So far, information is a function of probabilities.

Today:

- QM is about more than probabilities

Wave-Particle duality

- True for any quantum 'particle'

We shall stick to light

Light is a wave

- moving periodic disturbance
- obeys the principle of superposition

If Φ_1 is a light wave of amplitude I_1

and Φ_2 is also a wave with amplitute I_2

Then $\Phi_1 + \Phi_2$ is also a light wave.

Φ_1 and Φ_2 can be complex numbers

$\Phi_1 = |\Phi_1| e^{i \cdot \varphi_1}$

Energy in the light field $E \propto |\Phi|^2$

Light is (also) a particle

- energy of light is carried in discrete packets/quanta
  - 1 quanta of light is called a photon
  - 1 photon of light frequency f has energy $E = h \times f$
    - plank's constant $\approx 6.6 \times 10^{-34} J \cdot s$

Aside: 1 laser pointer ~ 1mW power

- = $1 \times 10^{-3} J$ of energy per second
- Optical freq ~ 10^{14} Hz
- => 1 optical photon has energy $h \times 10^{14} \approx 10^{-20} J$
- => laser pointer $\approx$ stream of 10^{17} photons
- => a wave description is sufficient

For 2 waves of amplitutdes

- $\Phi_1 = \sqrt{I_1} e^{i \cdot \varphi_1}$
- $\Phi_2 = \sqrt{I_2} e^{i \cdot \varphi_2}$

Total intensity

- $I = |\Phi_1 + \Phi_2|^2 = |\Phi_1|^2 + |\Phi_2|^2 + \Phi_1^* \Phi_2 + \Phi_1 \Phi_2^*$

Review:

- $\Phi_1 = a + i \cdot b$
- $\Phi_1^* = a - i \cdot b$
- Also, $\Phi_1 = \sqrt{I_1} e^{i \cdot \varphi_1}$, then $\Phi_1^* = \sqrt{I_1} e^{-i \cdot \varphi_1}$
- $e^{i \cdot \theta} = cos\theta + i \cdot sin\theta$
- energy of a wave of amplitutde Φ is $E \propto |\Phi|^2$
- $\Phi_1 = a + i \cdot b = \sqrt{I_1} e^{i \cdot \varphi_1} = \sqrt{I_1} (cos\theta + i \cdot sin\theta)$
- Real part $\Rightarrow a = \sqrt{I_1} cos\theta$
- imaginary part $\Rightarrow b = \sqrt{I_1} sin\theta$
- $I = I_1 + I_2 + 2\sqrt{I_1 I_2} cos(\varphi_2 - \varphi_1)$

How to explain interferences of light photon by photon?

For a single photon,

- $\Phi \equiv$ probability amplitude

  - a mathematical construct which cannot be compared to anything measurable

But, the probability of finding a photon at x, $prob(x) = |\Phi|^2$

Recall, for waves, $Energy \propto |\Phi|^2$

- for photons, $Energy = h \cdot f \times$ (Prob. you have a photon in that place)
- $\therefore Energy \propto |\Phi|^2$

With just 1 slit open,

- Prob. for finding a photon at x $= P_1(x) = |\Phi|^2$

With the 2nd slit open,

- Prob. for finding a photon at $x = P_2(x) = |\Phi_2|^2$
- with both slits open, $P = |\Phi_1 + \Phi_2|^2 = P1 + P2 + () \cdot cos(\varphi_1 - \varphi_2) \neq P1 + P2$

Very different from classical prob theory scenarios

Eg. coin toss

Flip 2 coins

- Prob. of both heads = P1,
- tails = P2
- Prob. that both coins landed on same side $= P1 + P2$

observation: Only tiny things behave quantum mechanically (photons, atoms, electrons, , ...) Big things don't

NOT TRUE!

Which way' experiment

(double slit exp with photon detectors on the slits figure) shows no interference

Suppose you put tiny detectors at both slits,

$\Rightarrow$ you know which slit each photon went through

Then the prob. to see photon at point $x = P1 + P2$ no interference term!

The essential difference between 2 coins (adding prob.) and 2 slits (adding prob. amplitudes) is all about information

Quantum rules for adding probability and amplitudes (vs. classical world's adding probabilites)

- ONLY apply when the system is informationally isolated.
- if scramble again then the interference come back

informationally isolated $\Rightarrow$ produces no record anywhere in the universe

Weirdness of Quantum theory is bacause this probabilistic behavior is inherent/fundamental

It allows for mutually exclusive situations to exist simutaneously in a "quantum superposition"