• 4-90 minute New Zealand lectures available at http://vega.org.uk/video/subseries/8
• QED explains interactions of light and matter: all of chemistry and biology!
• Rules are simple
  – Many calculations are difficult
• Not explained by QED:
  – Gravitation
  – Nuclear interaction (e.g., radioactivity)
Light comes in chunks
**Grand Principle**: The probability of an event is equal to the square of the length of an arrow called the "probability amplitude".

**General Rule** for drawing arrows if an event can happen in alternative ways: Draw an arrow for each way the event can happen, and then add the arrows by hooking the head of one to the tail of the next. The final arrow is drawn from the tail of the first arrow to the head of the last one.
Colors from an oil film

- Stopwatch
- Front reflection arrow
- Back reflection arrow
- 5%
- 0.2
- 16%
- 0.2

Percentage of Reflection

- Red
- Blue

0% red
0% blue
8% red
8% blue
16% red
16% blue

Bluish violet
Red
Blue black (dim violet)
Violet
Blue (dim violet)
Violet
Reddish violet

Thickness

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Mirror reflection

- Light source (S) to screen (Q) to detector (photomultiplier) (P)
- Expected path of reflection
- Angle of incidence
- Angle of reflection

Mirror diagram:

- Path of light from S to Q to P
- Time curve

Diagram labels:
- A, B, C, D, E, F, G, H, I, J, K, L, M
- S, Q, P
Light reflects at odd angles
WATER AND MIRAGES

Water and mirages

Diagram showing light rays bending at the water surface due to the difference in temperature between cooler air and warmer air.
Light travels in straight lines.
Why a lens works

[Diagram of a lens focusing light with labeled points and arrows indicating time progression.]
Events with multiple steps

Step 1: S to A
Step 2: A to C
S to C combined

Light source

GLASS

Step 1
Step 2
Step 3

1.0
0.2
1.0

GLASS

Light source

A

1
2
3

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Two things happening simultaneously.

- X to A
- Y to B
- X to A and Y to B

\[ X \quad Y \]
\[ \text{unit arrow} \quad \text{unit arrow} \quad \text{unit arrow} \]
\[ 0.25 \quad 0.5 \]

- X to B
- Y to A
- X to B and Y to A

\[ X \quad Y \]
\[ \text{unit arrow} \quad \text{unit arrow} \quad \text{unit arrow} \]
\[ 0.5 \quad 0.5 \quad 0.5 \]

- X to A and Y to B
- X to B and Y to A

\[ \text{amplitude for entire event (final arrow)} \]
The 3 QED actions

• A photon goes from place to place: $P(A \text{ to } B)$

• An electron goes from place to place: $E(A \text{ to } B)$

• An electron emits or absorbs a photon: $j \sim -0.1$
Two electrons move

\[ E(1 \text{ to } 3) \times E(2 \text{ to } 4) \]
\[ E(1 \text{ to } 4) \times E(2 \text{ to } 3) \]
\[ E(1 \text{ to } 5) \times j \times E(5 \text{ to } 3) \times E(2 \text{ to } 6) \times j \times E(6 \text{ to } 4) \times P(5 \text{ to } 6) \]

\[ \alpha j^4 \]
The positron

(a)  (b)  (c)

Space

(a)  (b)  (c)

Space

Time

T_{10}  T_{08}  T_{06}  T_{04}  T_{02}  T_{00}
Transmission

(proton electron scattered photon incoming photon)

(a) Light source

(b) Amplitudes

(c) Final arrow for event—light goes from S to B through glass

(d) Final arrow for light to go through slightly opaque material

Scattering with some absorption

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Magnetic moment of electron

Theory: \[ \frac{1}{159,652} \times 182.79 \times 10^{-12} \] (PRD 77 053012 (2008))

Experiment: \[ \frac{1}{159,652} \times 180.85 \times 10^{-12} \] (http://en.wikipedia.org/wiki/Precision_tests_of_QED)

QED works!