Group theory, Topology and Spin-1/2 Particles

From Dirac's belt to fermions

Louan Mol

Unversité Libre de Bruxelles

Brussels Summer School of Mathematics 2022

Table of contents

Dirac's belt trick and rotations

Dirac's belt trick

You need:

- a belt (not necessarily Dirac's)
- a heavy book

Rules:

1. you can only move the end of the belt
2. you cannot twist or rotate it

Goal: untwist a 2π-twist.

$\Rightarrow$ it tuns out to be impossible ! One turn negates the twist: $2\pi \to -2\pi$.

Therefore, possible for a 4π twist ...

Why is that ?

Space of rotations: SO(3) as a group

Rotations in 3-dimensional space: matrices that acts on $\mathbb{R}^3$ s.t.

1. preserve the scalar product: $O^T O = \mathbb{1}$ ($\Leftrightarrow O$ is orthogonal)
2. preserve the orientation: $\det O = 1$

Special othogonal group

SO(3) is the set of 3×3 real matrices such that $O^T O = \mathbb{1}$ and $\det O = 1$.

Three "fundamental" rotations:

$$x : \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} \quad y : \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \quad z : \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$\Rightarrow$ It forms a group.

Space of rotations: SO(3) as a topological space

Fundamental data that describes a rotation:

- an axis of rotation, i.e. a unit vector $\vec{n}$ $\rightarrow$ 2 parameters
- an angle of rotation $\theta \in [-\pi, \pi]$ (with $-\pi \sim \pi$) $\rightarrow$ 1 parameter

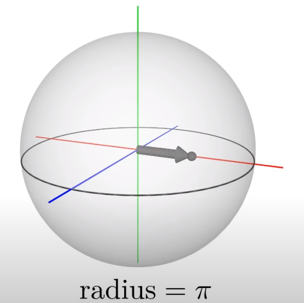
The space of rotations can then alternately be defined as a **3-sphere of radius π and its antipodal points identified**:

$$\boxed{\mathrm{SO}(3) \cong B^3(\pi)/\sim}$$

and for each point:

$$\text{direction} \leftrightarrow \text{axis}$$

$$\text{norm} \leftrightarrow \text{angle}$$



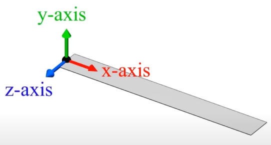
$\Rightarrow$ It forms a topological space.

(group + topological space = Lie group)

Back to the belt

Mathematical description of the belt ?

- a belt is a strip, which is just a path + an orientation.
- given axis on the middle line along the belt, each set of axis is related by a rotation
- a belt configuration is equivalent to a continuous set of axis and therefore to a continuous set of translations, i.e. a path in SO(3)



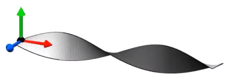
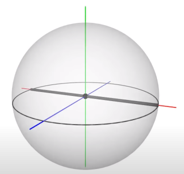
There is a bijection:

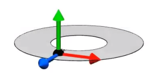
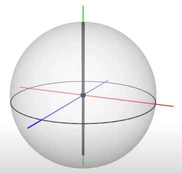
$$\boxed{\text{belt configuration} \Leftrightarrow \text{path in SO(3)}}$$

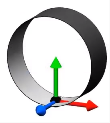
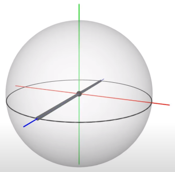
This gives us a new language to analyze the problem !

Dictionary

Belt | **Path**

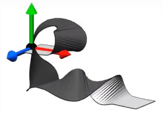
 $\longleftrightarrow$ 

 $\longleftrightarrow$ 

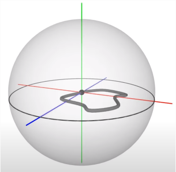
 $\longleftrightarrow$ 

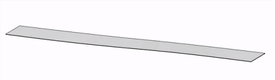
(The color code is consistent.)

Belt | **Path**

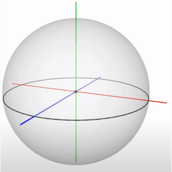


$\longleftrightarrow$



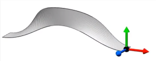
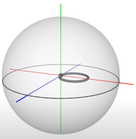
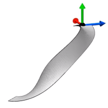
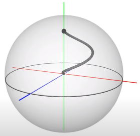


$\longleftrightarrow$



(The color code is consistent.)

Back to Dirac's belt trick

 $\longleftrightarrow$   $\longleftrightarrow$ 

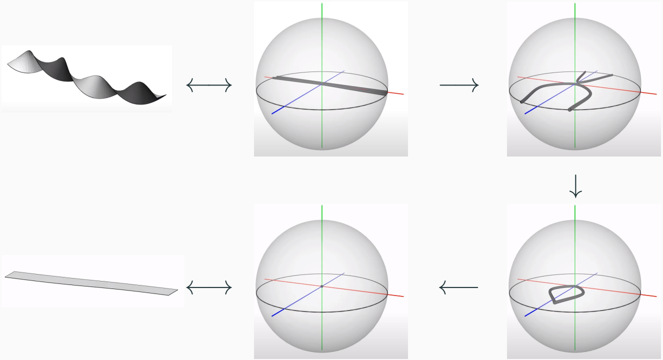
Belt		**Path**
specific configuration	$\longleftrightarrow$	specific path
moving the ends	$\longleftrightarrow$	continuous deformation
ends have same orientation	$\longleftrightarrow$	closed path (loop)
can be flattened	$\longleftrightarrow$	contractible

$\Rightarrow$ we are allowed to continuously deform the paths while keeping its starting and ending points at the origin

The question is then: **which loops are contractible ?**

The 4π-twist

We saw in the beginning the the 4π-twist can be flattened, how can we see this in terms of paths ?



$\Rightarrow$ the 4π-twist is contractible ! What about the 2π-twist ?

Problems of our "proof": difficult to see and case by case ...

We want a more consistent study of paths in topological spaces.

Homotopy theory

Homotopoy theory primer

Starting observation: depending on the topological space, all loops might not be contractible. Moreover, some loops are "fundamentally different" from each other.
Examples: $\mathbb{R}^3$, 2-sphere, torus, etc.

Topological space X.

Path in X: continuous map $\gamma : S^1 \to X$

γ_1 and γ_2 are *homotopically equivalent* ($\sim$) if one can be deformed into the other. I.e. if there exists $H : [0,1] \times S^1 \to X$ such that

$$H(0,t) = \gamma_1(t) \qquad \text{and} \qquad H(1,t) = \gamma_2(t).$$

This is an equivalence relation.

For each $x_0 \in X$, we define

$$\pi_1(X, x_0) = \{\text{all loops based at } x_0\}/\sim,$$

it is the set of "fundamentally different" loops passing through x_0.

Fundamental group

Group structure:

- **Product** of paths: $\gamma_1 \cdot \gamma_2 = \gamma_1$ then γ_2
- **Inverse** path: $\gamma^{-1} = \gamma$ traversed in the opposite direction
- For equivalence classes: $[\gamma_1] \cdot [\gamma_2] = [\gamma_1 \cdot \gamma_2]$ and $[\gamma]^{-1} = [\gamma^{-1}]$

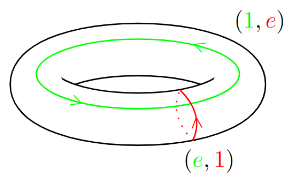
Important fact: up the isomorphism, $\pi_1(X, x_0)$ does not depend on x_0
$\Rightarrow$ we denote it as $\pi_1(X)$, it is called the fundamental group of X.

Contractible loops are the ones in $[e]$ ($\sim$ to a point).

How to compute the fundamental group ? Difficult task, not discussed here.

Examples:

- $\pi_1(\mathbb{R}^2) = \{e\}$
- $\pi_1(S^2) = \{e\}$
- $\pi_1(\mathbb{T}^2) = \mathbb{Z} \times \mathbb{Z}$
- $\pi_1(\mathbb{R}^2 \backslash \{pt\}) = \mathbb{Z}$



Fundamental group of $\mathbf{SO}(3)$

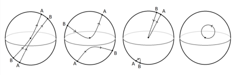
Question we had: **are all loops in $\mathbf{SO}(3)$ contractible ?**

In homotopy language: **is $\pi_1(\mathbf{SO}(3))$ trivial ?**

> The belt trick is a way of physically demonstrating that the fundamental group of $\mathrm{SO}(3)$ is $\mathbb{Z}_2$.

Electrons

In quantum mechanics


A
B
B
A
B
A
A
B
B
A
A
B

Quantum spin and SU(2)

Conclusion

Blocks

Three different block environments are pre-defined and may be styled with an optional background color.

Some text.

aaaaa

Default

Block content.

Alert

Block content.

Example

Block content.

Backup slides

Sometimes, it is useful to add slides at the end of your presentation to refer to during audience questions.

The best way to do this is to include the `appendixnumberbeamer` package in your preamble and call `\appendix` before your backup slides.

metropolis will automatically turn off slide numbering and progress bars for slides in the appendix. [1]

References i

R. Graham, D. Knuth, and O. Patashnik.
Concrete mathematics.
Addison-Wesley, Reading, MA, 1989.