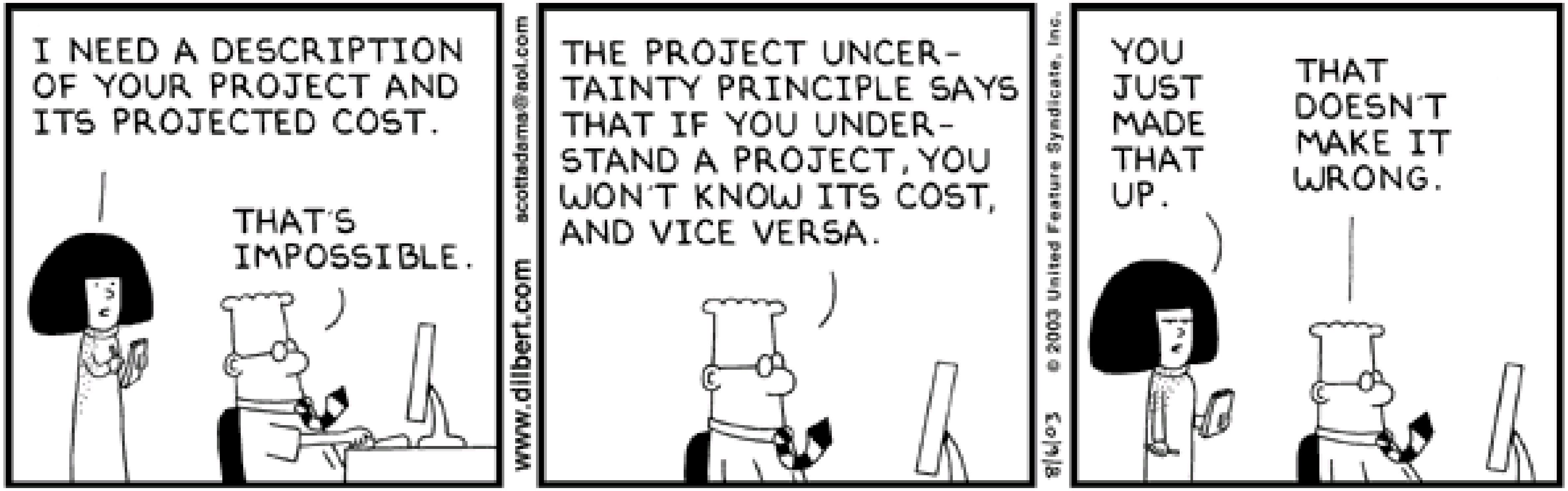
"… separation of the observer from the phenomenon to be observed is no longer possible."

Werner Heisenberg,
German physicist (1901-1976)

"Heisenberg may have slept here."

Anonymous



Current Assignments ...

Office hours:
3-4 Tuesdays
& Thursdays

For today

- Read Sections 12.7, 13.1

For Lecture 21

- Read Sections 13.2 - 13.7

Homework #4

- Posted March 7. Due 11:00 AM, Friday, March 22

Homework #5

- Handed out today. Due 11:00 AM, Friday, April 5

Writing Assignment #2

- Posted Feb. 28. Due 11:00 AM, Thursday, April 4

Suggested Conceptual Exercises

- Chapter 13: 1,3,5,7,9,11,13,15,17,19,21,23,25,27,29,31,33

Tutorial #9

- Homework #3 will be returned

PHY 100S – THE MAGIC OF PHYSICS
Tutorial #9

Noon-1PM, Thursday, March 21

Today's tutorial in RW 142 is cancelled.

Please join the tutorial group in UC 177, also meeting at this time.

University College (15 King's College Circle)

Review of Lecture 19

Textbook, Chapter 12

- The quantization of light
- The quantum theory of radiation
- Matter waves, matter fields
- The quantum theory of matter
- [Quantum nonlocality and uncertainty]

Plan for Lecture 20

Textbook, Sections 12.5 - 12.6

- The quantum theory of matter
- Quantum nonlocality and uncertainty

Textbook, Section 13.1

- The Uncertainty Principle

L19: The Wave Theory of Matter

Every material particle has wave properties with a wavelength equal to h/mv, where m is the particle’s mass and v is its velocity.

$$\boxed{\lambda = h/mv}$$

How do we know that matter has wave properties?

Textbook Figure 12.8

Voted #1 in a 2002 poll of "the most beautiful experiments in physics" by Physics World magazine.

The double slit experiment can be done with electrons.

Electron Double Slit Animations

Detailed description of both versions of the double slit experiment

- http://www.upscale.utoronto.ca/GeneralInterest/Harrison/DoubleSlit/DoubleSlit.html

Results for the electrons

- http://www.upscale.utoronto.ca/GeneralInterest/Harrison/DoubleSlit/Flash/Histogram.html

Results for waves and particles

- http://www.upscale.utoronto.ca/GeneralInterest/Harrison/DoubleSlit/Flash/DoubleSlit.html

Electron Double Slit - Results

- The result is an wave interference pattern, like that produced by photons.
- The interference pattern also builds up spot by spot, showing that matter is made of particles.

Textbook Figure 12.9

Textbook Figure 12.10

Movie of the experiment produced by Hitachi Ltd:

- http://rdg.ext.hitachi.co.jp/rd/moviee/doubleslite-n.wmv

The Quantum Theory of Matter

- A new type of field called a <u>matter field</u> exists in nature.
- Like EM fields, matter fields are quantized.
- For example, the matter field for electrons is allowed to possess enough energy for either 0 electrons, or 1 electron, or 2 electrons, and so on.
- Electrons (and other material particles) exist because matter fields are quantized in just these energy increments.

Visualizing the Double Slit Experiment for a Single Electron

Textbook
Figure 12.12

The matter field moves through the two slits, and collapses into a single electron when it hits the screen.

How is an electron similar to a photon?

(A) Both have electric charge.

(B) Both have mass.

(C) Both move at lightspeed.

[✓ (D)] Both hit a tiny point on a viewing screen in the double slit experiment.

[✓ (E)] Both are quanta.

Quantum Nonlocality

Key ideas of quantum physics

- Quantization of the EM field
- Existence of the matter field
- Quantization of the matter field
- The nonlocal collapse of the quantized EM or matter field to an uncertain small point of interaction
  - → This is called <u>quantum nonlocality</u>

Quantum Uncertainty

- The electron pattern on the screen builds up point by point, but is there any way to tell exactly where any particular electron is going?
- No, there is not!
  - → With identical electrons and identical preparations, we get different results.
  - → This is unprecedented in Newtonian physics, and is the core of the difference between the quantum world and the deterministic Newtonian one.

Quantum Uncertainty

Textbook
Figure 12.13

Although the location of any individual electron impact is impossible to predict, the overall pattern is well defined.

Probability

- The pattern is a pattern of probabilities:
  - → The intensity of the matter field at any point represents the probability that an electron will hit the screen at that point.
- But this is not a probability like a coin toss, which appears random because we don’t know the initial conditions precisely; this is an innate probability.
  - → There is nothing more we could know about the electron that would help us predict where it will go.

Schroedinger's Equation

- Matter waves are predictable because of the predictability of the statistical patterns.
- Schroedinger Equation describes the motion of the matter wave for any material particles.
  - → It correctly describes experimental results such as the double slit experiment with electrons.
  - → It can also be applied to electrons in atoms…

→ ***Chapter 13***

How does quantum uncertainty differ from the uncertainty involved in a coin flip?

(A) With sufficient information, quantum uncertainties can be removed, but no amount of information can make a coin flip's outcome predictable.

[✓ **(B)**] With sufficient information, a coin flip's outcome can be predicted, but no amount of information can remove quantum uncertainties.

(C) They don't differ in any essential way--with sufficient information, both types of uncertainty can be removed.

(D) They don't differ in any essential way--no amount of information can remove either type of uncertainty.

Quantifying Quantum Uncertainty

- Consider a quantized matter field containing enough energy for just one electron, moving through empty space along the x-axis.
- The intensity of the matter field at any point represents the probability that an electron will be found at that point.
- The matter field is spread out in space and has a wavelike character as shown in the figure.

Textbook

Figure 13.2

Quantifying Quantum Uncertainty

- The wave representing a single particle whose uncertainty in position is Δx, moving along the x-axis. It is a wave spread out over a limited distance.
- We need a way of representing the matter field for a single particle → <u>wave packet</u>
- This shows that the electron does not have a precise position or a precise wavelength.

Textbook
Figure 13.2

Position & Velocity of Wave Packets

- Δx = uncertainty in position
- Δv = uncertainty in velocity

- What happens to λ if we decrease Δx?
  - → λ decreases

- What happens to v if we decrease Δx?
  - → $\lambda = h/mv$, so $v = h/m\lambda$
  - → shorter λ means larger velocity and also means a larger uncertainty in velocity, Δv

Position & Velocity of a Wave Packet

Textbook
Figure 13.3

Δx of packet A $>$ Δx of packet B

λ of packet A $>$ λ of packet B

Δv of packet A $<$ Δv of packet B

The Uncertainty Principle

In 1927, Werner Heisenberg showed that the product of Δx and Δv was constant.

The position and velocity of every material particle are uncertain. Although either uncertainty can take on any value, the two are related by the fact that their product must approximately equal Planck's constant divided by the particle's mass. In symbols,

$$(\Delta x)\cdot(\Delta v) \approx h/m$$

where h is Planck's constant and m is the particle's mass.

Uncertainty in Position & Velocity

Textbook Figure 13.4

Δx and Δv have a range of possibilities, but if one is small the other must be large.

Relevance of the Uncertainty Principle

- Because h is so small, uncertainties in x and v are relevant only for subatomic particles.
- The Uncertainty Principle means that no object can ever be truly motionless.
  - → If Δx is small, Δv must be large and so v will also be large.
  - → Significant effects in the quantum world.

Textbook Figure 13.5

Concept Check 3

A particle having a very precise velocity has a wave packet that:

[✓ **(A)**] occupies a wide region of the x-axis

(B) occupies a narrow region of the x-axis

(C) moves with a wide range of velocities

[✓ **(D)**] moves with a narrow range of velocities