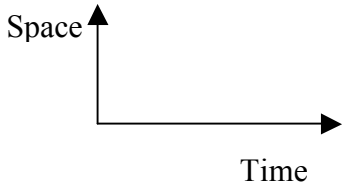

## The Big Idea

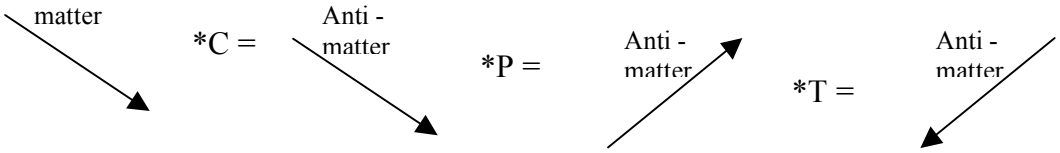
The interaction of subatomic particles through the four fundamental forces is the basic foundation of all the physics we have studied so far. There's a simple way to calculate the probability of collisions, annihilations, or decays of particles, invented by physicist Richard Feynman, called Feynman diagrams. Drawing Feynman diagrams is the first step in visualizing and predicting the subatomic world. All the Standard Model rules of the previous chapter are used here. You are now entering the weird world of particle physics.

## Key Concepts

- To make a Feynman diagram, you plot time on the horizontal axis and position on the vertical axis. This is called a space-time diagram.

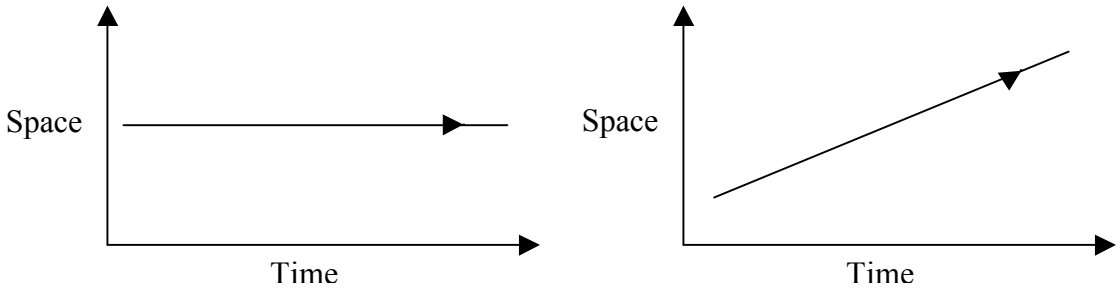



- The fifth conservation law: CPT symmetry. States that if you charge conjugate (i.e. change matter to anti-matter), Parity reversal (i.e. mirror reflection) and then reverse the flow of time, a matter particle is exactly the same as the anti-matter particle (see below)

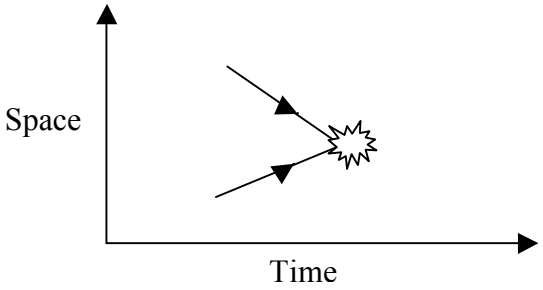



This is why anti-matter has its time arrow pointing backwards. And on collision diagrams, the matter is identical to the anti-matter after a CPT operation.

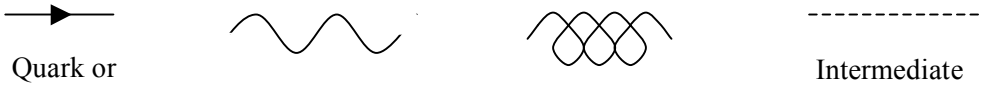
- If a particle is not moving, then we say that its space coordinate is fixed. Of course, if it's just sitting there, then it's moving through *time*. On the diagram below (left), the horizontal line shows the path of motion of a stationary particle. The diagram to the right shows the path of motion of a particle moving away from the origin at some speed.




- Here are two particles colliding! Watch out!

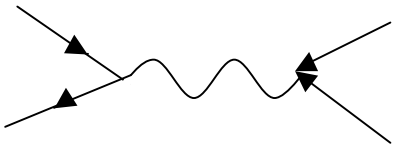



- We use the following symbols in Feynman diagrams:



Quark or Lepton (matter) | Photon | Gluon | Intermediate Vector Boson ($W^-$, $W^+$, or $Z^0$)

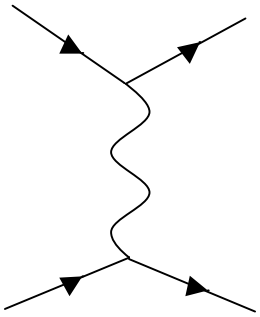
- *Annihilation Diagram:* When matter and antimatter particles collide, they annihilate, leaving behind pure energy in the form of electromagnetic radiation (photons!). The Feynman diagram for that process looks like this:



Note that space and time axes have been left out; they are understood to be there.
Also note that the arrow on the bottom is supposed to be backwards. We do that any time we have an antiparticle. Some people like to think of antiparticles as traveling backwards in time. Let's forget about that for a while.

It is *very* important that you remember that time is the horizontal axis! A lot of people see the drawing above and think of it as two particles coming together at an angle. These two particles are in a *head-on* collision, not hitting at an angle.

- *Scattering Diagram:* Here is the Feynman diagram for two electrons coming towards each other then repelling each other through the electromagnetic force (via *exchange* of a *virtual* photon). Note that the particles are always separated in space (vertical axis) so that they never touch. Hence they are scattering by exchanging virtual photons which cause them to repel. You can think of a virtual photon as existing for an instant of time. Therefore there is no movement in time (horizontal) axis.



## Feynman Diagrams Problem Set

For the following Feynman diagrams, describe in words the process that is occurring. For instance: (a) what type of interaction: annihilation or scattering (b) what are the incoming particles? (c) which kind of boson mediates the interaction? (d) which fundamental force is involved in the interaction? (e) what are the outgoing particles?

Also, for each, decide if the interaction shown is *allowed*. An interaction is allowed if it does not violate any of the rules set out by the Standard Model of physics. If the interactions violate some rule, state which rule it violates. If they do not violate a rule, say that the interaction is allowed.

*Hint:* the best approach is to verify that the incoming and outgoing particles can interact with the boson (force particle) then to look at each vertex where more than one particle is coming together. Look immediately to the left of the vertex (before) and immediately to the right of the vertex (after). For instance, one rule states that the total electric charge before a vertex must equal the total electric charge after a vertex. Is that true? Check all the conserved quantities from the previous chapter in this way.

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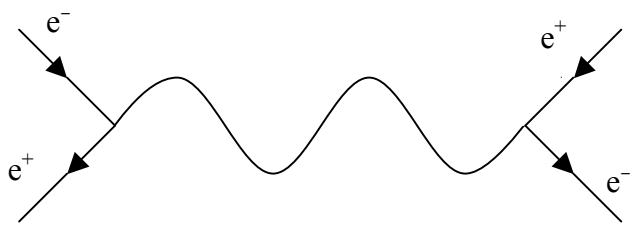


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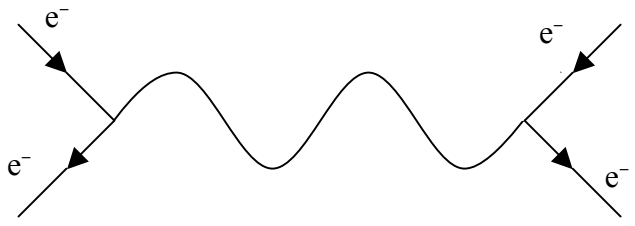

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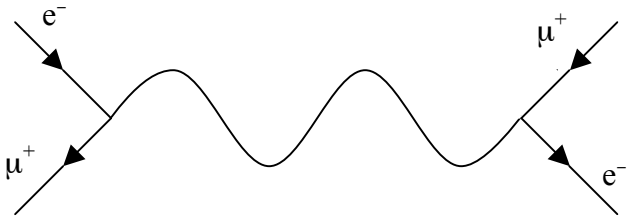
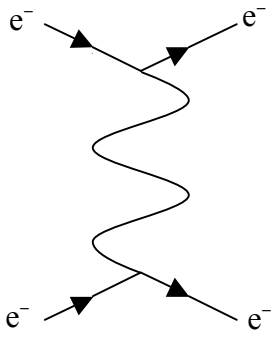



4. a.

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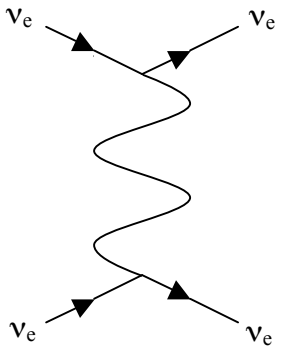


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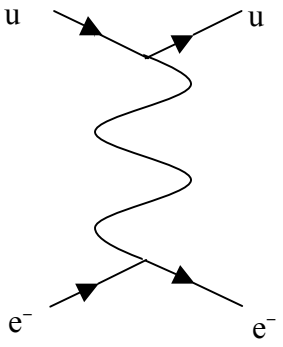


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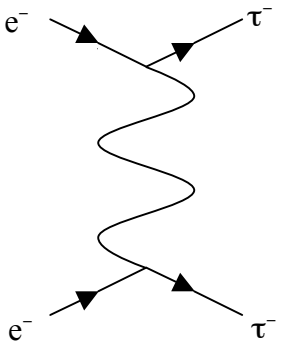


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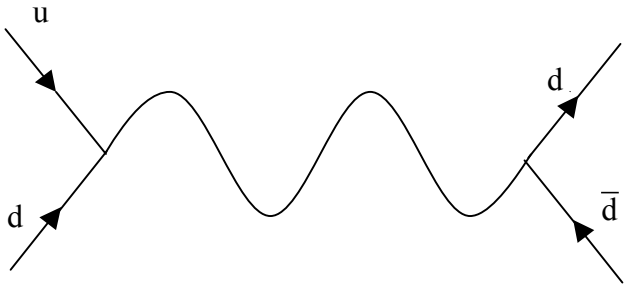

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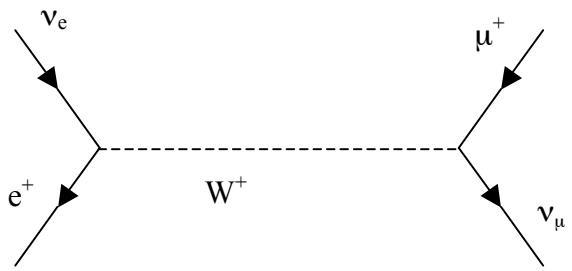
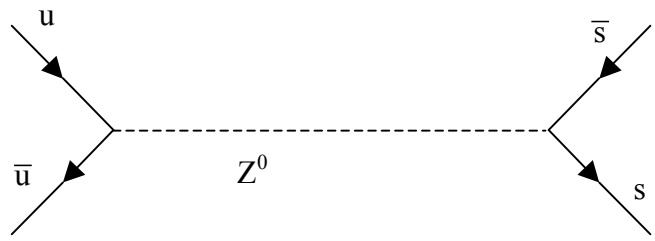
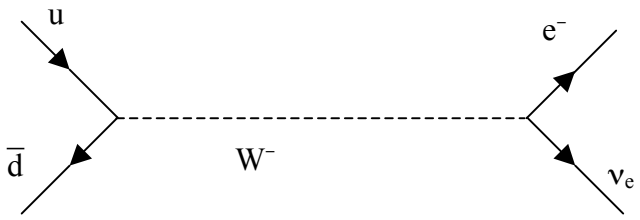

$\nu_e$
$\mu^+$
$e^+$
$W^+$
$\nu_\mu$

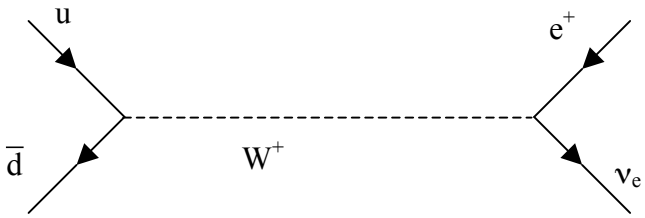
8.


u
$\overline{s}$
$\overline{u}$
$Z^0$
s

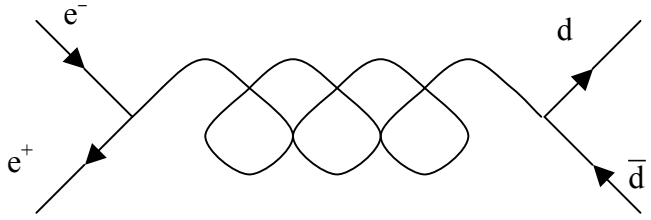
9.


u
$e^-$
$\overline{d}$
$W^-$
$\nu_e$

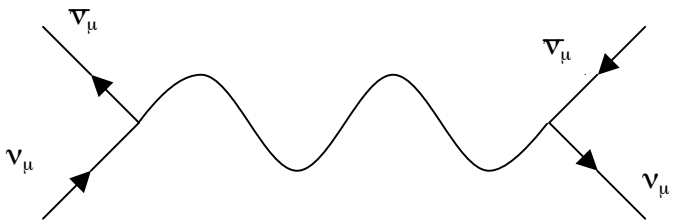
10.


u
$e^+$
$\overline{d}$
$W^+$
$\nu_e$

11.


$e^-$
d
$e^+$
$\overline{d}$

12.

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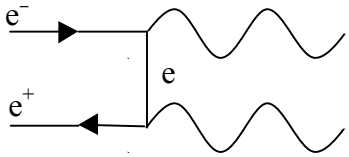
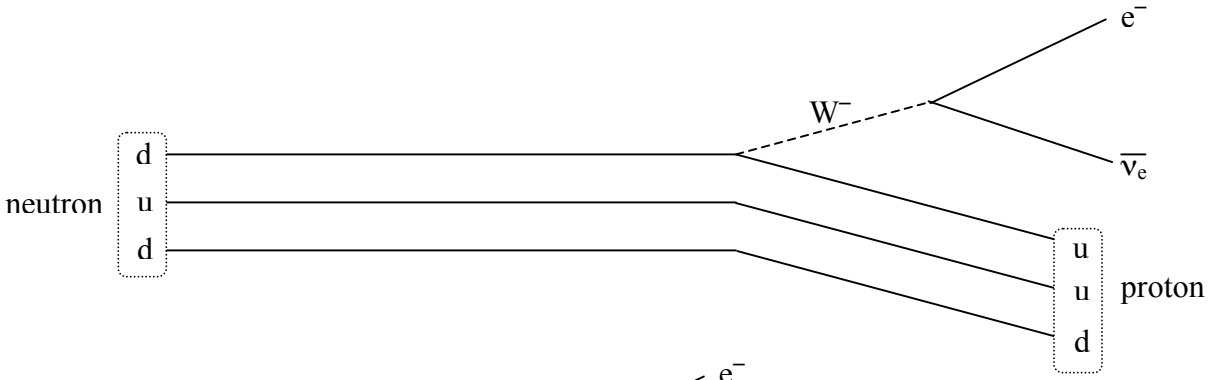



In this case, the electron and positron are exchanging virtual electron/positron pairs.

14.

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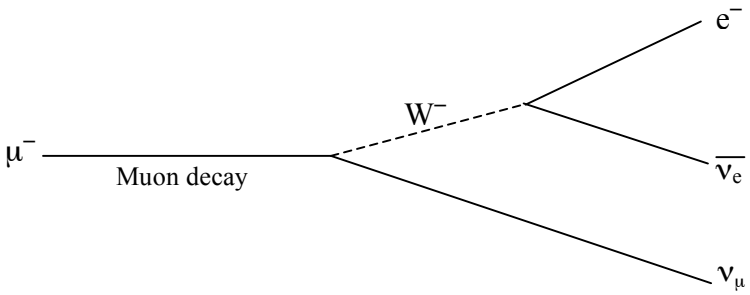


16. Draw all of the possible Feynman diagrams for the annihilation of an electron and positron, followed by motion of an exchange particle, followed by the creation of a new electron and positron.

17. Draw the Feynman diagram for the collision of an up and anti-down quark followed by the production of a positron and electron neutrino.