To do so, each observer $K$ plugs into $\mathcal{V}$ the two events (which are objective) an its *own* label $K$ (since this is the only non-random choice possible).

But then two *different* observers $K$ and $K'$ will pick *different* coordinates $(t_i, \vec{x}_i)$ (measured by different clocks) to compute their value of $\vec{v}$, which obviously can yield different outcomes (as expected for velocities). Note that for the velocities to be really different it must be $[K'] \neq [K]$, i.e., the two inertial *systems* must belong to different *frames*.

- Example 2: Duration & Simultaneity

  A very natural question is how much time passed between two events $E_1$ and $E_2$. The formal prescription how to answer this question is given by the algorithm $\mathcal{T}(E_1, E_2; K)$:

  1. `Select the event` $(t_1, \vec{x}_1)_K \in E_1$.
  2. `Select the event` $(t_2, \vec{x}_2)_K \in E_2$.
  3. `Compute and return the value` $\Delta t = t_2 - t_1$.

  For the very same reason as for the velocity algorithm above, the return value of course will depend on the chosen "clock events" $(t_i, \vec{x}_i)$. And so for the very same reason that velocities can be observer-dependent, time intervals can be as well. Since we define "simultaneity" as the property $\Delta t = 0$, this possibility for observer-dependent results directly transfers to our notion of simultaneity!

Note that we did not make *quantitative* statements about the outcomes for different observers. We neither showed *how* velocities depend on the frame nor whether simultaneity really *is* relative. (It could just be the case that in our world $t_2 - t_1$ always equals $t_2' - t_1'$ for a fixed event.) This depends on the actual numbers of the coordinates. Such statements therefore require quantitative statements about the relation of $(t, \vec{x})_K \in E$ and $(t', \vec{x}')_{K'} \in E$, which we do not know at this point (this is exactly the question for the functional form of the coordinate transformation $\varphi$).

However, what we did show is the *possibility* that simultaneity is relative, just as we already expect velocities to be! So when we later find the correct transformation $\varphi$ and (surprise!) that indeed simultaneity is not an observer independent fact, you should not be surprised.

*Question:* Can the values of the electric and magnetic fields $\vec{E}$ and $\vec{B}$ be included in $\mathcal{E}$? If not, can you think of an algorithm that determines the electric and magnetic fields $\vec{E}$ and $\vec{B}$ using only coincidence data available in $\mathcal{E}$? Do you expect the electromagnetic field to be observer-dependent?

7 | Henceforth: ↓ **Lecture 3** [29.10.25]

> Unless noted otherwise, all frames will be *inertial* (with Cartesian coordinates).
> → We will (almost exclusively) work with *inertial coordinate systems*.

We use the concept of inertial systems because to describe physics by equations, coordinates are a useful tool. As it turns out, Cartesian coordinates allow for particularly simple equations (at least if space is Euclidean). So our concept of inertial systems as defined above is the most useful one.

8 | Physical Models:

Let us fix a bit of terminology:

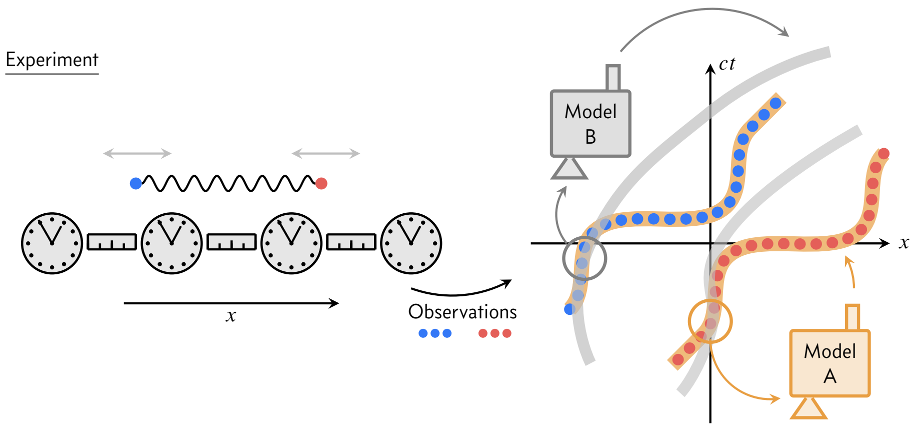
- ⁂ *(Physical) laws* are ontic features of reality (↑ *scientific realism*).

  Physical laws can only be *discovered*; they can neither be invented nor modified.

- ⁂ *(Physical) models* are algorithms used to describe reality.
  These algorithms are typically encoded in the language of mathematics.

  Physical models are *invented* and can be *modified*; I will use the terms *model* and *theory* interchangeably.

¡! These definitions are by no means conventional and you will find many variations in the literature. For the following discussion, it is only important that the terms we use have precise meaning.




¡! The validity of models cannot be *proven*; we can only gradually increase our trust in a model by repeated observations (experiments) – or reject it as invalid by demonstrating that its predictions contradict reality (↑ *Karl Popper*). Note that models might describe reality only approximately and in specific parameter regimes and still be useful.

You may dismiss this focus on terminology as "philosophical banter." Conceptual clarity, however, is absolutely crucial for science – in particular for RELATIVITY. Whenever there is confusion in physics, it is often rooted in the conceptual fuzziness of our thinking.

## 1.2. Galilei's principle of relativity

**9** | Example: Newtonian mechanics

**i** | Definition of the model:

- $\triangleleft$ Closed system of $N$ massive particles with masses $m_i$ and positions $\vec{x}_i$.
- $\triangleleft$ Force exerted by $k$ on $i$:

$$F_{k\to i}(\vec{x}_k - \vec{x}_i) = (\vec{x}_k - \vec{x}_i)\, f_{k\leftrightarrow i}(|\vec{x}_k - \vec{x}_i|) \tag{1.15}$$

It is $f_{k\leftrightarrow i} = f_{i\leftrightarrow k}$ and therefore $F_{k\to i}(\vec{x}_k - \vec{x}_i) = -F_{i\to k}(\vec{x}_i - \vec{x}_k)$.

→ *Newtonian equations of motion* (in some inertial system $K$):

$$m_i \frac{\mathrm{d}^2 \vec{X}_i}{\mathrm{d}t^2} = \sum_{k\neq i} \vec{F}_{k\to i}(\vec{X}_k - \vec{X}_i) \tag{1.16}$$

We denote with $\vec{X}_i \equiv \vec{X}_i(t)$ coordinate-valued *functions*; i.e., $\vec{x}_i = \vec{X}_i(t)$ determines a spatial point $\vec{x}_i$ for given $t$.

*Remember:* This model fully implements "Newton's laws of motion":

1. Lex prima:

> *A body remains at rest, or in motion at a constant speed in a straight line, unless acted upon by a force.*

This is the ↓ *principle of inertia*. It is part of the definition of the concept of a Newtonian force used in Eq. (1.16). Note that it is *not* a consequence of Eq. (1.16) for $F_{k\to i}\equiv 0$. It rather defines (together with the lex tertia below) the frames and coordinate systems (← *inertial systems*) in which Eq. (1.16) is valid (recall IN).

2. Lex secunda:

   > *When a body is acted upon by a net force, the body's acceleration multiplied by its mass is equal to the net force.*

   This is just the functional form of Eq. (1.16) in words.

3. Lex tertia:

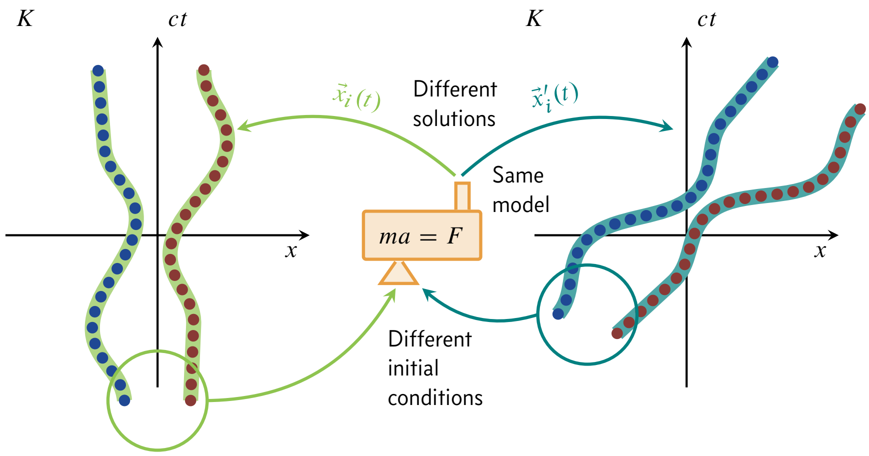
   > *If two bodies exert forces on each other, these forces have the same magnitude but opposite directions.*

   This is guaranteed by the property $F_{k\to i}=-F_{i\to k}$ of the forces. Together with the lex secunda this is an expression of momentum conservation. For two particles:

$$m_1\frac{\mathrm{d}v_1}{\mathrm{d}t}+m_2\frac{\mathrm{d}v_2}{\mathrm{d}t}=\frac{\mathrm{d}p_1}{\mathrm{d}t}+\frac{\mathrm{d}p_2}{\mathrm{d}t}=F_{2\to 1}+F_{1\to 2}=0 \tag{1.17}$$

   This implies in particular that two identical particles ($m_1=m_2$) that are both at rest at $t=0$ must obey $v_1(t)=-v_2(t)$ for all times (recall IN*).

**ii** | Application of the model:




As a working hypothesis, let us assume that the model Eq. (1.16) describes the dynamics of massive particles perfectly (from experience we know that there are at least regimes where it is good enough for all practical purposes).

**iii** | Symmetries of Newtonian mechanics:

To understand the solution space of Eq. (1.16) better, it is instructive to study transformations that map solutions to other solutions.

**a** | ⁂ *Galilei transformations*:

We define the following coordinate transformation:

$$\boxed{G\,:\,\mathbb{R}^4\to\mathbb{R}^4\,:\,(t,\vec{x})\mapsto(t',\vec{x}')\quad\begin{cases}t'=t+s\\ \vec{x}'=R\vec{x}+\vec{v}t+\vec{b}\end{cases}} \tag{1.18}$$

A Galilei transformation $G$ is characterized by 10 real parameters:

- $s \in \mathbb{R}$: Time translation (1 parameter)
- $\vec{b} \in \mathbb{R}^3$: Space translation (3 parameters)
- $\vec{v} \in \mathbb{R}^3$: Boost (3 parameters)
- $R \in \mathrm{SO}(3)$: Spatial rotation (3 parameters; rotation axis: 2, rotation angle: 1)

The set of all transformations forms (the matrix representation of) a group:

$$\mathcal{G}_+^\uparrow = \{G(R,\vec{v},s,\vec{b})\} \quad ⁂\ \textit{Proper orthochronous Galilei group} \tag{1.19}$$

with group multiplication

$$G_3 = G_1 \cdot G_2 = G(\underbrace{R_1R_2}_{R_3}, \underbrace{R_1\vec{v}_2+\vec{v}_1}_{v_3}, \underbrace{s_1+s_2}_{s_3}, \underbrace{R_1\vec{b}_2+\vec{v}_1s_2+\vec{b}_1}_{\vec{b}_3}) \tag{1.20}$$

You derive this multiplication in ➔ Problemset 1 and show that the group axioms are indeed satisfied.

As a special case, the multiplication yields the rule for addition of velocities in Newtonian mechanics:

$$G(\mathbb{1},\vec{v}_1,0,\vec{0}) \cdot G(\mathbb{1},\vec{v}_2,0,\vec{0}) = G(\mathbb{1},\underbrace{\vec{v}_1+\vec{v}_2}_{\vec{v}_3},0,\vec{0}) \tag{1.21}$$

The full Galilei group is generated by the proper orthochronous transformations together with space and time inversion:

$$\mathcal{G} = \langle \mathcal{G}_+^\uparrow \cup \{P,T\}\rangle \quad ⁂\ \textit{Galilei group} \tag{1.22a}$$

$$P:\ (t,\vec{x}) \mapsto (t,-\vec{x}) \quad \text{Space inversion (parity)} \tag{1.22b}$$

$$T:\ (t,\vec{x}) \mapsto (-t,\vec{x}) \quad \text{Time inversion} \tag{1.22c}$$

**b** | Galilei covariance & Form-invariance:

Details: ➔ Problemset 1

⊲ Coordinate transformation Eq. (1.18)

We express the total differential and the trajectory in the new coordinates:

$$\frac{\mathrm{d}}{\mathrm{d}t} = \frac{\mathrm{d}t'}{\mathrm{d}t}\frac{\mathrm{d}}{\mathrm{d}t'} = \frac{\mathrm{d}}{\mathrm{d}t'} \tag{1.23}$$

and

$$\vec{X}_i'(t') = R\vec{X}_i(t) + \vec{v}t + \vec{b} = R\vec{X}_i(t'-s) + \vec{v}(t'-s) + \vec{b} \tag{1.24a}$$

$$\Leftrightarrow \quad \vec{X}_i(t) = R^{-1}\left[\vec{X}_i'(t') - \vec{v}(t'-s) - \vec{b}\right] \tag{1.24b}$$

Note that $\vec{X}_i'(t')$ corresponds to a spacetime point $(t',\vec{x}_i')$ with $\vec{x}_i' \equiv \vec{X}_i'(t')$ which is the image $(t',\vec{x}_i') = G(t,\vec{x}_i)$ of a spacetime point $(t,\vec{x}_i)$ with $\vec{x}_i \equiv \vec{X}_i(t)$.

Thus the left-hand side of the Newtonian equation of motion Eq. (1.16) reads in new coordinates:

$$m_i\frac{\mathrm{d}^2\vec{X}_i(t)}{\mathrm{d}t^2} = m_i\frac{\mathrm{d}^2}{\mathrm{d}t'^2}R^{-1}\left[\vec{X}_i'(t') - \vec{v}(t'-s) - \vec{b}\right] = R^{-1}\,m_i\frac{\mathrm{d}^2\vec{X}_i'(t')}{\mathrm{d}t'^2} \tag{1.25}$$

Note that the quantity $m_i \frac{d^2}{dt^2}\vec{X}_i(t)$ is not *invariant*; it transforms with an $R^{-1} \in \mathrm{SO}(3)$.

And the right-hand side:

$$\sum_{k\neq i} \vec{F}_{k\to i}(\vec{X}_k(t) - \vec{X}_i(t)) = R^{-1} \sum_{k\neq i} \vec{F}_{k\to i}(\vec{X}'_k(t') - \vec{X}'_i(t')) \tag{1.26a}$$

Here we used the form of the force Eq. (1.15), that $\vec{X}_k(t) - \vec{X}_i(t) = R^{-1}[\vec{X}'_k(t') - \vec{X}'_i(t')]$ and $|\vec{X}_k(t) - \vec{X}_i(t)| = |\vec{X}'_k(t') - \vec{X}'_i(t')|$ because of $R \in \mathrm{SO}(3)$.

Note that the force on the right-hand side is not *invariant* either; luckily, it transforms with *the same* $R^{-1} \in \mathrm{SO}(3)$; it "co-varies" with the left-hand side!

In conclusion, Newton's equation of motion Eq. (1.16) reads in the new coordinates:

$$\underbrace{R^{-1}\, m_i \frac{d^2 X'_i(t')}{dt'^2} = R^{-1} \sum_{k\neq i} \vec{F}_{k\to i}(\vec{X}'_k(t') - \vec{X}'_i(t'))}_{\to\ \textit{Covariance}} \tag{1.27a}$$

$$\overset{\times R}{\Leftrightarrow} \quad \underbrace{m_i \frac{d^2 X'_i(t')}{dt'^2} = \sum_{k\neq i} \vec{F}_{k\to i}(\vec{X}'_k(t') - \vec{X}'_i(t'))}_{\to\ \textit{Form-invariance}} \tag{1.27b}$$

(You can easily check that this holds for $P$ and $T$ as well.)

$\rightarrow$

Newton's EOMs Eq. (1.16) are *form-invariant* under Galilei transformations.

*Or:* Newton's EOMs Eq. (1.16) are Galilei-*covariant*.

### ↓ Interlude: Nomenclature

Let $X$ be some group of coordinate transformations (here: $X = \mathcal{G}$ the Galilei group).

- A *quantity* is called $X$-*invariant* if it does not change under the coordinate transformation. Such quantities are called $X$-*scalars*.

  An example is the mass $m$ in Eq. (1.16) (which is also constant).

- A *quantity* is called $X$-*covariant* if it transforms under some given representation of the $X$-group. If this representation is the trivial one (i.e., the quantity does not change at all) this particular $X$-covariant quantity is then also an $X$-scalar.

  An example of a Galilei-covariant (but not invariant) quantity is the force $\vec{F}_{k\to i}$ which transforms under a representation of $\mathcal{G}$.

- An *equation* is called $X$-*covariant* if the quantity on the left-hand side and on the right-hand side are $X$-covariant (under the same $X$-representation).

  An example is Newton's lex secunda Eq. (1.16) where $m_i \frac{d^2}{dt^2} x_i(t)$ transforms in the same (non-trivial) representation as $\vec{F}_{k\to i}$.

- $X$-covariant *equations* have the feature that a $X$-transformation leaves them *form-invariant*, i.e., they "look the same" after $X$-transformations because their left- and right-hand side vary in the same way (they "co-vary"). Note that the quantities in a form-invariant equation do not have to be *invariant*.

  An example is again Eq. (1.16) as we just showed. Note that $\vec{x}'_i(t')$ and $\vec{x}_i(t)$ are *different* vectors such that the two sides of the equation as not *in*variant (but *co*variant).

c | Active symmetries:

There is something additional and particularly useful to be learned from the coordinate transformation above. We showed:

$$\text{If} \quad \vec{X}_i(t) \quad \text{satisfies} \quad m_i \frac{\mathrm{d}^2 \vec{X}_i(t)}{\mathrm{d}t^2} = \sum_{k \neq i} \vec{F}_{k\to i}(\vec{X}_k(t) - \vec{X}_i(t)) \tag{1.28a}$$

$$\text{then} \quad \vec{X}'_i(t') \quad \text{satisfies} \quad m_i \frac{\mathrm{d}^2 \vec{X}'_i(t')}{\mathrm{d}t'^2} = \sum_{k \neq i} \vec{F}_{k\to i}(\vec{X}'_k(t') - \vec{X}'_i(t')) \tag{1.28b}$$

But $t'$ in the lower statement is just a dummy variable that can be renamed to whatever we want:

$$\text{If} \quad \vec{X}_i(t) \quad \text{satisfies} \quad m_i \frac{\mathrm{d}^2 \vec{X}_i(t)}{\mathrm{d}t^2} = \sum_{k \neq i} \vec{F}_{k\to i}(\vec{X}_k(t) - \vec{X}_i(t)) \tag{1.29a}$$

$$\text{then} \quad \vec{X}'_i(t) \quad \text{satisfies} \quad m_i \frac{\mathrm{d}^2 \vec{X}'_i(t)}{\mathrm{d}t^2} = \sum_{k \neq i} \vec{F}_{k\to i}(\vec{X}'_k(t) - \vec{X}'_i(t)) \tag{1.29b}$$

Use colors to highlight the changes.

→ $\vec{X}'_i(t) = R\vec{X}_i(t-s) + \vec{v}(t-s) + \vec{b}$ is a *new solution* of Eq. (1.16)!

Note that for $s = 0$ it is $\vec{X}'_i(0) = R\vec{X}_i(0) + \vec{b}$ and $\dot{\vec{X}}_i(0) = R\dot{\vec{X}}_i(0) + \vec{v}$, i.e., the solution $\vec{X}'_i(t)$ satisfies different initial conditions.

→ We say:

The Galilei group $\mathscr{G}$ is an ⁂ *invariance group* or an *(active) symmetry* of Eq. (1.16).

**↓ Interlude: Active and passive transformations**

It is important to understand the conceptual difference between the two last points:

- In the previous step we took a specific trajectory (solution of Newton's equation) and expressed it in different coordinates. We then found that the differential equation obeyed by *the same physical trajectory* in these new coordinates "looks the same" as in the old coordinates. We called this peculiar feature of the differential equation "Galilei-covariance" or "form-invariance". This type of a transformation is called *passive* because we keep the physics the same and only change our description of it.
- In the last step, we have shown that there is a dual interpretation to this: If a differential equation is form-invariant under a coordinate transformation, then we can exploit this fact to construct *new solutions* from given solutions (in the same coordinate system!). This type of transformation is called *active* because we keep the coordinate frame fixed and actually *change the physics*. You can therefore think of active transformations/symmetries as "algorithms" to construct new solutions of a differential equation (a quite useful feature since solving differential equations is often tedious).

10 | Galilean relativity:

i | Remember:

The law of inertia holds (by definition) in all inertial systems.

→ The "inertial test" IN cannot be used to distinguish inertial systems.

This is a tautological statement because we *define* inertial systems in this way!

*Empirical fact:*

*Every* mechanical experiment (not just the "inertial test") yields the same result in all inertial systems.

This is not a tautology but an empirically tested feature of reality.

This motivates the following postulate (first given by Galileo Galilei):

> **§ Postulate 2: Galilei's principle of Relativity GR**
>
> No mechanical experiment can distinguish between inertial systems.

¡! In this formulation, GR encodes a (so far uncontested) empirical fact. In particular, it does neither refer nor rely on (the validity of) any *physical model*, e.g., Newtonian mechanics. As such we should expect that it survives our transition to SPECIAL RELATIVITY.

Here is a more operational formulation of GR: You describe a detailed experimental procedure using equipment governed by mechanics (springs, pendula, masses, ...) that can be performed in a closed (but otherwise perfectly equipped) laboratory. Then you copy these instructions without modifications and hand them to scientists with labs in different inertial systems. They all perform your instructions and get some results (e.g. the final velocities of a complicated contraption of pendula). When they report back to you, their results will all be identical. This is the essence of GR.

ii | In the language of *models* that describe the mechanical laws faithfully, GR can be reformulated:

> **§ Postulate 3: Galilei's principle of Relativity GR'**
>
> The equations that describe mechanical phenomena *faithfully* have the same form in all inertial systems.

If this would not be the case you could distinguish between different inertial systems by checking which formula you have to use to describe your observations. Imagine a rotating (non-inertial) frame where you have to use a modified version of Newton's EOMs (that include additional terms for the Coriolis force) to describe your observations.

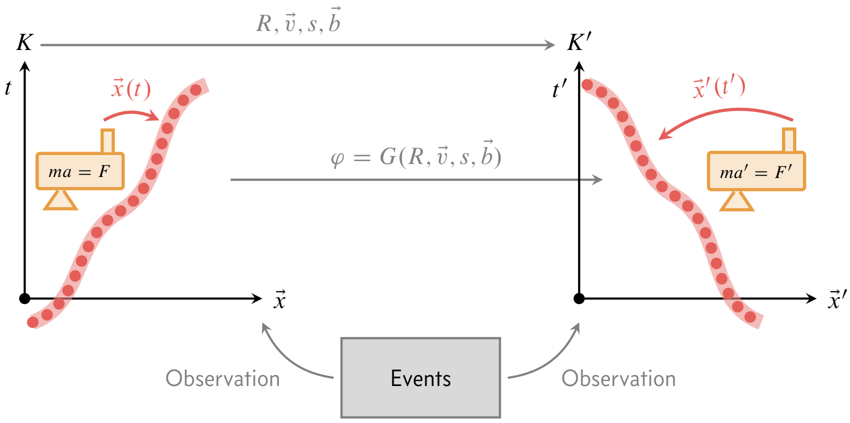
Note that "the same form" actually means that the models are *functionally equivalent* (have the same solution space). Functional equivalence is equivalent to the *possibility* to formulate the model (= equation of motion) in the same form.

iii | *Under the assumption* (!) that Newtonian physics (in particular Eq. (1.16)) describes mechanical phenomena *faithfully*, this implies:

*Newton's equations of motion have the same form in all inertial systems.*

¡! This statement is *not* equivalent to `GR` or `GR'` as it relies on an independent empirical claim (namely the validity of Newton's equation as a model of mechanical phenomena).

We can now combine this claim with our (purely mathematical!) finding concerning the invariance group of Newton's equations:




→ Preliminary/Historical conclusion:

$$\boxed{\varphi(K \xrightarrow{R,\vec{v},s,\vec{b}} K') \stackrel{?}{=} G^{-1}(R,\vec{v},s,\vec{b}) \in \mathscr{G}}$$

Recall that rotating the coordinate *axes* by $R$ makes the coordinates of fixed events rotate in the *opposite* direction $R^{-1}$ (the same is true for the other transformations). Thus we must use the *inverse* Galilei transformation $G^{-1}$ for the mapping $(t, \vec{x}) \mapsto (t', \vec{x}')$ from $K$ to $K'$.

Note that due to the semi-direct product structure of $\mathscr{G}_+^\uparrow$ [recall Eq. (1.20)] it is $G^{-1}(R,\vec{v},s,\vec{b}) \stackrel{\circ}{=} G(R^{-1}, -R^{-1}\vec{v}, -s, -R^{-1}(\vec{b} - s\vec{v}))$ for a generic Gaililei transformation (➔ Problemset 1). Only for special cases (where only one of the four transformations is non-trivial) this simplifies as one would expect, e.g., $G^{-1}(R,\vec{0},0,\vec{0}) = G(R^{-1},\vec{0},0,\vec{0})$.

Since this is a course on RELATIVITY, we should be skeptical (like Einstein) and ask:

$\boxed{\text{Is this true?}}$

## 1.3. Einstein's principle of special relativity

11 | <u>Mathematical fact:</u>

$\boxed{\text{The Maxwell equations of electrodynamics are } \textit{not} \text{ Galilei-covariant.}}$

Proof: ➔ Problemset 1

Here for your (and my) convenience the Maxwell equations in vacuum (in cgs units):

$$\text{Gauss's law (electric):} \quad \nabla \cdot \boldsymbol{E} = 0 \tag{1.30a}$$

$$\text{Gauss's law (magnetic):} \quad \nabla \cdot \boldsymbol{B} = 0 \tag{1.30b}$$

$$\text{Law of induction:} \quad \nabla \times \boldsymbol{E} = -\frac{1}{c}\partial_t \boldsymbol{B} \tag{1.30c}$$

$$\text{Ampère's circuital law:} \quad \nabla \times \boldsymbol{B} = \frac{1}{c}\partial_t \boldsymbol{E} \tag{1.30d}$$

"Handwavy explanation" for the absence of Galilei symmetry:

The Maxwell equations imply the wave equation for both fields:

$$\left(\nabla^2 - \frac{1}{c^2}\partial_t^2\right)\boldsymbol{X} = \boldsymbol{0} \quad \text{for } \boldsymbol{X} \in \{\boldsymbol{E}, \boldsymbol{B}\}\,. \tag{1.31}$$

Here the speed of light $c$ plays the role of the phase and group velocity of the waves; i.e., all light signals propagate with $c$. Form-invariance under some coordinate transformation $\varphi$ implies that the same light signal propagates with *the same velocity* $c$ in all coordinate systems related by $\varphi$. This is clearly incompatible with the Galilean law for adding velocities (according to which a signal with velocity $u'_x$ in frame $K'$ propagates with velocity $u_x = u'_x + v_x$ in frame $K$ if $K \xrightarrow{v_x} K'$).

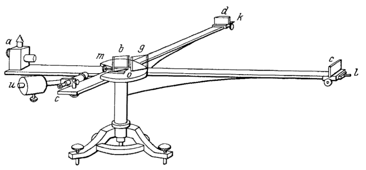
**12** | The simplest escape from our predicament:

*Maybe there is no relativity principle for electrodynamics?*

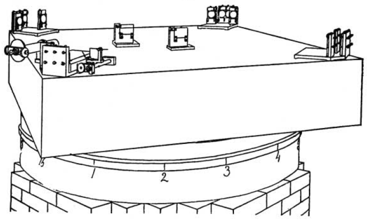
*Reasoning:* If we cling to the validity of Newtonian mechanics and Galilean relativity GR, we are forced to assume $\varphi = G$ as the transformation between inertial systems. Since the Maxwell equations are *not* form-invariant under these transformations, they look differently in different inertial systems. So there must be a (class of) designated inertial coordinate systems $[K_0]$ in which the Maxwell equations in the specific form Eq. (1.30) you've learned in your electrodynamics course are valid.

→ $[K_0]$ = Frame in which the *"luminiferous aether"* is at rest (?)

**13** | Michelson Morley experiment (plots from [29,30]):



Michelson's original setup (1881)



Michelson & Morley's improved setup (1887)

→ The (two-way) speed of light is the same in all directions.

→ There is no "luminiferous aether" $[K_0]$.
(Or it is pulled along by earth – which contradicts the observed ↑ *aberration of light*.)

→ The speed of light $c$ *cannot* be fixed wrt. some designated reference frame $[K_0]$.

→ *No experimental evidence* that the Maxwell equations *do not hold* in all inertial systems.

→ *Relativity principle* for electrodynamics?!

- Historical note:

  A. Einstein writes in a letter to F. G. Davenport (see Ref. [31]):

> *[...] In my own development Michelson's result has not had a considerable influence. I even do not remember if I knew of it at all when I wrote my first paper on the subject (1905). The explanation is that I was, for general reasons, firmly convinced how this could be reconciled with our knowledge of electro-dynamics. One can therefore understand why in my personal struggle Michelson's experiment played no role or at least no decisive role.*

→ The Michelson Morley experiment did *not* kickstart SPECIAL RELATIVITY.

- Modern Michelson-Morley like tests of the isotropy of the speed of light achieve much higher precision than the original experiment. The authors of Refs. [32, 33], for example, report an upper bound of $\Delta c/c \sim 10^{-17}$ on potential anisotropies of the speed of light by rotating optical resonators.

↓ **Lecture 4** [05.11.25]

**14** | Two observations:

(1) *No* evidence that there is *no* relativity principle for electrodynamics.

(2) Why does Galilean relativity GR treat mechanics differently anyway?

Put differently: Why should mechanics, a branch of physics artificially created by human society, be different from any other branch of physics? This is not impossible, of course, but it certainly lacks simplicity! (To Galilei's defence: At his time "mechanics" was more or less identical to "physics".)

→ A. Einstein writes in §2 of Ref. [10] as his first postulate:

> *1. Die Gesetze, nach denen sich die Zustände der physikalischen Systeme ändern, sind unabhängig davon, auf welches von zwei relativ zueinander in gleichförmiger Translationsbewegung befindlichen Koordinatensystemen diese Zustandsänderungen bezogen werden.*

We reformulate this into the following postulate:

> **§ Postulate 4: (Einstein's principle of) Special Relativity** SR
>
> No ~~mechanical~~ experiment can distinguish between inertial systems.

Note the difference to Galilean relativity GR according to which no experiment *governed by classical mechanics* can distinguish between inertial systems. Einstein simply extended this idea to all of physics – no special treatment for mechanics!

¡! There are various names used in the literature to refer to SR. Here we call it the principle of *special* relativity, where the "special" refers to its restriction on *inertial systems* – as compared to the principle of *general* relativity in GENERAL RELATIVITY that refers to *all* frames (→ *later*). To emphasize its difference to Galilean relativity GR, some authors call SR the *universal* principle of relativity, where "universal" refers to its applicability on *all* laws of nature (not just the realm of classical mechanics).

**15** | But now that there are more contenders (mechanics, electrodynamics, quantum mechanics) all of which must be invariant under the same transformation $\varphi$, we have to open the quest for $\varphi$ again:

$$\boxed{\text{What is } \varphi?}$$