

# From double-slits to silly drawings

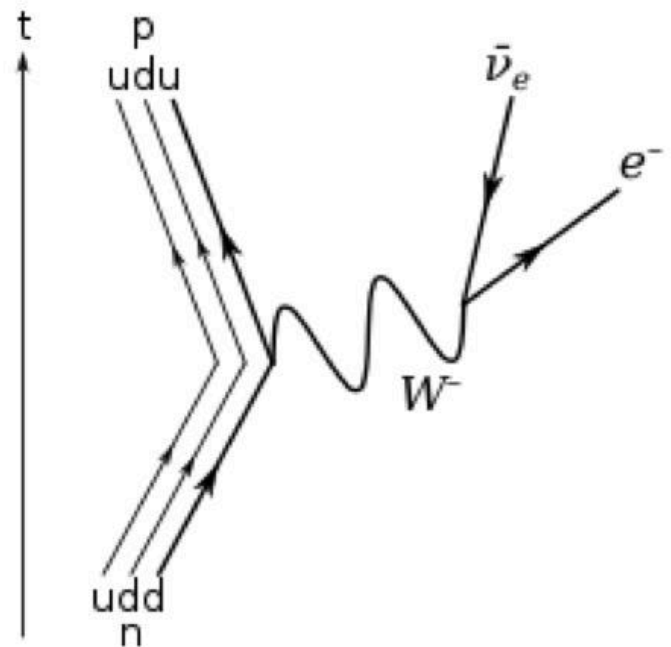
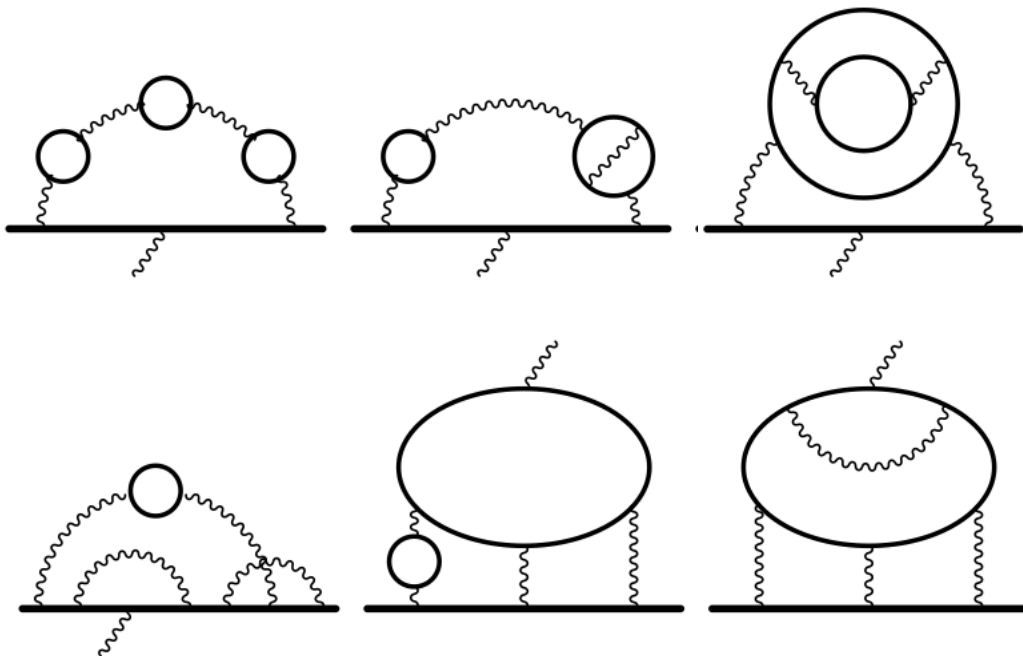
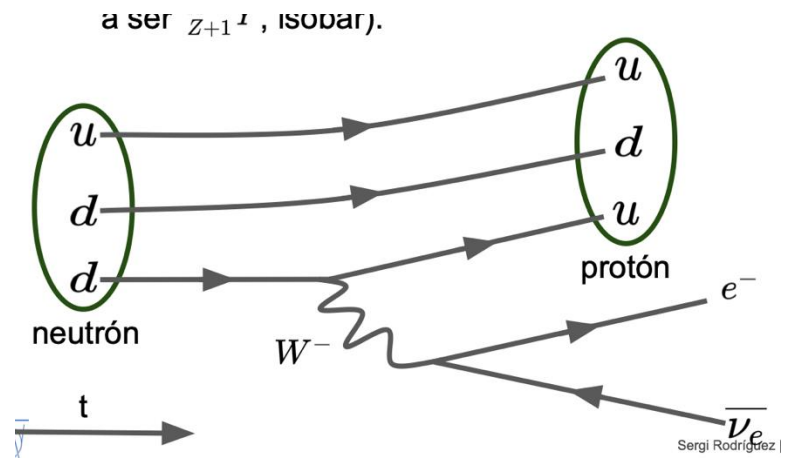
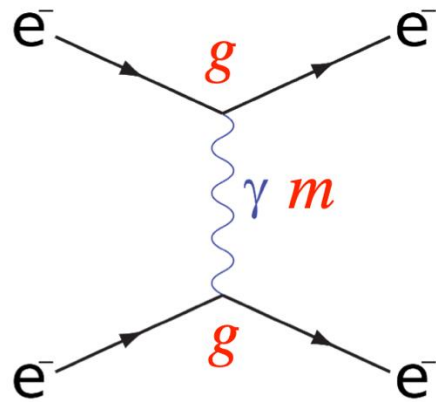
## Feynman's *mathemagic*



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Chinese University of Hong Kong



CERN International Teacher Weeks  
August 9, 2024



What are *Feynman diagrams*?

# Preliminaries ...



HOP IN THE TIME MACHINE, HOBBS! WE'RE GOING A FEW HOURS INTO THE FUTURE! I'LL HAVE FINISHED MY STORY BY THEN, SO WE'LL JUST PICK IT UP AND BRING IT BACK TO THE PRESENT! THAT WAY, I WON'T HAVE TO WRITE IT!



$$z \leftarrow z^2 + c$$

$c$ : a fixed number,

Always starting with  $z = 0$

$$c = -1$$

$$z_0 = 0$$

$$z_1 = 0^2 + (-1) = -1$$

$$z_2 = (-1)^2 + (-1) = 0$$

$$z_3 = 0^2 + (-1) = -1$$

$$z_4 = (-1)^2 + (-1) = 0$$

⋮

**BLACK**

**BOUND**

$$c = 1$$

$$z_0 = 0$$

$$z_1 = 0^2 + (1) = 1$$

$$z_2 = 1^2 + (1) = 2$$

$$z_3 = 2^2 + (1) = 5$$

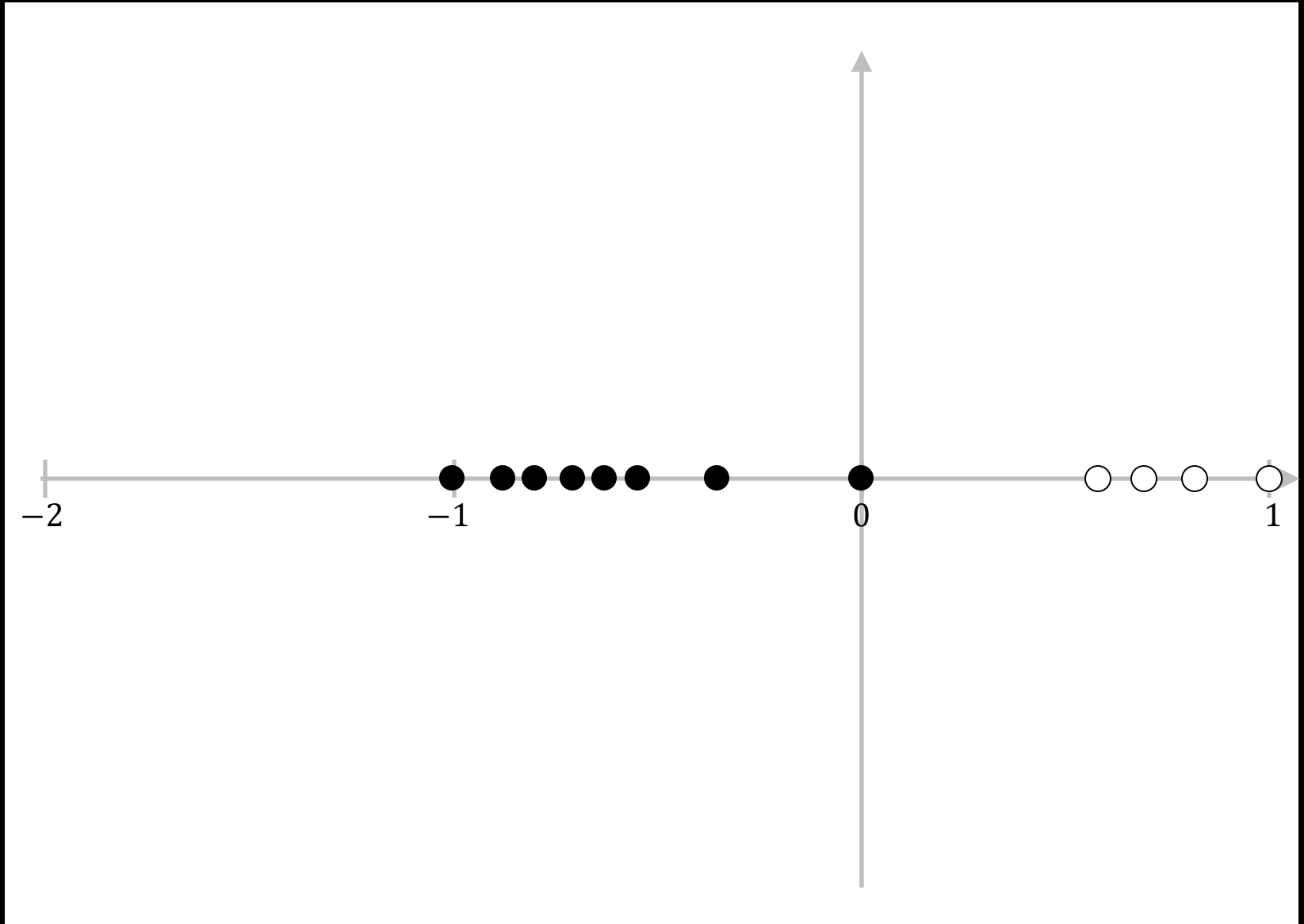
$$z_4 = 5^2 + (1) = 26$$

⋮

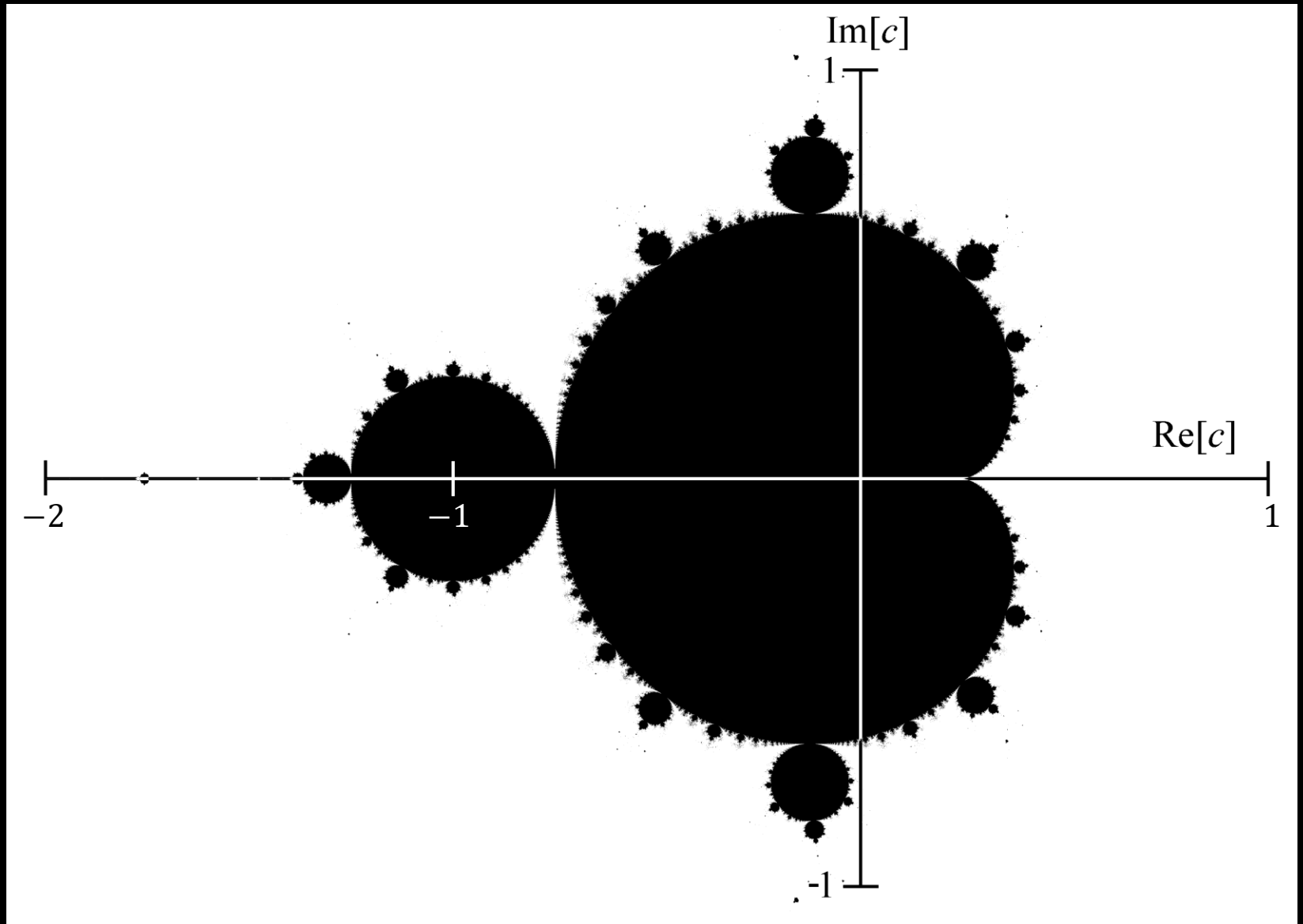
**COLORS**  
(according to  
divergence speed)

**DIVERGENT**

$$z \leftarrow z^2 + c$$

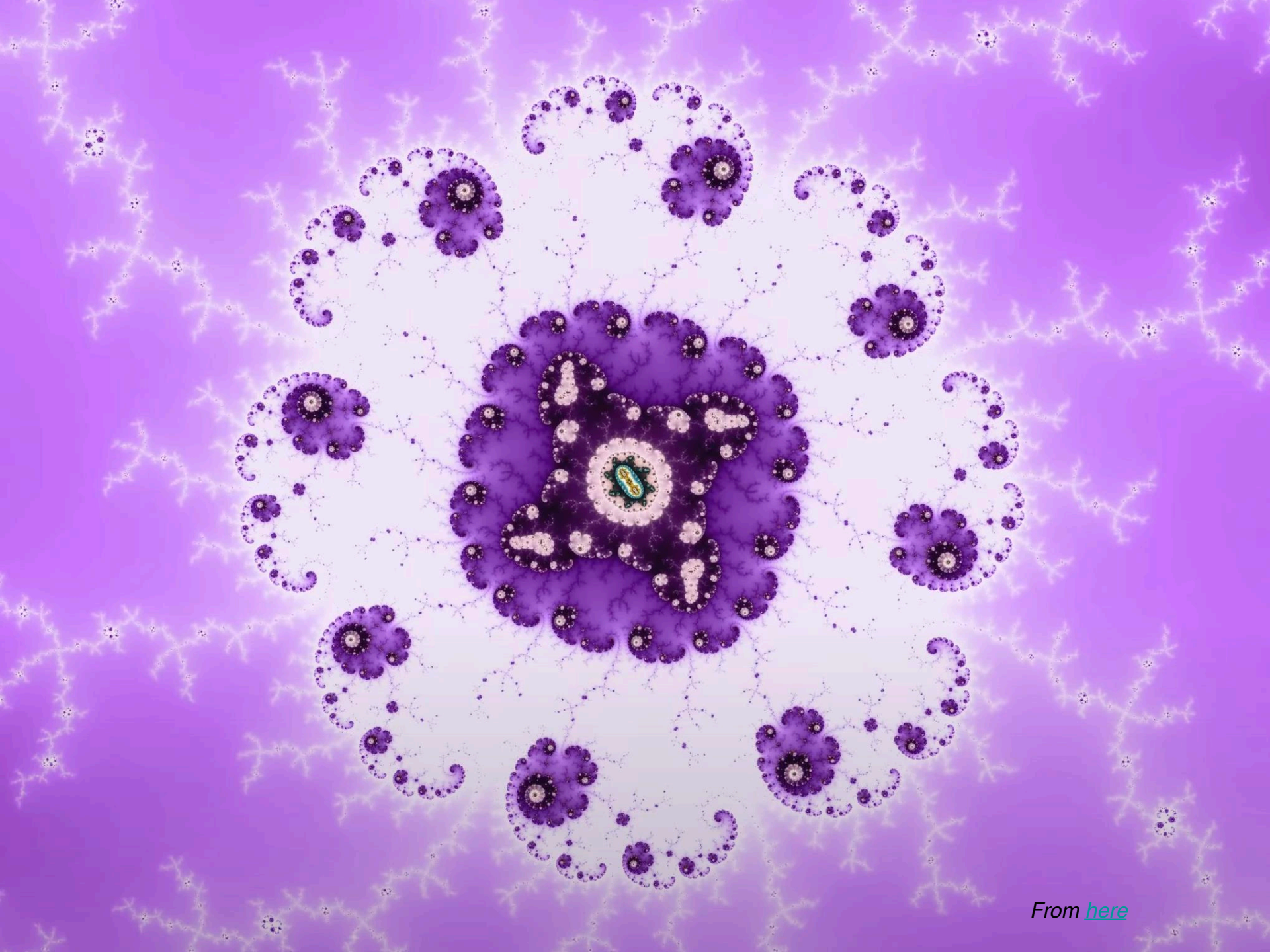


<https://www.youtube.com/watch?v=pCpLWbHVNhk>



<https://www.youtube.com/watch?v=pCpLWbHVNhk>





From [here](#)

A proof ...

**“Simplifying” our representations**



**Periodic Table of Elements**  
© AllAboutGemstones.com

		Group																						
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18					
Period	1	1 <b>H</b>																	2 <b>He</b>					
	2	3 <b>Li</b>	4 <b>Be</b>																	5 <b>B</b>	6 <b>C</b>	7 <b>N</b>	8 <b>O</b>	9 <b>F</b>
3	11 <b>Na</b>	12 <b>Mg</b>	III B	IV B	V B	V I B	V II B	V III B	IB	IIB	13 <b>Al</b>	14 <b>Si</b>	15 <b>P</b>	16 <b>S</b>	17 <b>Cl</b>	18 <b>Ar</b>								
4	19 <b>K</b>	20 <b>Ca</b>	21 <b>Sc</b>	22 <b>Ti</b>	23 <b>V</b>	24 <b>Cr</b>	25 <b>Mn</b>	26 <b>Fe</b>	27 <b>Co</b>	28 <b>Ni</b>	29 <b>Cu</b>	30 <b>Zn</b>	31 <b>Ga</b>	32 <b>Ge</b>	33 <b>As</b>	34 <b>Se</b>	35 <b>Br</b>	36 <b>Kr</b>						
5	37 <b>Rb</b>	38 <b>Sr</b>	39 <b>Y</b>	40 <b>Zr</b>	41 <b>Nb</b>	42 <b>Mo</b>	43 <b>Tc</b>	44 <b>Ru</b>	45 <b>Rh</b>	46 <b>Pd</b>	47 <b>Ag</b>	48 <b>Cd</b>	49 <b>In</b>	50 <b>Sn</b>	51 <b>Sb</b>	52 <b>Te</b>	53 <b>I</b>	54 <b>Xe</b>						
6	55 <b>Cs</b>	56 <b>Ba</b>	57 *	72 <b>Hf</b>	73 <b>Ta</b>	74 <b>W</b>	75 <b>Re</b>	76 <b>Os</b>	77 <b>Ir</b>	78 <b>Pt</b>	79 <b>Au</b>	80 <b>Hg</b>	81 <b>Tl</b>	82 <b>Pb</b>	83 <b>Bi</b>	84 <b>Po</b>	85 <b>At</b>	86 <b>Rn</b>						
7	87 <b>Fr</b>	88 <b>Ra</b>	89 +	104 <b>Rf</b>	105 <b>Ha</b>	106 <b>Sg</b>	107 <b>Bh</b>	108 <b>Hs</b>	109 <b>Mt</b>	110 <b>Ds</b>	111 <b>Rg</b>	112	113 <b>Uut</b>	114 <b>Uuq</b>	115 <b>Uup</b>	116 <b>Uuh</b>	117 <b>Uus</b>	118 <b>Uuo</b>						
		<i>s-block</i>		<i>d-block</i>									<i>p-block</i>											
<i>f-block</i>	Lanthanide Series	57 * <b>La</b>	58 <b>Ce</b>	59 <b>Pr</b>	60 <b>Nd</b>	61 <b>Pm</b>	62 <b>Sm</b>	63 <b>Eu</b>	64 <b>Gd</b>	65 <b>Tb</b>	66 <b>Dy</b>	67 <b>Ho</b>	68 <b>Er</b>	69 <b>Tm</b>	70 <b>Yb</b>	71 <b>Lu</b>								
	Actinide Series	89 + <b>Ac</b>	90 <b>Th</b>	91 <b>Pa</b>	92 <b>U</b>	93 <b>Np</b>	94 <b>Pu</b>	95 <b>Am</b>	96 <b>Cm</b>	97 <b>Bk</b>	98 <b>Cf</b>	99 <b>Es</b>	100 <b>Fm</b>	101 <b>Md</b>	102 <b>No</b>	103 <b>Lr</b>								

**H - Gas**



Non-Metals



Alkali Metals

**Li - Solid**



Transition Metals



Alkali Earth Metals

**Br - Liquid**



Rare Earth Metals



Other Metals

**Tc - Synthetic**

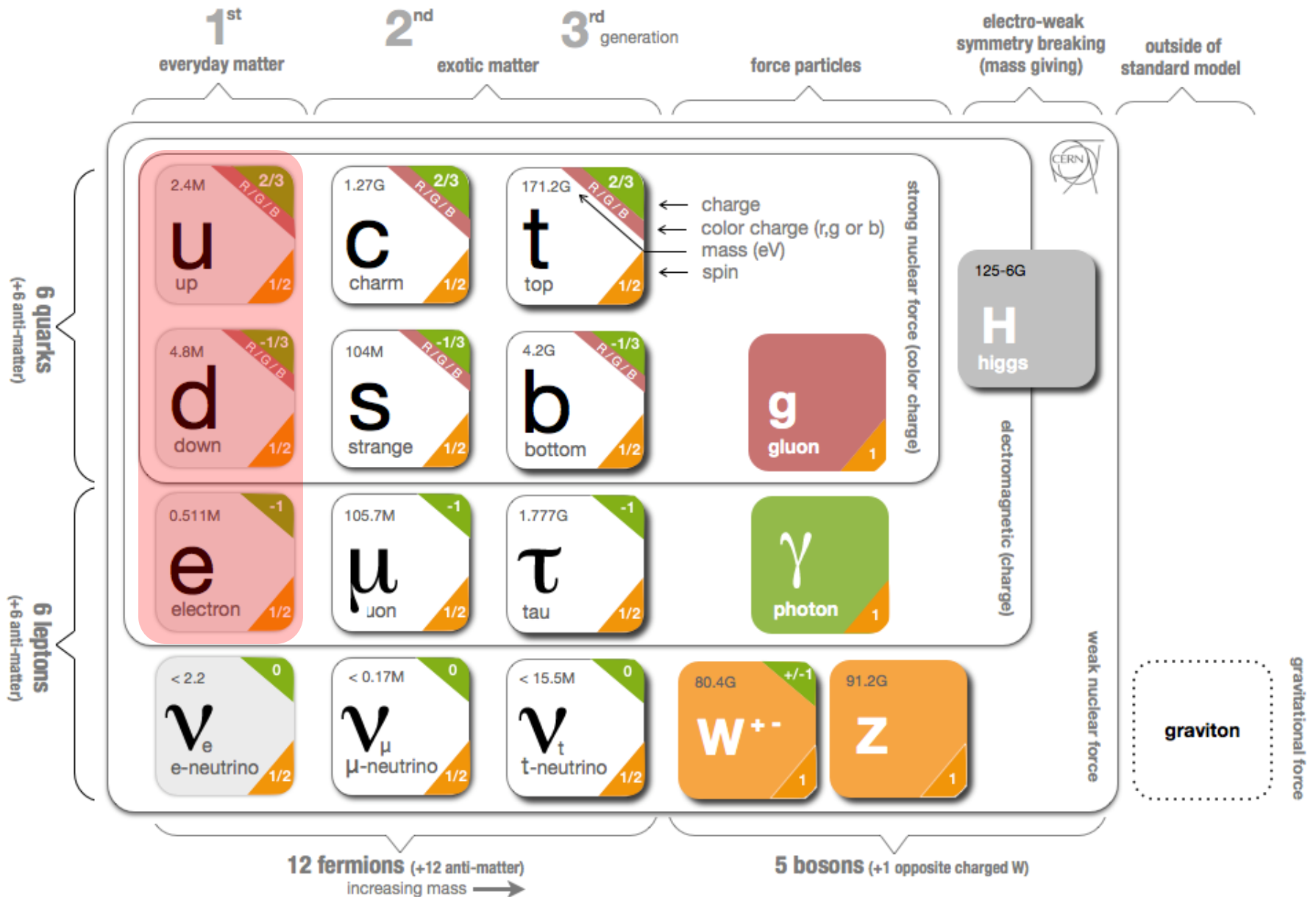


Halogens



Inert Elements

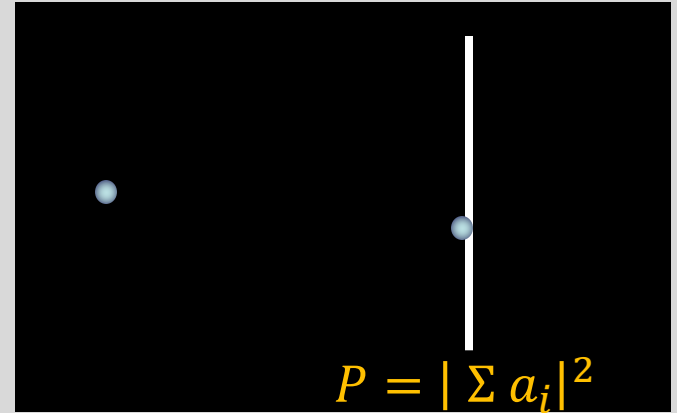
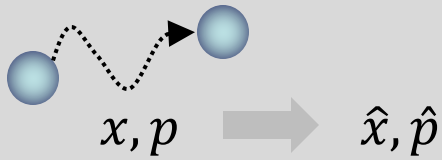




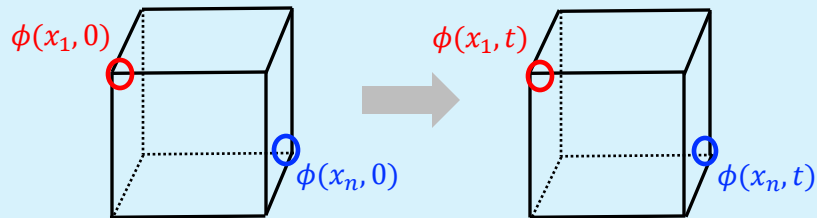
... and then what?



CLASSICAL MECHANICS:



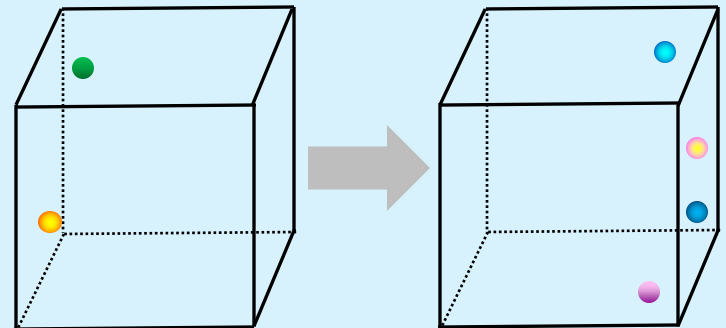
AT HIGH ENERGIES (SHORT DISTANCES):

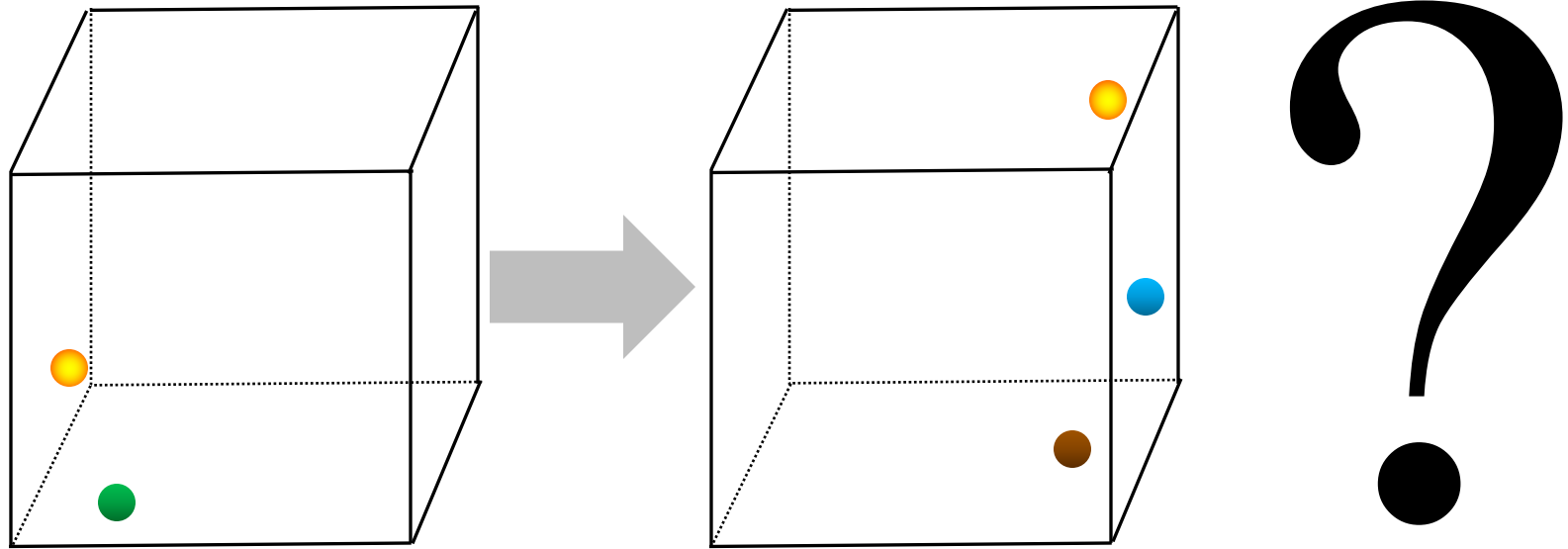


Each  $\phi(x) \longrightarrow \hat{\phi}(x)$

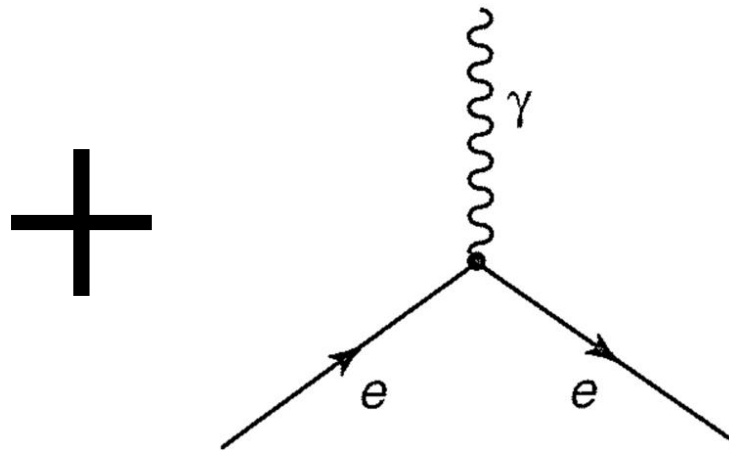
Excitations at each point: *quanta of that field*

We cannot ignore particle production

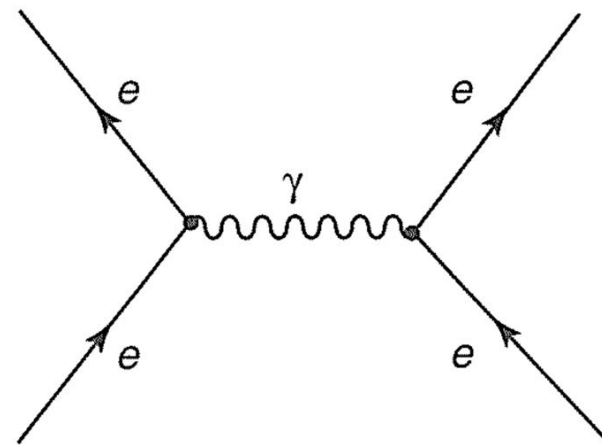
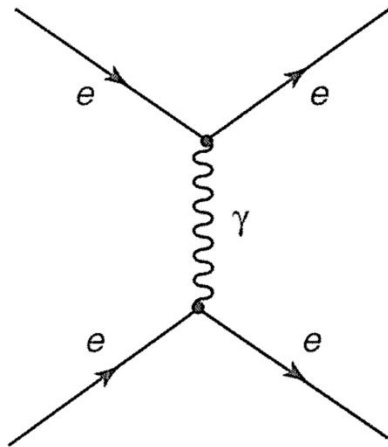




“All possible histories” are those that can be built by combining a few “basic vertices” that represent fundamental interactions.

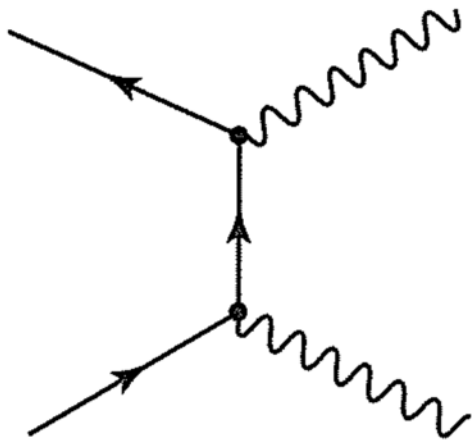


time

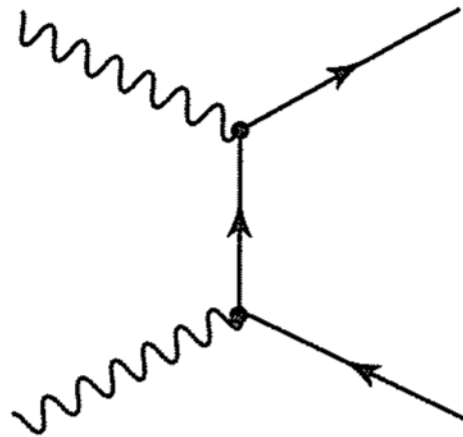


# Other combinations

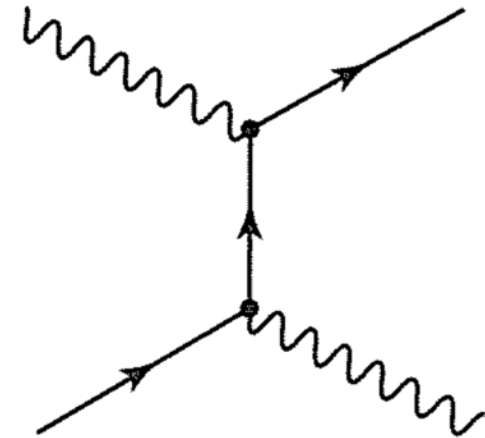
time  $\longrightarrow$



Pair annihilation  
 $e^+ + e^- \rightarrow \gamma + \gamma$



Pair production  
 $\gamma + \gamma \rightarrow e^+ + e^-$



Compton scattering  
 $e^- + \gamma \rightarrow e^- + \gamma$

What is  $\frac{1}{0.98}$ ?

$$\frac{1}{1 - 0.02} \approx 1 + 0.02$$

$$\approx 1 + 0.02 + 0.02^2$$

$$\approx 1 + 0.02 + 0.02^2 + 0.02^3$$

$$\dots$$

$$\frac{1}{1 - x} = 1 + x + x^2 + x^3 + \dots$$

- It is an infinite series, but we only may need two terms.
- We know how to obtain the series, but **not “by inspection”**.
- Maybe a supersmart alien species calls this function the *“all ones”*

*Each Feynman diagram* stands for an *expression* that produces *one complex number*.

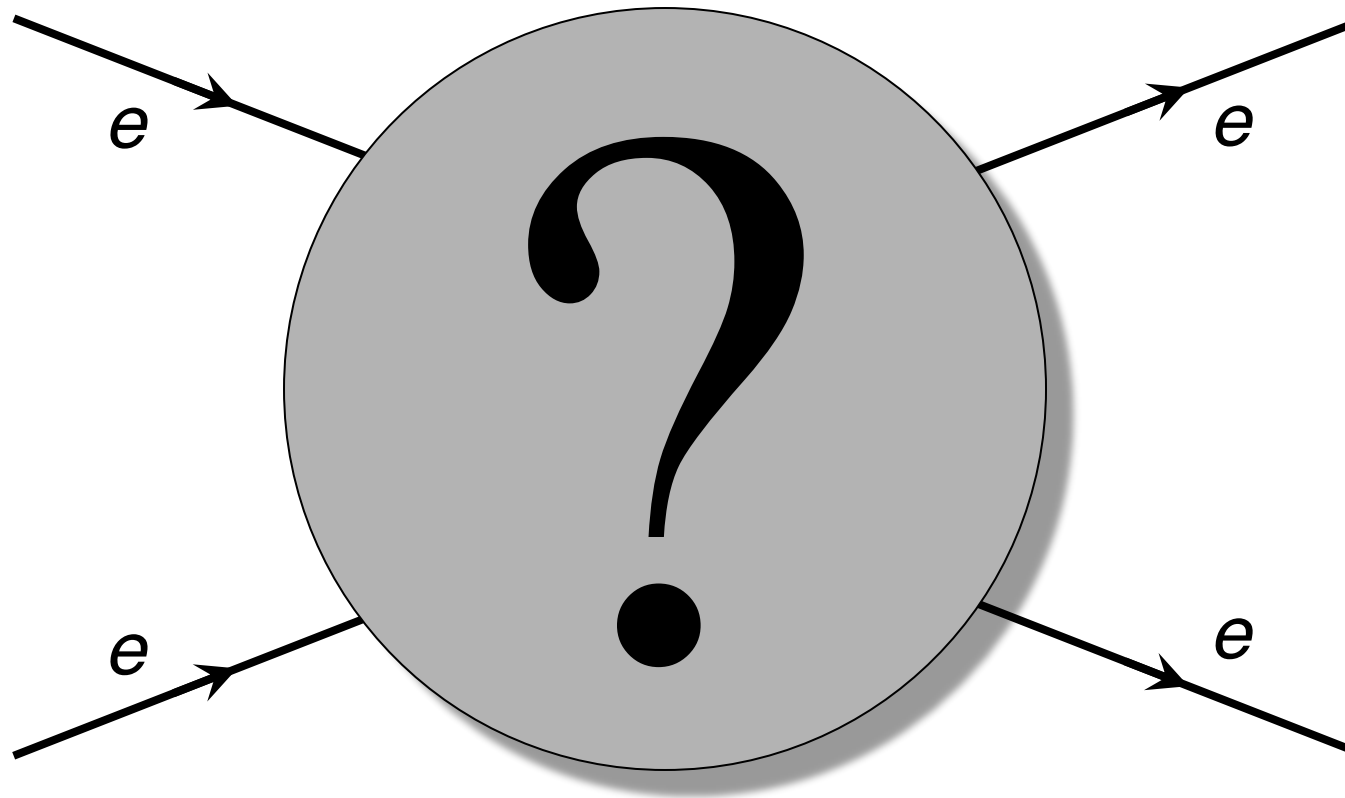
They are terms in a series; they are just written in an exceedingly intuition-friendly notation.

Once we know the valid vertices and what particles **enter** and **exit** a process, *we can write 'by inspection' all the terms needed!!!*

***The sum of those expressions is the probability amplitude for the process.***

For example,

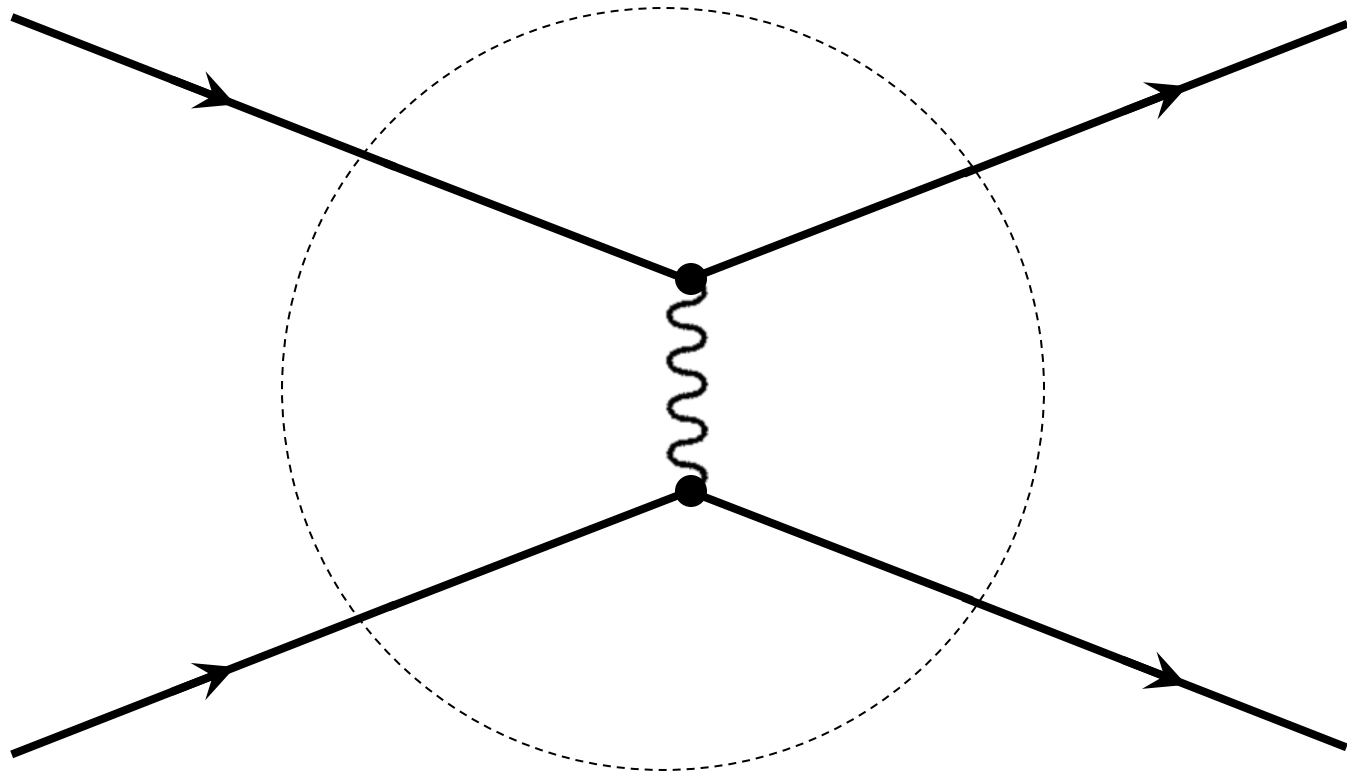
time  $\longrightarrow$





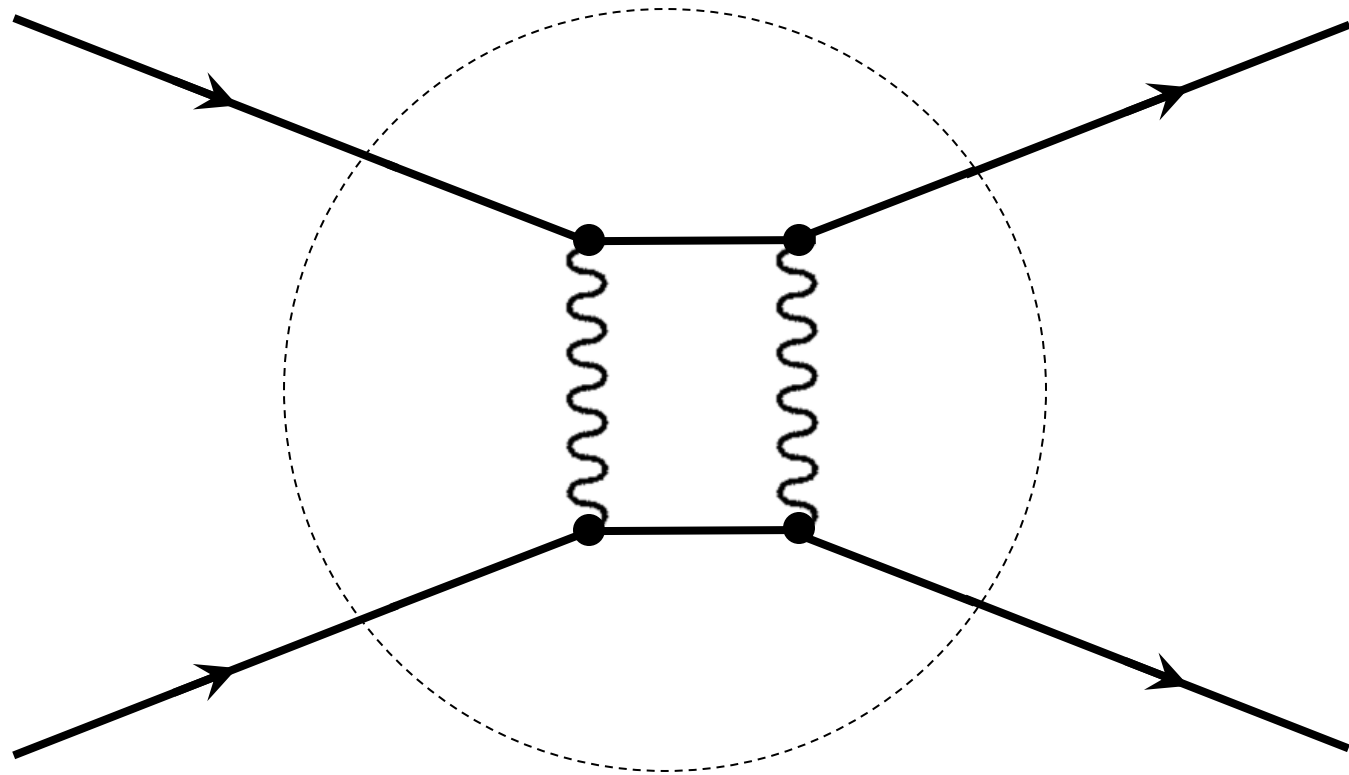
For example,

time 



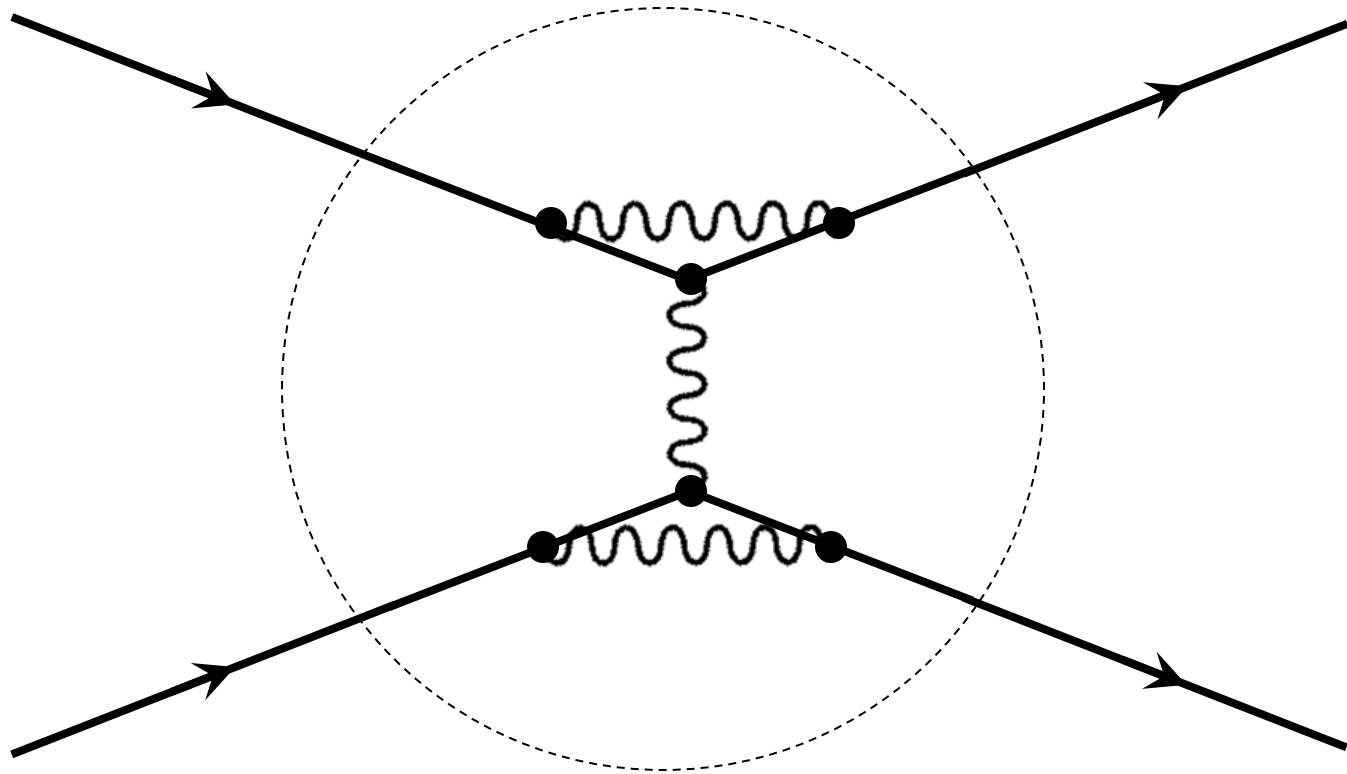
For example,

time 



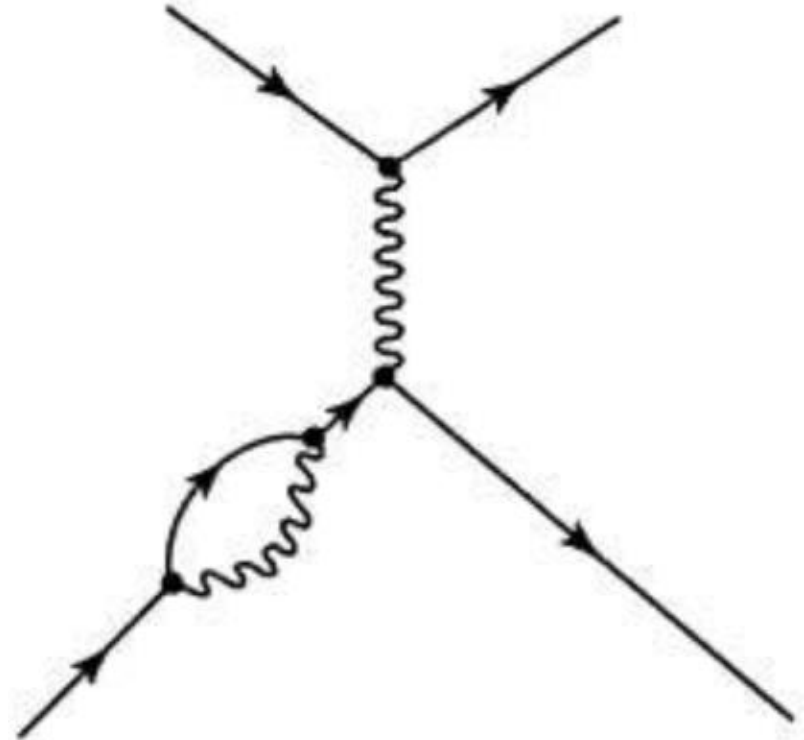
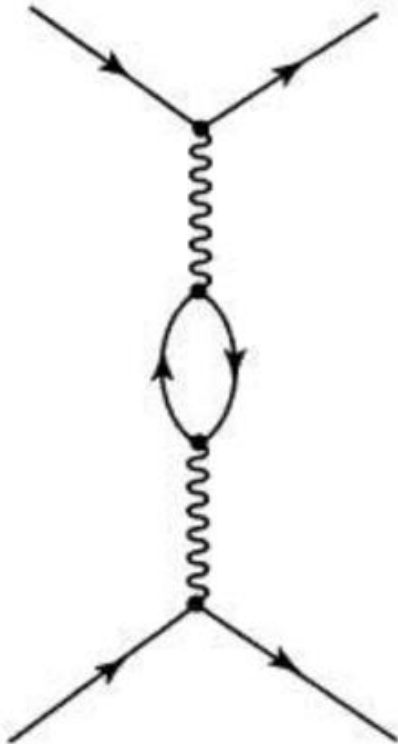
For example,

time 

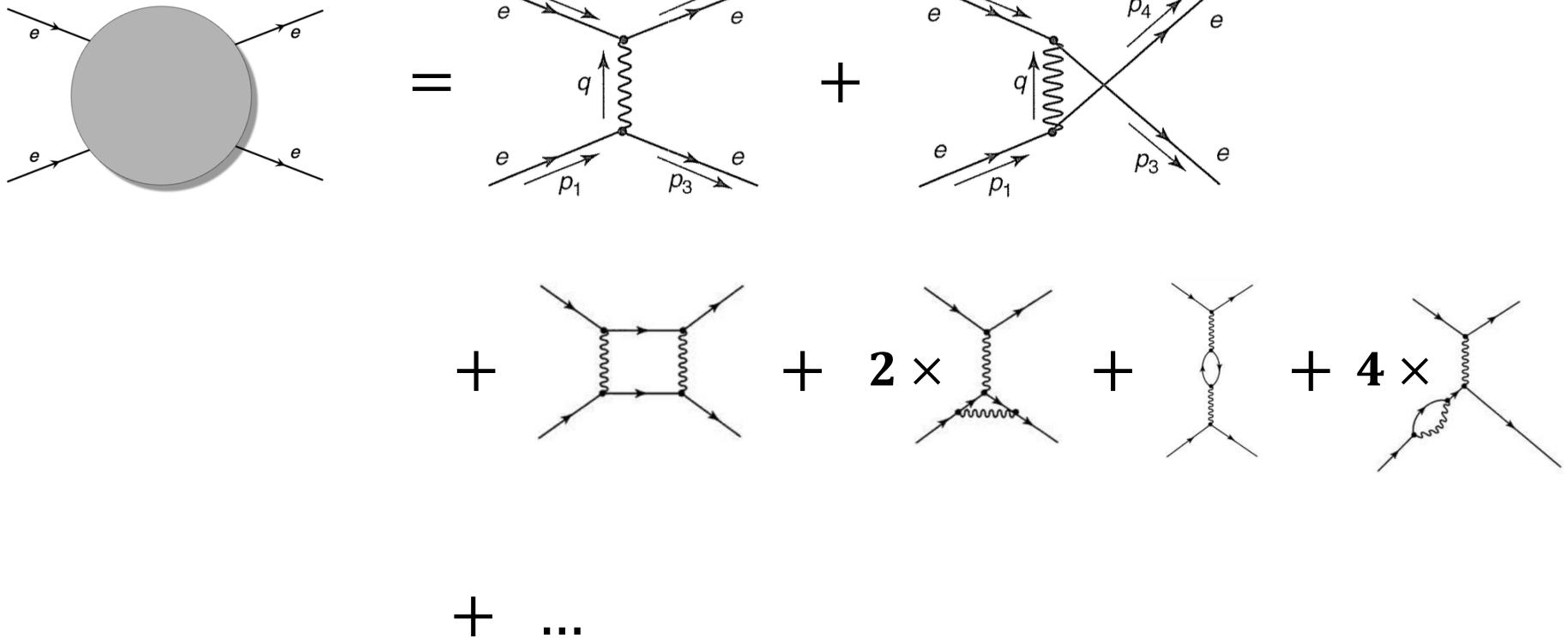


For example,

time  $\longrightarrow$

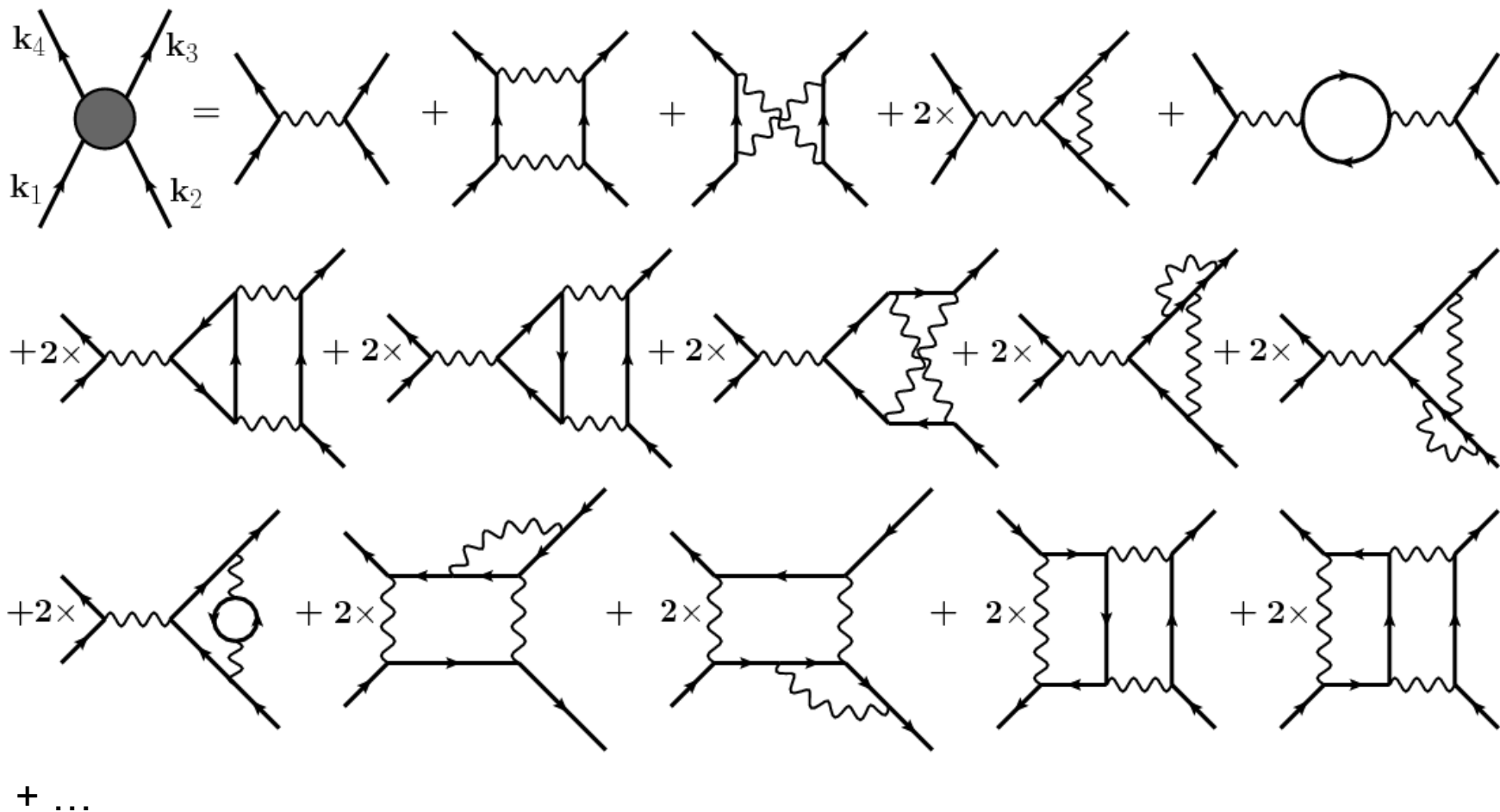


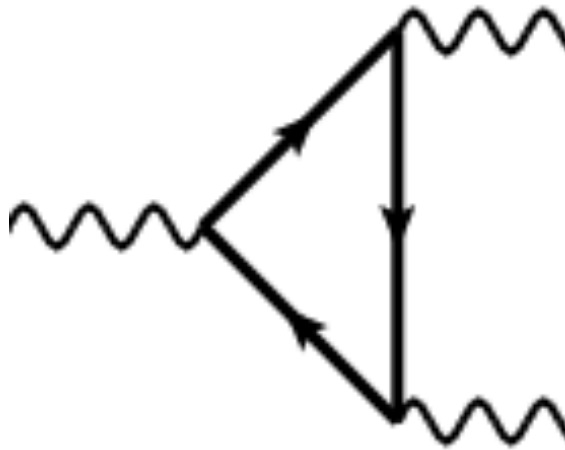
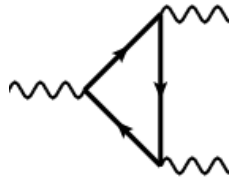
time  $\longrightarrow$



- In QED, for each diagram: **more vertices  $\rightarrow$  smaller value**
- Only the connections are important (angles are irrelevant)
- For very high precision, thousands of terms may be needed

time  $\longrightarrow$





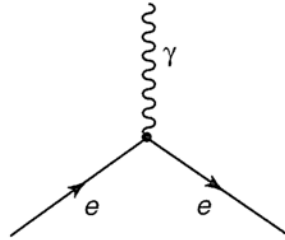
Also, remember that “proof” at the beginning?

- The two “90 degree rotations” that make it “work” are absurd because **expressions** and **what they represent** do not share rotational properties
- On the other hand, when we rotate a Feynman diagram (i.e., we “rotate an expression”), we get valid expressions!

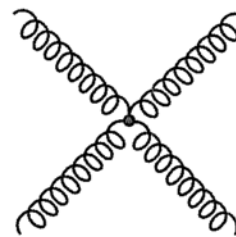
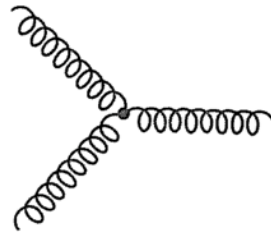
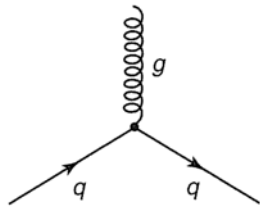


# Interaction summary (w/o the Higgs boson)

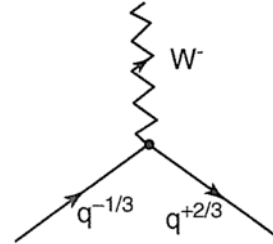
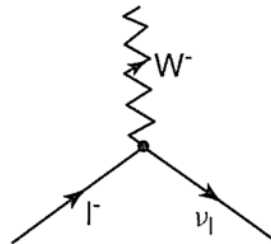
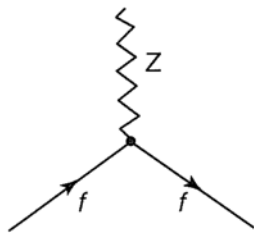
**QED:**



**QCD:**



**Weak:**

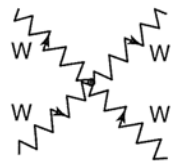


	Fermions			Bosons	Force carriers
Quarks	<i>u</i> up	<i>c</i> charm	<i>t</i> top	$\gamma$ photon	
	<i>d</i> down	<i>s</i> strange	<i>b</i> bottom	<i>Z</i> Z boson	
Leptons	$\nu_e$ electron neutrino	$\nu_\mu$ muon neutrino	$\nu_\tau$ tau neutrino	<i>W</i> W boson	
	<i>e</i> electron	$\mu$ muon	$\tau$ tau	<i>g</i> gluon	

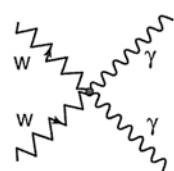
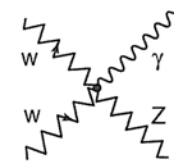
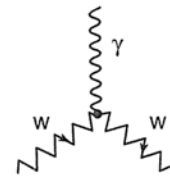
**Cabibbo-Kobayashi-Maskawa**

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

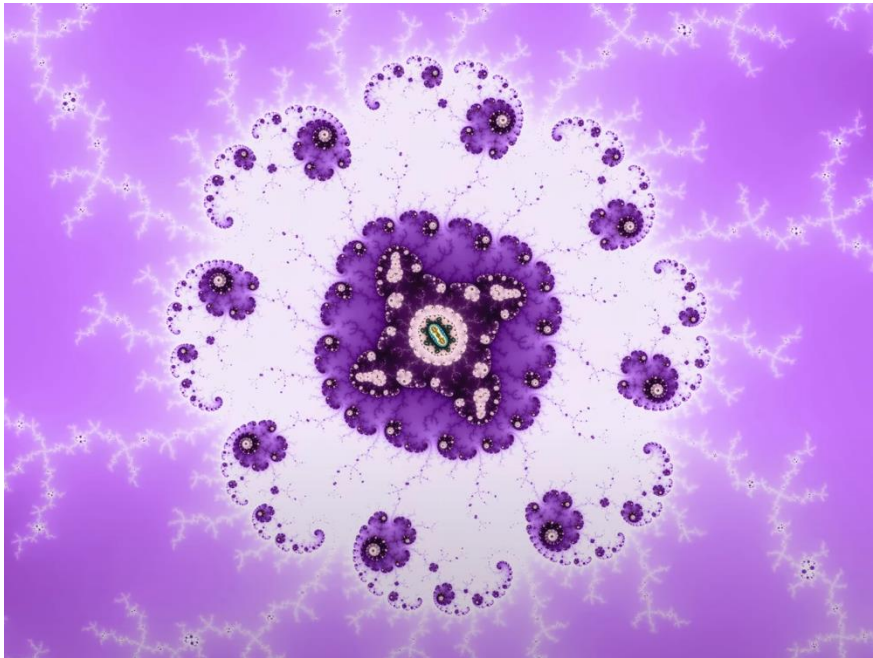
**W/Z:**



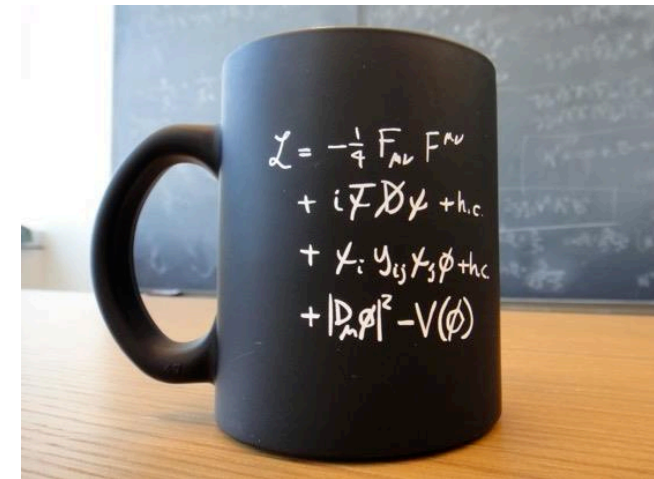
**(WIZ)h:**



- Each **valid vertex** corresponds to a **term** in the Standard Model Lagrangian.
- i.e., Feynman diagrams are *terms in the perturbative expansion of the probability amplitude of a process.*



$$z \leftarrow z^2 + c$$



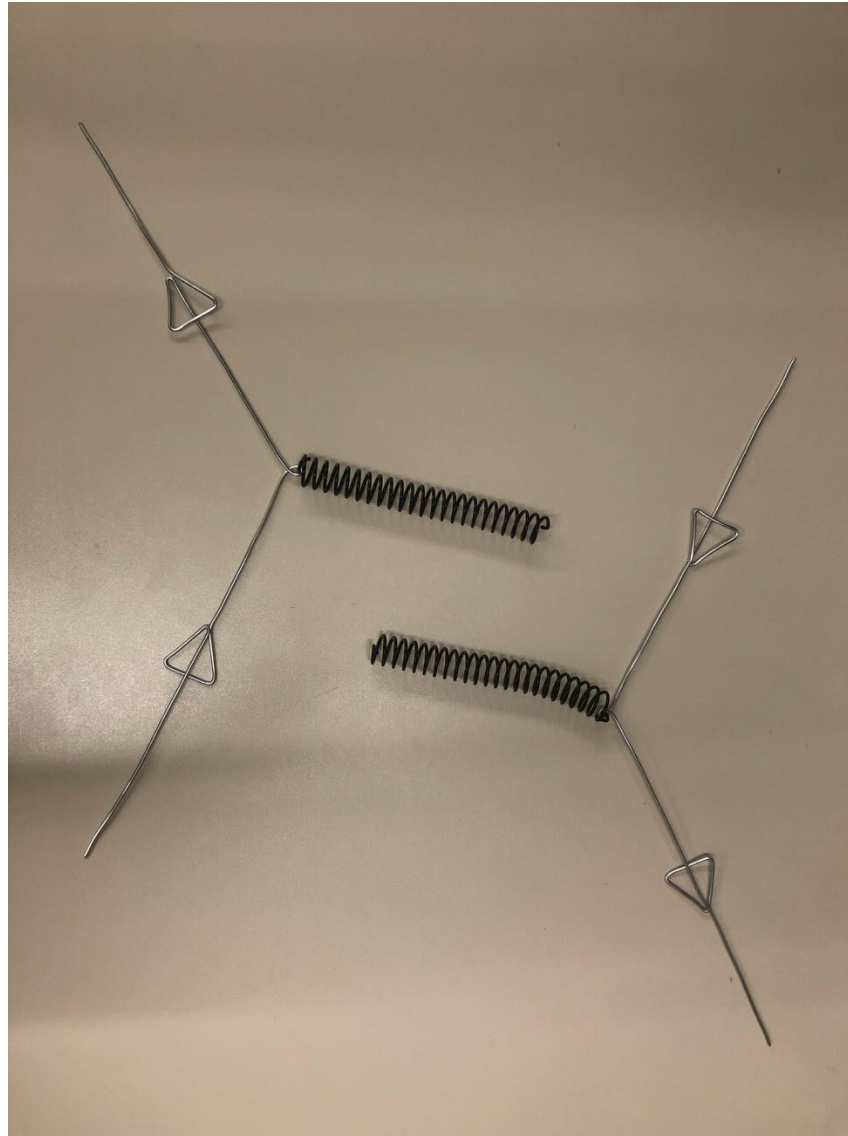








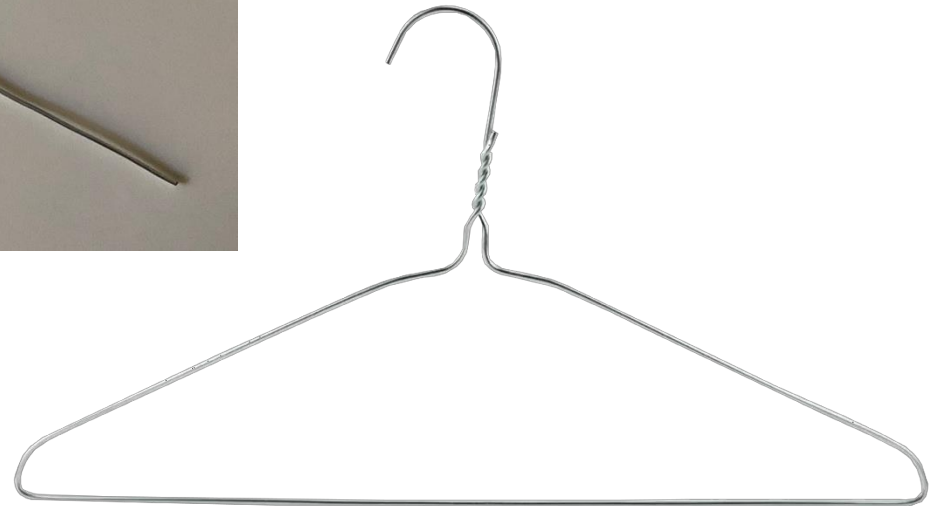
# DIY version of the Universe's lego blocks...



# DIY version of the Universe's lego blocks...



*From a notebook's spiral and a wire coat hanger*







***Combine and twist away... ☺***