Quantum states

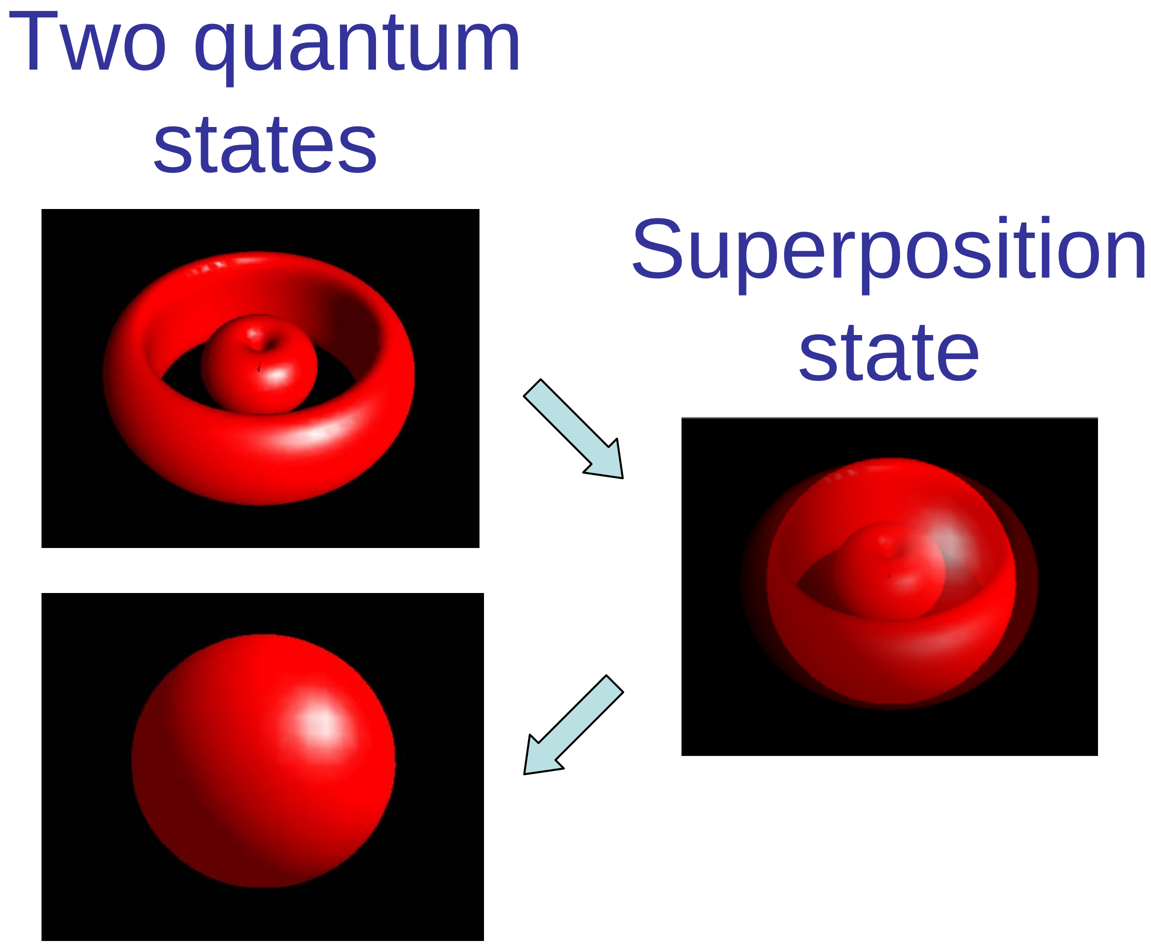
Ch. 13.3

- A quantum state corresponds to a specific wave packet (= wave function).
- A quantum state is characterized by a set of quantum numbers, such as the energy E.
- Quantum numbers can be measured exactly. For example, the uncertainty ΔE is zero for a stable state, where one can take an infinite time Δt for measuring the energy.

Strange effects involving quantum states

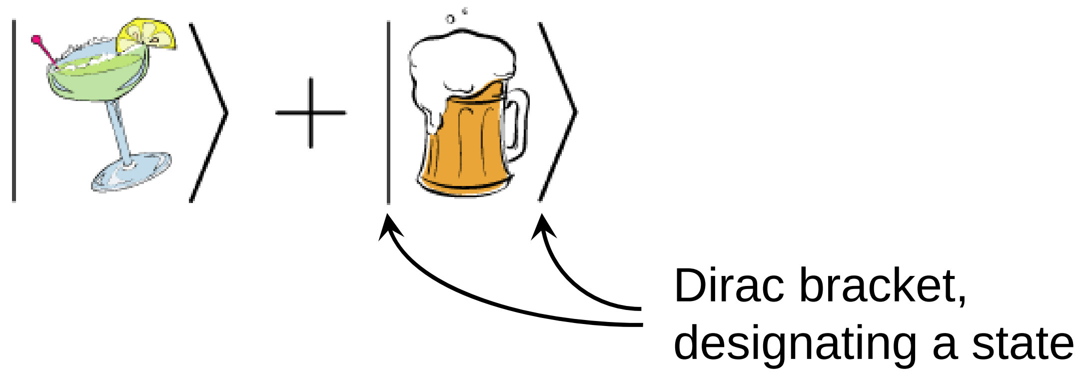
- **Quantum 'jump'**: During the transition from one quantum state to another, the wave packet morphs continuously.
- **Superposition**: *One* particle is in *two* quantum states at the same time.
- **Entanglement**: *Two* particles in *two* quantum states can become intertwined inseparably.

This occurs for electrons, photons, or any quantum object.



- During a quantum jump an electron morphs from one wave packet into another (shown in three dimensions).
- While it is morphing, an electron is in a superposition state.

A superposition state (1 particle, 2 states)



- Margarita or beer?
- This superposition state (of mind) gives equal probabilities to choosing margarita or beer.
- The actual outcome is not determined until the experiment is performed (in a bar).
- The question arises whether our brain makes such quantum decisions. Is that “free will”?

How do we make decisions ?
What is going on in our brain ?

A. Classical physics: Every decision we ever make is determined in advance, but we don't know it.

B. Quantum physics: Decisions are unpredictable.

C. Complexity: The brain is not a quantum system. It contains 100 billion neurons, and each neuron by itself is too large to be a quantum system. A new branch of physics is searching for simple laws of complex systems (such as the Santa Fe Institute). How do primitive ants build a complex ant nest (next slide). Each of them obeys simple rules, like a neuron.

⇐ Leaf cutter ants

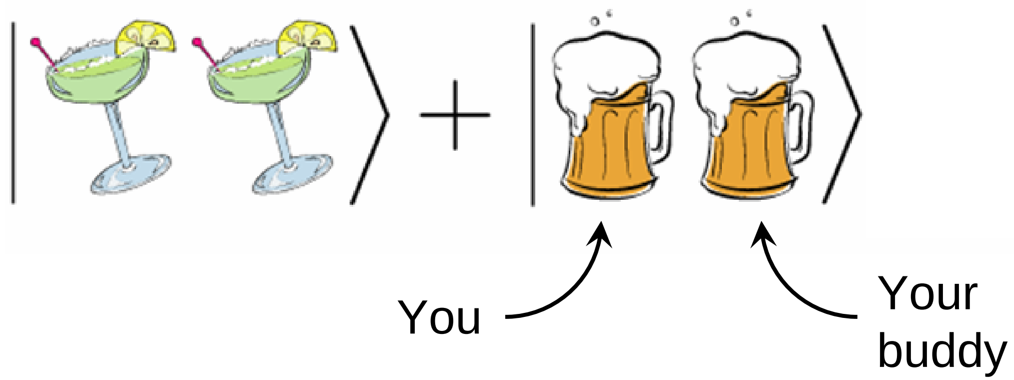
Cast of an ant nest

⇓

School of fish avoiding a sea lion

An entangled state (2 particles, 2 states)

It takes more than one particle (person) to become entangled.

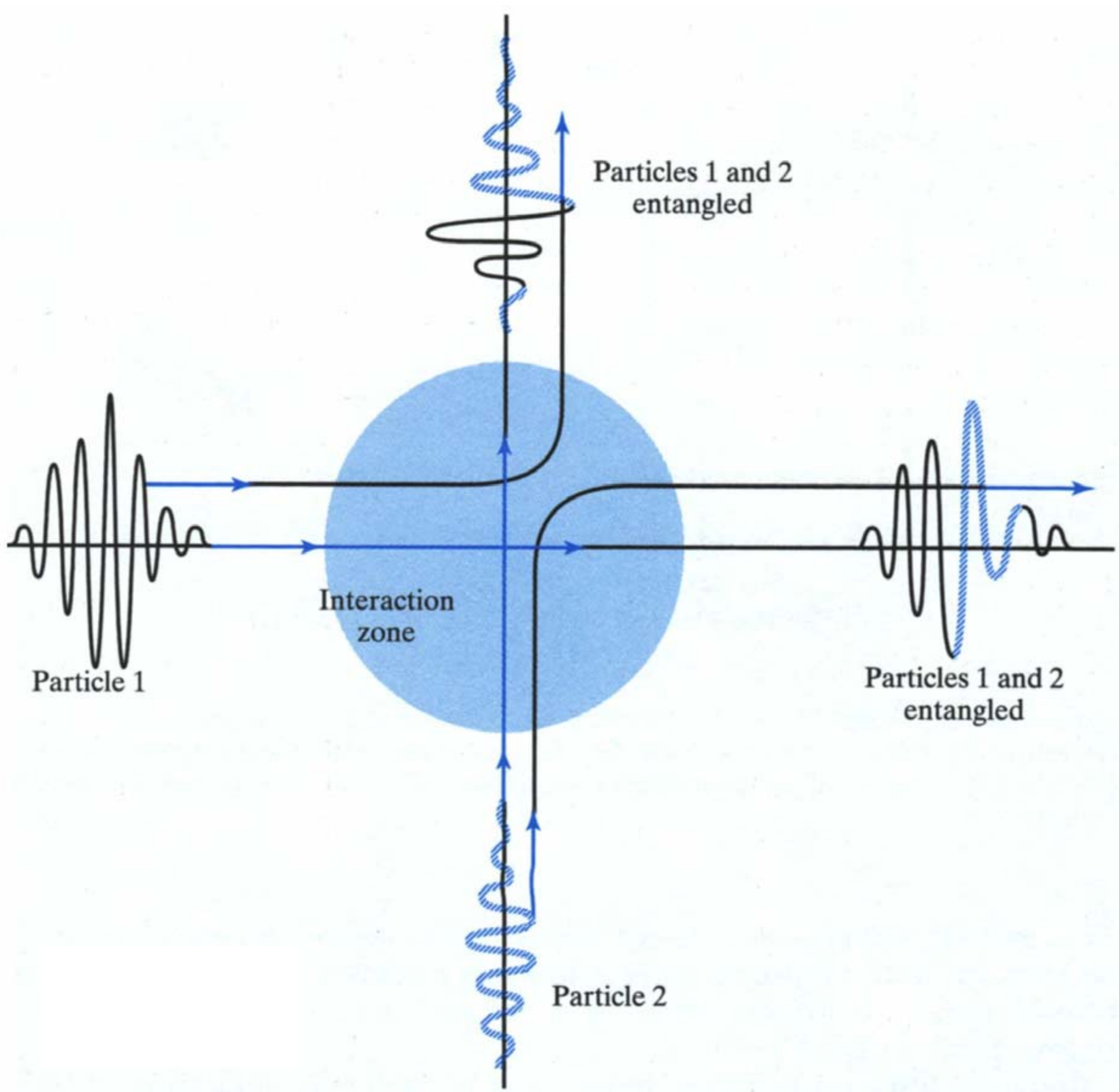


- You and your buddy are hitting a bar.
- Both of you have a hard time deciding what to order.
- Eventually you decide for beer.
- Your buddy follows suit.
- Had you decided for margarita, your buddy would have ordered margarita as well.

Another entangled state

- Two contrarians are hitting a bar.
- Both have a hard time deciding what to order.
- Eventually one of them decides for beer.
- The other orders …?

Quantum nonlocality: Spooky action at a distance



Two entangled particles cannot be separated, even after they leave the interaction zone, where they became entangled. They act as a single object. Thus, they appear in two different places at the same time.

Manipulating one of the entangled wave packets affects the other.

Quantum computing (optional)

- A normal computer uses at *bit* which is either 0 or 1 .
- A *qubit* (quantum bit) is a superposition of 2 quantum states.
- A quantum computer is good at cracking codes (= factoring large numbers) and at searching large data bases.
- In practice, the most sophisticated calculation performed so far is $21 = 3 \cdot 7$.
- But there has been enormous progress in creating complex quantum states which Schrödinger and Einstein could only ponder theoretically.

qubits

- Take two states of an electron, labeled $|0\rangle$ and $|1\rangle$
- Superposition of 2 states of 1 electron:

  $|0\rangle + |1\rangle$ = 1 *qubit*
- Superposition of 4 states of 2 electrons:

  $|0,0\rangle + |1,1\rangle + |1,0\rangle + |0,1\rangle$ = 2 *qbits*
- Superposition of $2^{\boldsymbol{n}}$ states of ***n*** electrons:

  = ***n*** *qubits*

Each of the quantum states $|..\rangle$ has a certain probability as pre-factor, which is omitted here.

Many *qubits* are very powerful

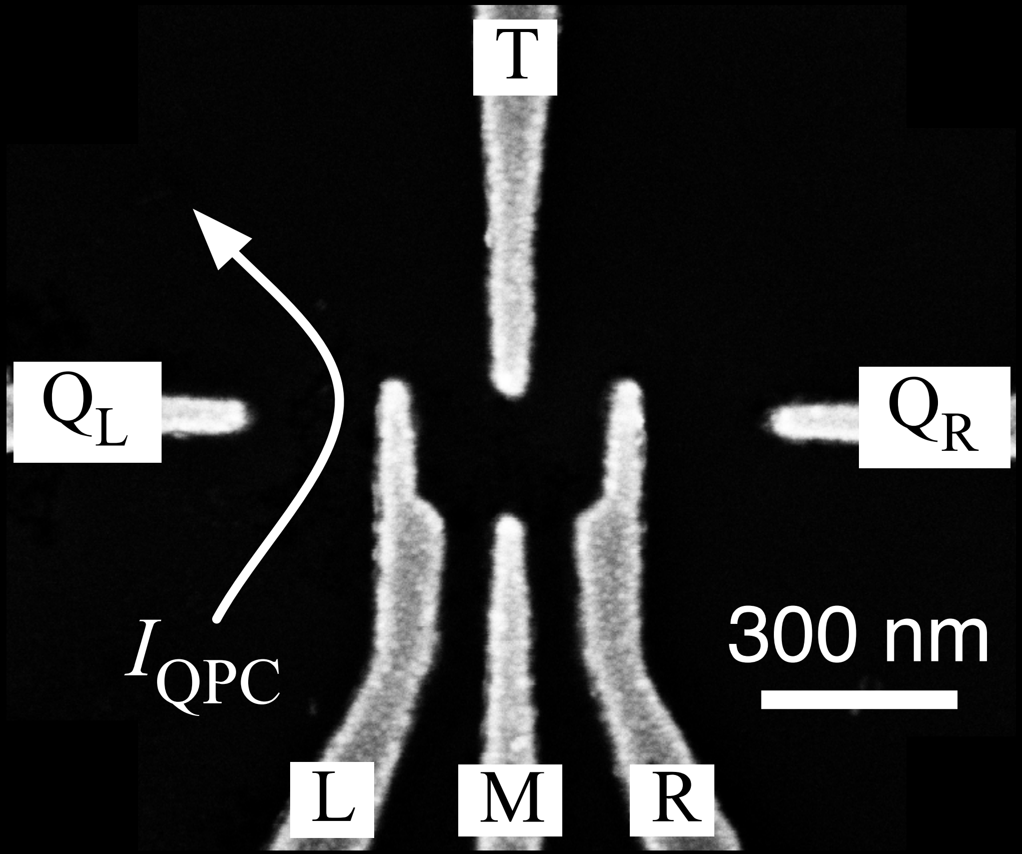
- A normal computer can process only 1 combination of ***n*** bits (typically 64 bits).

- A quantum computer processes all 2^{n} combinations of two states at the same time. This corresponds to a normal computer with 2^{n} processors.

- Processing 64 *qubits* instead of 64 *bits* increases the speed by a factor of

$$2^{64} = 2 \cdot 10^{19} = 20000000000000000000$$

A a single-electron trap for a *qubit*



The electron is captured between the four electrodes.

The current I_{QPC} senses whether an electron is in the trap.