

◊ CHAPTER 24 ◊  
QUANTUM  
ELECTRODYNAMICS

NOW WE'RE GOING TO  
FIND OUT WHAT  
CHARGE "REALLY IS."

WEIRD. THAT'S  
WHAT IT IS....



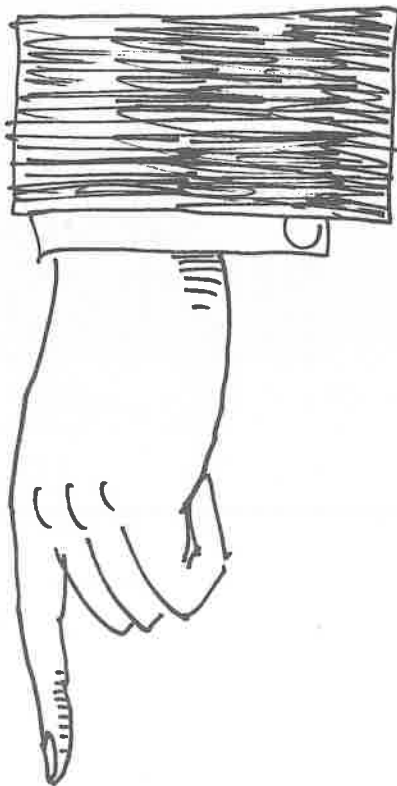
WE SAW THAT ELECTROMAGNETIC THEORY ALREADY CONTAINS RELATIVITY (SEE P. 176). WHEN QUANTUM MECHANICS IS ADDED, THE THEORY BECOMES KNOWN AS

# QUANTUM ELECTRO-DYNAMICS (OR QED).



TELL ME ABOUT IT!

TO DISCUSS THIS, WE HAVE TO SAY A LITTLE ABOUT QUANTUM MECHANICS, THE STRANGE SYSTEM THAT PHYSICS NOW USES TO DESCRIBE THE WORLD. AMONG ITS STRANGER IDEAS ARE THESE:



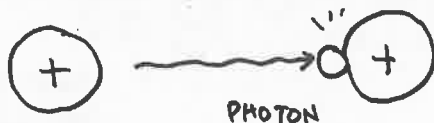
\* **LIGHT** IS MADE UP OF MASSLESS PARTICLES CALLED **PHOTONS**. THIS IS O.K., BECAUSE PARTICLES CAN ACT LIKE WAVES.

\* NATURE IS INHERENTLY **UNCERTAIN**. IN PARTICULAR, IT IS IMPOSSIBLE TO SPECIFY A PARTICLE'S PRECISE MOMENTUM AND POSITION AT THE SAME TIME.

SO LET'S GO BACK TO THE POINT WHERE TWO POSITIVE CHARGES WERE REPELLING EACH OTHER. WE WONDERED HOW THE ELECTRIC FORCE GETS ACROSS SPACE?



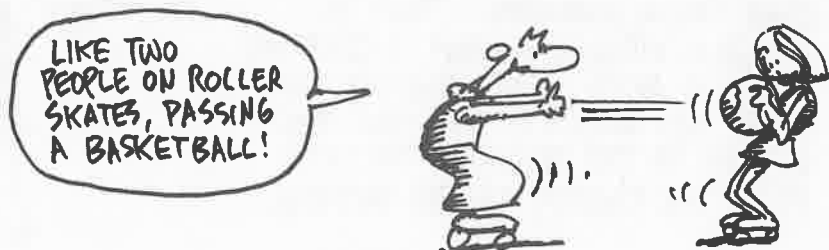
QUANTUM ELECTRODYNAMICS SAYS THAT THE FORCE IS CAUSED BY PARTICLES PASSING BETWEEN THE CHARGES — PARTICLES OF LIGHT, OR **PHOTONS**. THESE PHOTONS HAVE ENERGY BUT NO MASS, AND THEY TRAVEL AT THE SPEED OF LIGHT.



THE STRANGE PART IS THAT THESE ARE NOT "REAL" PHOTONS LIKE THE ONES YOU SEE WITH YOUR EYES, BUT **VIRTUAL** PHOTONS — A SORT OF GHOSTLIKE PARTICLE THAT VIOLATES THE CONSERVATION OF ENERGY AND "EXISTS" FOR ONLY A LIMITED TIME.

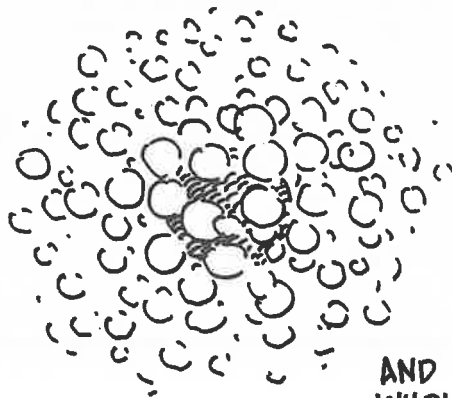


THE FORCE IS QUANTUM MECHANICAL IN NATURE, BUT A CLASSICAL ANALOGY IS THAT WHEN ONE CHARGE EJECTS A PHOTON, IT RECOILS SLIGHTLY. WHEN THE OTHER CHARGE CATCHES IT, IT ALSO RECOILS. THE NET EFFECT OF MANY SUCH EXCHANGES IS A REPULSIVE FORCE!



LIKE TWO PEOPLE ON ROLLER SKATES, PASSING A BASKETBALL!

WHAT ABOUT THESE "VIRTUAL" PHOTONS? EVEN A SINGLE CHARGE HAS A CLOUD OF VIRTUAL PHOTONS AROUND IT. THE CHARGE CONSTANTLY CREATES, EJECTS, AND ABSORBS VIRTUAL PHOTONS.



AND THIS IS THE WHOLE QED PICTURE (ALMOST!).



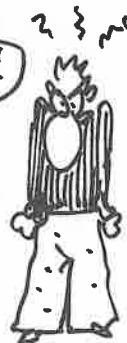
CHARGE IS JUST THE ABILITY TO MAKE VIRTUAL PHOTONS!

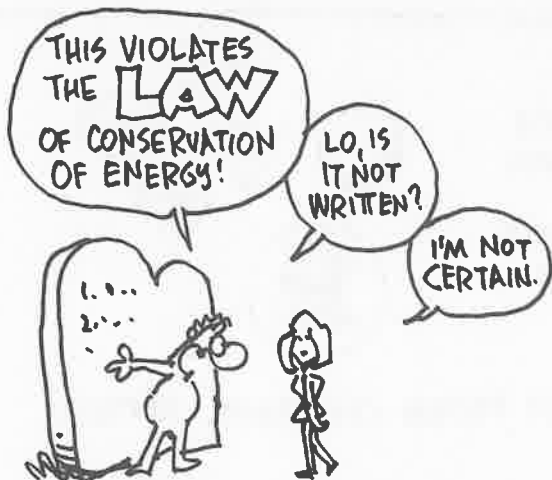
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AND THE ELECTRIC FIELD IS NOTHING BUT THE VIRTUAL PHOTON CLOUD!

\*\*\*\*\*

THE STRANGEST PART OF THIS, OF COURSE, IS THAT THE VIRTUAL PHOTONS COME "FROM NOWHERE." THAT IS, AFTER A VIRTUAL PHOTON IS CREATED, THERE IS MORE TOTAL ENERGY THAN THERE WAS BEFORE IT EXISTED: THE ENERGY OF THE ORIGINAL PARTICLE PLUS THE ENERGY OF THE PHOTON.

OUTRAGEDUS!

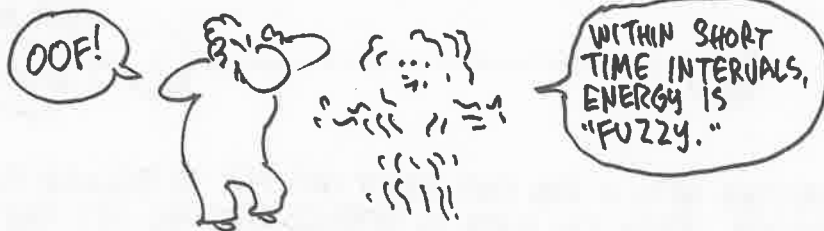




THIS IS WHERE QUANTUM UNCERTAINTY COMES IN.

## ONE FORM OF THE UNCERTAINTY PRINCIPLE

IS THIS: YOU CANNOT MAKE AN EXACT DETERMINATION OF ENERGY AND TIME SIMULTANEOUSLY.



THIS MEANS THAT THE ENERGY ACCOUNT CAN BE UNBALANCED — BUT ONLY FOR A TIME. A LARGE ENERGY DEFICIT MUST BE MADE UP IN A VERY SHORT TIME, WHILE A SMALL DEFICIT CAN "SIT" FOR A WHILE. (MATHEMATICALLY,  $\Delta E \cdot \Delta t \geq h$ : THE PRODUCT OF THE ENERGY VIOLATION TIMES THE TIME OF THE VIOLATION CAN'T BE LESS THAN A CERTAIN SMALL NUMBER  $h$ .)



IN OTHER WORDS, A VERY ENERGETIC VIRTUAL PHOTON, ONE WITH A LARGE KICK, CAN'T GET FAR, EVEN AT THE SPEED OF LIGHT, BUT MUST BE REABSORBED QUICKLY TO BALANCE THE ENERGY...



WHEREAS A LOW-ENERGY PHOTON CAN TRAVEL FARTHER.

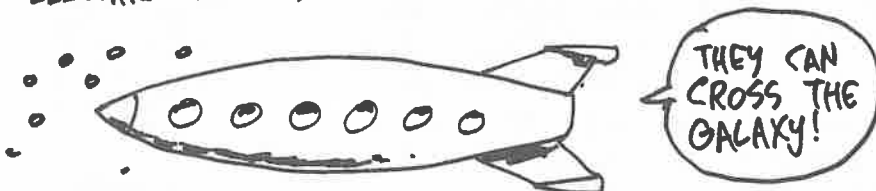


THE SMALL ENERGY VIOLATION CAN BE TOLERATED LONGER.

THIS EXPLAINS WHY THE ELECTRIC FORCE  
**GROWS WEAKER WITH DISTANCE!**



PHOTONS WITH A BIG KICK CAN'T GET FAR TO DELIVER THEIR ENERGY. WHEN THE MATH IS WORKED OUT, WE GET THE FAMILIAR INVERSE-SQUARE LAW OF CLASSICAL PHYSICS. AND THERE'S NO LOWER LIMIT ON THE ENERGY OF A VIRTUAL PHOTON. A VERY LOW-ENERGY ONE CAN LAST FOR YEARS, AND TRAVEL LIGHT-YEARS. THE RANGE OF THE ELECTRIC FORCE IS UNLIMITED!



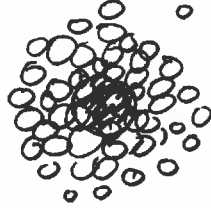
WAIT!!  
THIS THEORY SAYS THAT  
ELECTRIC FIELDS ARE  
CLOUDS OF VIRTUAL PHOTONS—  
PARTICLES THAT AREN'T EVEN  
"REAL!" IF ALL THESE  
GHOSTS DO IS EXPLAIN WHAT  
WE ALREADY KNOW, THEN

**WHAT GOOD  
ARE THEY?**

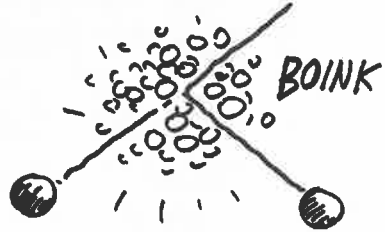
HOW DO WE KNOW THEY  
ARE "REALLY THERE?"



THERE IS A WAY TO MAKE VIRTUAL PHOTONS REAL! HERE'S A CHARGE IN ITS CLOUD OF VIRTUAL PHOTONS:



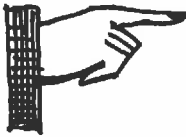
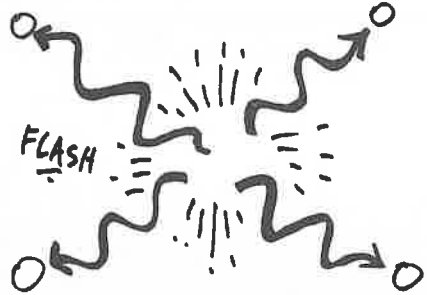
SUPPOSE WE KNOCK THE CHARGE AWAY FROM ITS VIRTUAL PHOTONS, SAY BY HITTING IT WITH ANOTHER PARTICLE.



THE VIRTUAL PHOTONS ARE ORPHANED, WITHOUT THEIR SOURCE CHARGE TO REABSORB THEM!



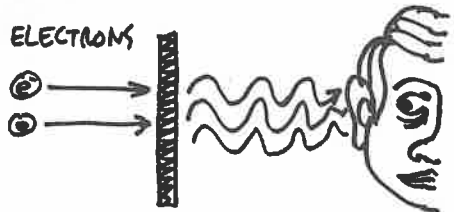
SO THEY BECOME REAL, FLYING AWAY WITH THE ENERGY PICKED UP FROM THE COLLISION.



IF WE SHAKE OR MOVE A CHARGE, REAL PHOTONS SHOULD COME FLYING OUT!

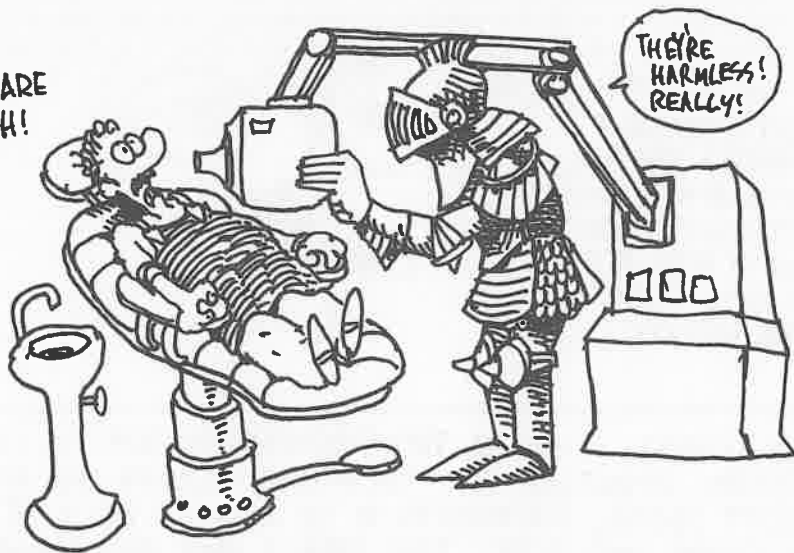


THIS IS HOW X-RAYS ARE MADE: SHOOT ELECTRONS INTO A HEAVY METAL, WHERE THEY ARE JERKED TO A STOP. THEIR VIRTUAL PHOTONS FLY OUT AS REAL X-RAYS.

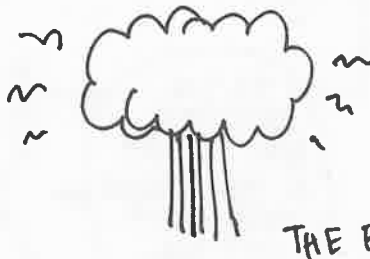
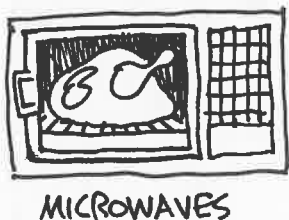
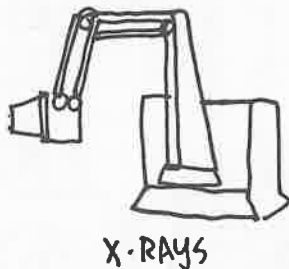
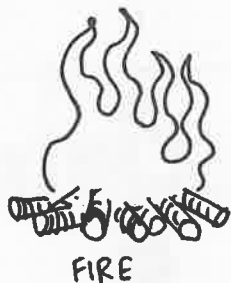




AND X-RAYS ARE  
REAL ENOUGH!



THE PHOTONS NEEDN'T BE X-RAYS. A RADIO TRANSMITTER JIGGLES ELECTRONS, SHAKING OFF PHOTONS, WHICH YOU PICK UP WITH YOUR RECEIVER. IN A LIGHT BULB, ELECTRONS IN THE HOT FILAMENT SHAKE OFF VISIBLE LIGHT PHOTONS. AS WE HAVE SEEN FROM THE CLASSICAL THEORY, WHENEVER A CHARGE IS ACCELERATED, AN ELECTROMAGNETIC WAVE — VIRTUAL PHOTONS MADE REAL — RADIATE OUT. MOST OF THE FAMILIAR SOURCES OF RADIATION SHAKE THEIR PHOTONS OUT OF THE VIRTUAL CLOUDS OF CHARGES.



IF THE QUANTUM THEORY  
PREDICTED ONLY  
FAMILIAR EFFECTS, IT  
WOULDN'T BE MUCH TO  
GET EXCITED ABOUT.  
BUT IT DOES MORE:  
IT ALSO PREDICTS  
NEW RESULTS.



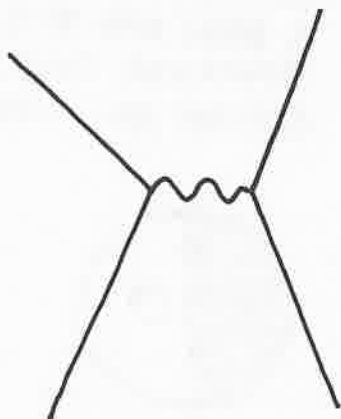
FOR EXAMPLE, IT IMPLIES TINY DISCREPANCIES FROM THE CLASSICAL THEORY: DEVIATIONS FROM THE INVERSE-SQUARE LAW AT VERY SHORT RANGE, DIFFERENCES IN THE MAGNETIC FIELD OF THE ELECTRON, AND MORE. THESE EFFECTS HAVE BEEN CONFIRMED BY DELICATE EXPERIMENTS, GIVING US CONFIDENCE THAT WE NOW HAVE THE CORRECT THEORY OF THE ELECTROMAGNETIC FORCE.



THE WHOLE IDEA OF FORCES BEING CARRIED BY "EXCHANGE PARTICLES" LIKE PHOTONS HAS BEEN BROADLY EXTENDED IN PHYSICS. THE PHYSICIST'S MOTTO:



THE **STRONG** NUCLEAR FORCE, WHICH BINDS PROTONS TOGETHER IN THE NUCLEUS, IS NOW DESCRIBED BY AN EXCHANGE OF PARTICLES CALLED **MESONS**. THE **WEAK** NUCLEAR FORCE HAS BEEN UNIFIED TO THE ELECTROMAGNETIC FORCE BY THEORIZING, AND THEN FINDING, "BROTHERS" OF THE PHOTON THAT CARRY THE FORCE.



GENERIC "FEYNMAN DIAGRAM" OF PARTICLE EXCHANGE

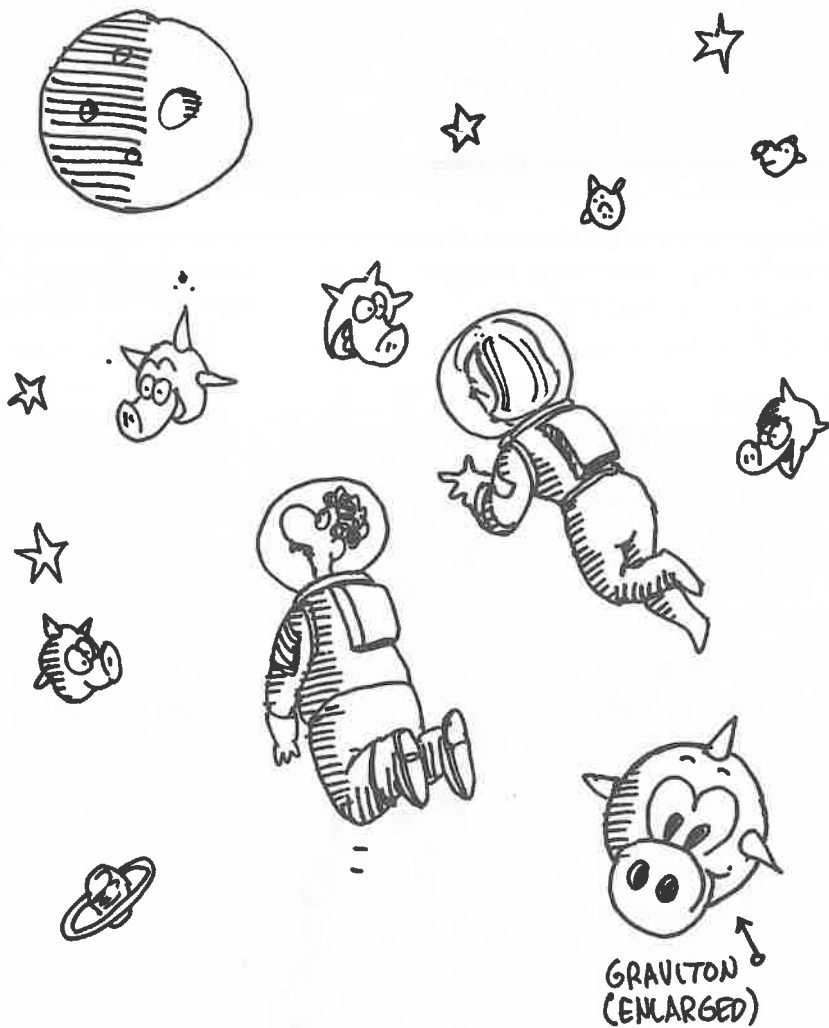


THE FORCE BETWEEN THE QUARKS WHICH MAKE UP THE NEUTRONS AND PROTONS IS ALSO THEORIZED TO COME FROM THE EXCHANGE OF PARTICLES CALLED **GLUONS**.



AND GRAVITY...?

AH, GRAVITY... GRAVITY SHOULD BE CAUSED BY THE EXCHANGE OF **GRAVITONS**... BUT WE DON'T EXPECT TO SEE ANY GRAVITONS SOON. THE GRAVITATIONAL FORCE IS JUST TOO WEAK. IT TAKES A WHOLE MOON OR PLANET TO EXERT AN APPRECIABLE GRAVITATIONAL FORCE. BUT WE'RE CONFIDENT THE GRAVITONS ARE "THERE."



PHYSICISTS STILL BELIEVE THAT ALL THE FORCES OF NATURE RESULT FROM THE EXCHANGE OF PARTICLES. BY RELATING THESE PARTICLES, WE HOPE TO DEVELOP A UNIFIED PICTURE OF ALL FORCES WITH A SMALL LIST OF RULES WHICH WILL DESCRIBE THE BASIS OF — EVERYTHING.

