement?
- Why are quantum computers not faster at every problem?

Key Ideas to Remember

- **Computation is physical.** Every computation must happen in a physical system.
- **Classical physics is extremely useful, but it is not the complete description of nature.**
- **Quantum mechanics was required because experiments revealed behavior that classical physics could not fully explain.**
- **Information is physical.** Information is abstract, but it must be stored, processed, or transmitted using something physical.
- **Quantum Information Science studies information carried by quantum systems.**
- Remember the four broad goals of QIS: **Understand. Compute. Communicate. Measure.**
- **A quantum computer is quantum because it deliberately represents and manipulates information using quantum states.**
- **A qubit is not simply a random classical bit.**
- **Superposition creates possibilities; interference shapes the outcome.**
- **Quantum computers compute differently; they are not faster at everything.**

Final Thought

Computer science usually teaches us to move upward through abstraction:

$$\text{bits} \to \text{instructions} \to \text{programs} \to \text{applications.}$$

Quantum Information Science asks us to move downward for a moment.
What is underneath the bit?
What physical system stores it?
What laws govern that system?
And if those laws are quantum mechanical, can we represent and process information differently?
This brings us back to the question with which we began:

What does nature allow information to do?

Classical computing gives us one extraordinarily powerful answer.

Quantum Information Science explores what else becomes possible when we use the quantum rules of nature directly.

Next Lecture: From Bits to Qubits

Today we focused on **why** Quantum Information Science exists.

Next time, we begin learning **how** quantum information is represented.

We will start with the familiar classical bit,

$$0 \qquad \text{or} \qquad 1,$$

and then study the quantum states

$$|0\rangle \qquad \text{and} \qquad |1\rangle.$$

We will learn what the notation means, what a qubit state represents, what probability amplitudes are, how superposition is written mathematically, and how measurement probabilities are calculated.

That will be our first formal step into quantum computing.