

# Thoughts & experiments in introductory-physics teaching

$$\frac{dE}{dt} = \Phi + \mathcal{R}$$

$$\frac{dP}{dt} = \mathbf{F} + \mathbf{G}$$

$$\frac{dL}{dt} = \mathbf{M} + \mathcal{T}$$



HVL - Western Norway University of Applied Sciences



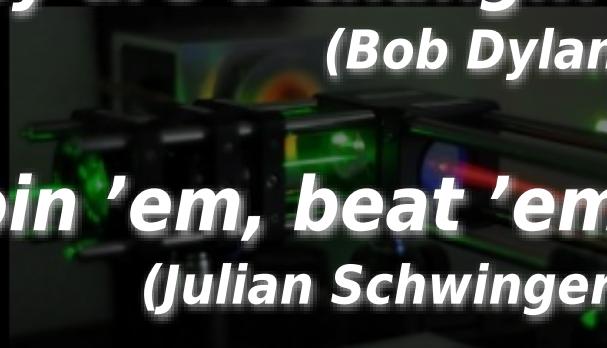
Luca Porta-Mana

HVL - Western Norway University of Applied Sciences



**The times they are a-changin'**

(Bob Dylan)



**If you can't join 'em, beat 'em**

(Julian Schwinger)



$$\frac{dN}{dt} = J$$

$$\frac{dQ}{dt} = I$$

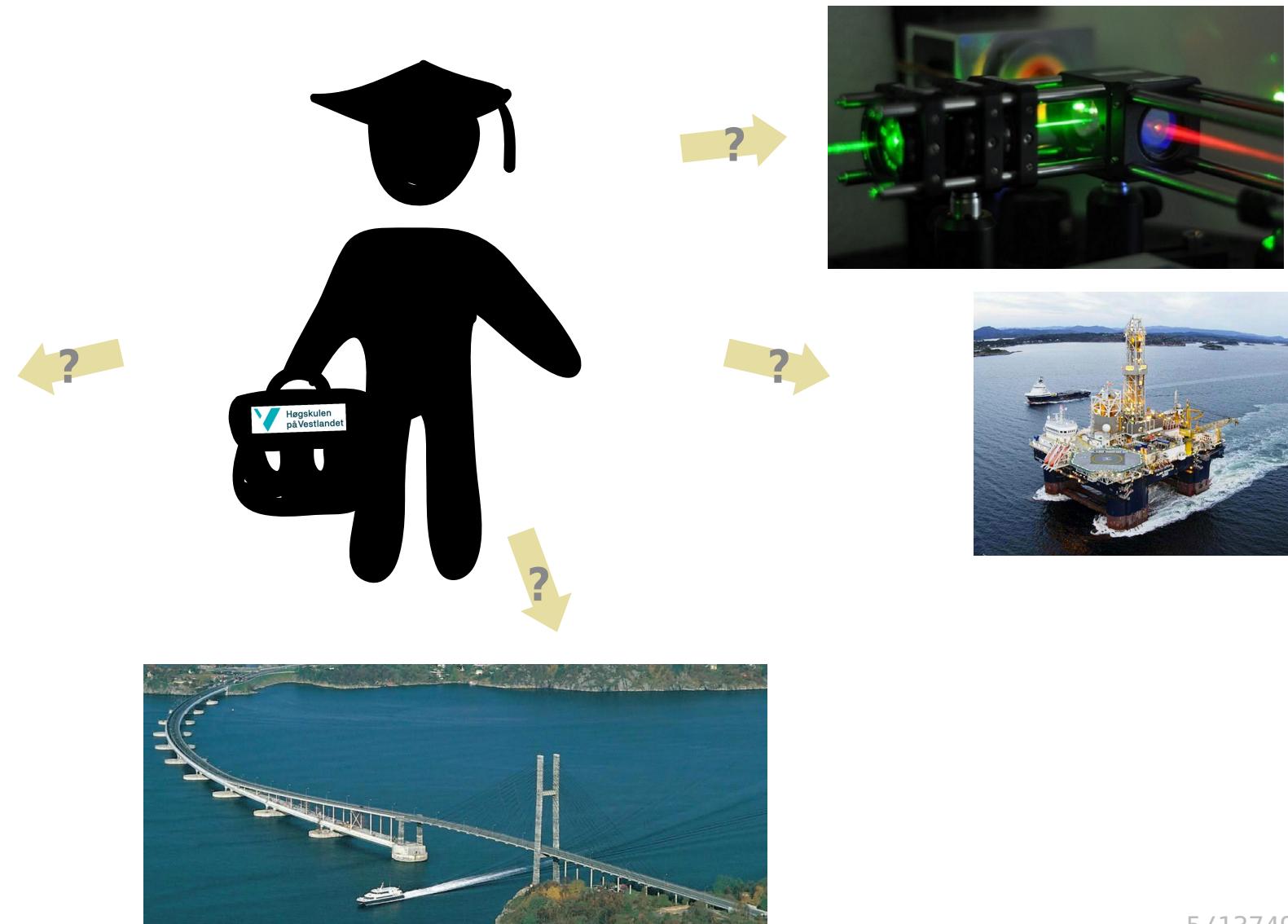
$$\frac{d\mathcal{B}}{dt} = -\mathcal{E}$$

$$\frac{dS}{dt} \geq \Psi$$

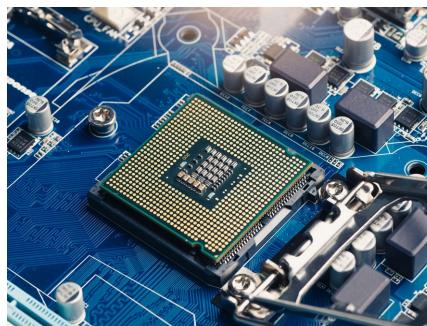
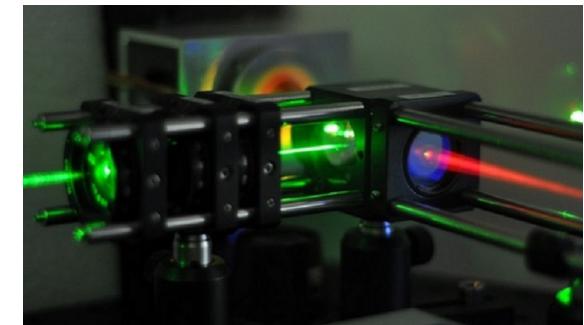
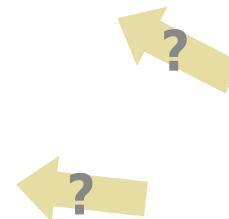
Current challenges & changes  
that should impact introductory-physics courses













## Mekanikk for ingeniørar

Inngår i:

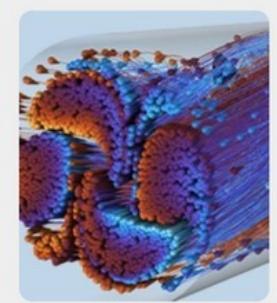
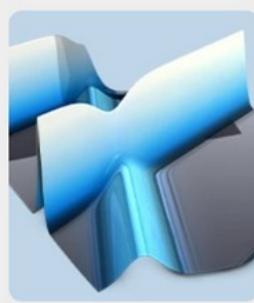
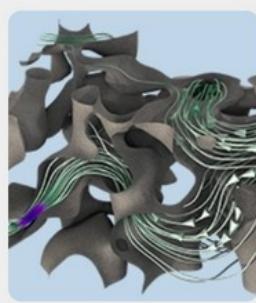
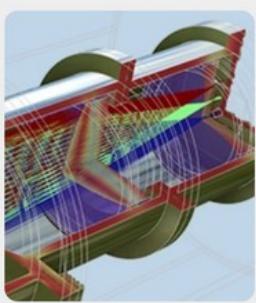
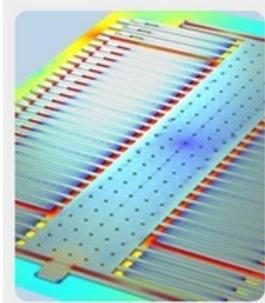
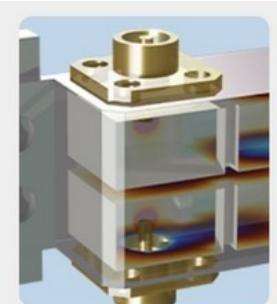
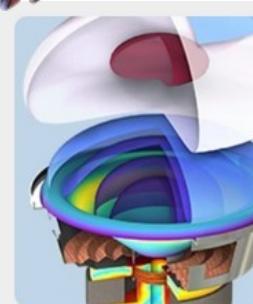
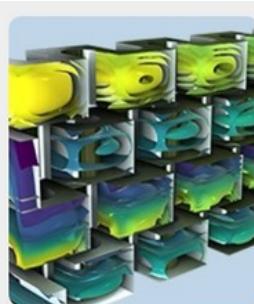
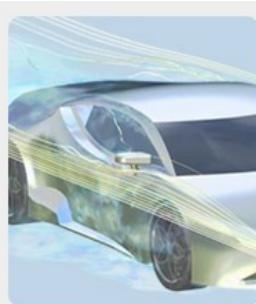
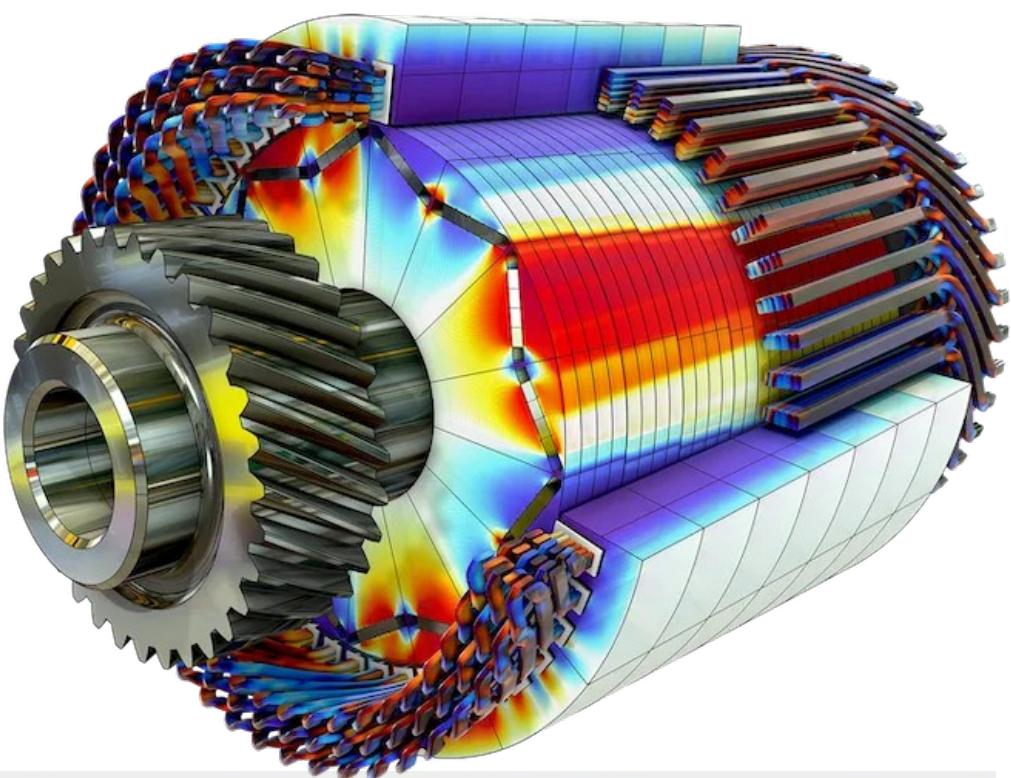
- › Dataingeniør      Data engineer
- › Elektroingeniør      Electrical engineer
- › Branningeniør      Fire-safety engineer
- › Byggingeniør      Building engineer
- › Kjemiingeniør      Chemical engineer
- › Maskiningeniør      Mechanical engineer



# 'Multiphysics'

Need for de-compartmentalization

Need for a bird-eye view



## multiphysics CYCLOPEDIA

### [Home](#)

#### [Physics, PDEs, and Numerical Modeling](#)

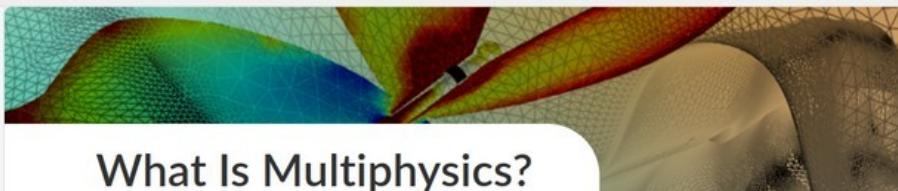
- [Finite Element Method](#)
  - [FEA Software](#)
- [Mesh Refinement](#)
- [HPC](#)

#### [Electromagnetics](#)

- [Electrostatics](#)
- [Steady Currents](#)
- [Magnetostatics](#)
- [Electroquasistatics](#)
- [Electromagnetic Waves](#)
- [Joule Heating Effect](#)
- [Microwave Heating](#)
- [Induction Heating](#)
- [Electromechanical Effects](#)
  - [Piezoelectricity](#)
  - [Piezoresistivity](#)

#### [Structural Mechanics](#)

- [Analysis of Deformation](#)
- [Stress and Equations of Motion](#)
- [Eigenfrequency Analysis](#)
- [Mode Superposition](#)
- [Response Spectrum Analysis](#)
- [Material Fatigue](#)
- [Thermal Expansion and Thermal](#)



## What Is Multiphysics?

***Multiphysics*** *mul-ti-fiz-iks* [mul-ti-fiz-iks] noun

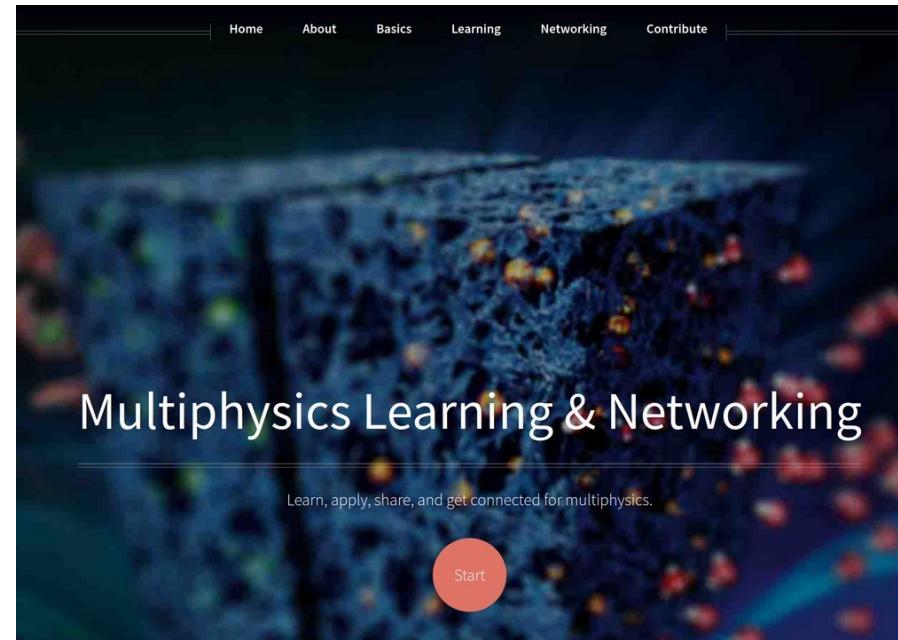
1. Coupled physical phenomena in computer simulation.
2. The study of multiple interacting physical properties.

## *Understanding Physics*

We can describe what happens in the world using sets of physical laws. Since the 1940s, we have been using computers to understand physical phenomena. Originally, computing resources were scarce, so physical effects were observed in isolation. But, as we know, physics do not occur in isolation in the real world.

## *It's a Multiphysics World*

The real world is multiphysics in nature.



## Hottest

History, Definition and Scope

Types of Multiphysics

Partial Differential Equation

Conservation Law

Mechanical Field

Books

Online Courses

Events

Forum

[Learn More](#)

## History, Definition and Scope

### Introduction to Multiphysics

We live in a multiphysics world. Real-life processes are inherently multiphysics. From atoms to galaxies, from amino-acids to living organisms, naturally built systems involve various types of physical phenomena operating at different spatial and temporal scales. We have been dealing with this multiphysics world even before the civilization of human beings. For example, a nature fire from lightning is a typical electrostatic, thermal, and chemical phenomenon. Fire starting with a hand drill involves both mechanical and thermal processes. Surprisingly, while multiphysics is part of nature and history of lives, the study of multiphysics, is not new either. Despite the studies which are by nature multiphysics but were not traditionally counted, multiphysics research has been on the playground for a couple of decades.



## Newest

 Website Updates

This website is tentatively released for internal testing.

## Newest

### Website Updates

This website is tentatively released for internal testing. The website is still under construction.



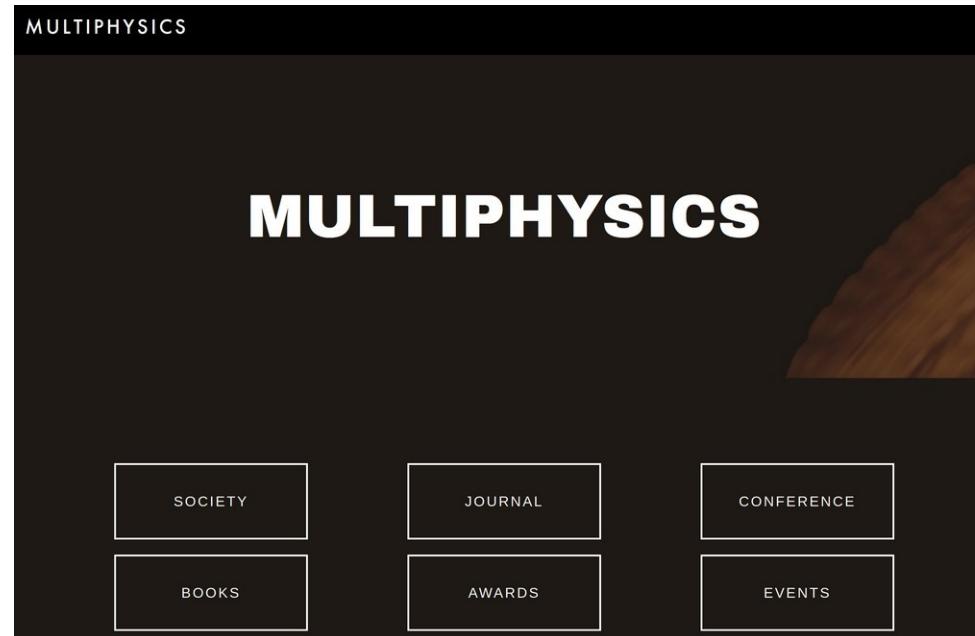
### Announcements

We are looking for support for the further development of this website. Sponsors will be showcased on the home page, bottom of every other page, or/and lists of sponsors and supporters.

[Learn More](#)

Multiphysics.us is structured in the way illustrated in the following figure. This **About** page gives out the basic information. Please visit the pages under **Basics** if you want to know about the basic theories of multiphysics including the necessary background knowledge, mathematics, monolithic physics, multiphysics, and implementations. More systematic and advanced knowledge can be found on the pages under **Learning**. You can also locate information for multiphysics research such as benchmark problems on these pages. Information about who are working on multiphysics and how to get connected to them can be found on the pages under **Networking**. To contribute to the further development of multiphysics.us, please check the pages under **Contribute**. You will find ways to donate to and to contact the website management and development team. Lists of sponsors and supporters can be also found there.





**MULTIPHYSICS**

## About Us

Multiphysics analysis has been developed over the recent past to better represent the behaviour of complex processes by the use of simultaneous modelling of a number of systems. This development is driven by the industrial need to further the understanding of real physical phenomena in order to develop and design safer and more efficient products which are environmentally friendly. Such analyses and investigations were impossible to perform in the past due to a lack of powerful computing systems.

The scope of the society is to address the latest advances in theoretical developments, numerical modelling and industrial applications which will promote the concept of simultaneous engineering. Typical combinations would involve a selection from subject disciplines such as Fluid, Structure, Explosive, Thermal, Acoustic, Magnetic and other similar disciplines.

**Aim and Objectives:**

The aim of the society is to enable all those interested in Multiphysics to discuss and disseminate the most up-to-date research findings for purposes of product and process improvements. This encompasses maximisation of Multiphysics dialogue across international borders at all levels, collaboration between researchers, institutions, industry and governments, and development of curriculum for the higher education sectors worldwide.

The objectives of the society encompass:

- maximisation of multiphysics dialogue across international borders at all levels,
- collaboration between researchers, institutions, industry and governments,
- development of curriculum for the higher education sectors worldwide.

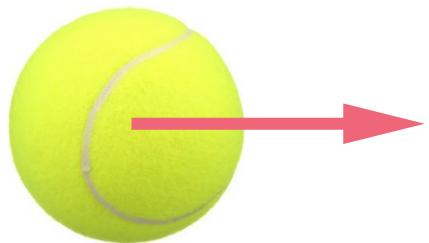
**MULTIPHYSICS**

## Society

A Venn diagram consisting of four overlapping circles. The circles are colored and labeled: "Fluid" (top), "Magnetic" (top-left), "Structure" (top-right), "Explosive" (bottom-right), "Thermal" (bottom), and "Acoustic" (bottom-left). The overlapping areas between the circles represent the combined fields of study, such as the intersection of Fluid and Magnetic being "Magnetic" and the intersection of all four being "Structure".

The International Society of Multiphysics acts as a focus for studies which demand simultaneous addressing of hitherto separate physical disciplines and combining them to generate relational mathematical models and validate them with controlled experiments to enhance the understanding of natural behaviour with a view to improving the quality of lives and promote an environmentally sustainable future.

## *Traditional intro-physics*

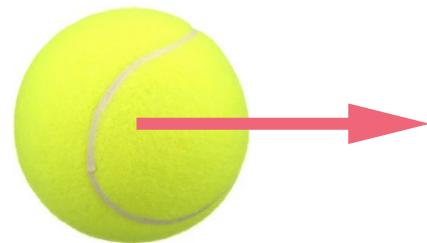


‘Bodies’  
‘Properties’ of bodies

“momentum of the tennis ball”  
“energy of the tennis ball”

...

## *Traditional intro-physics*



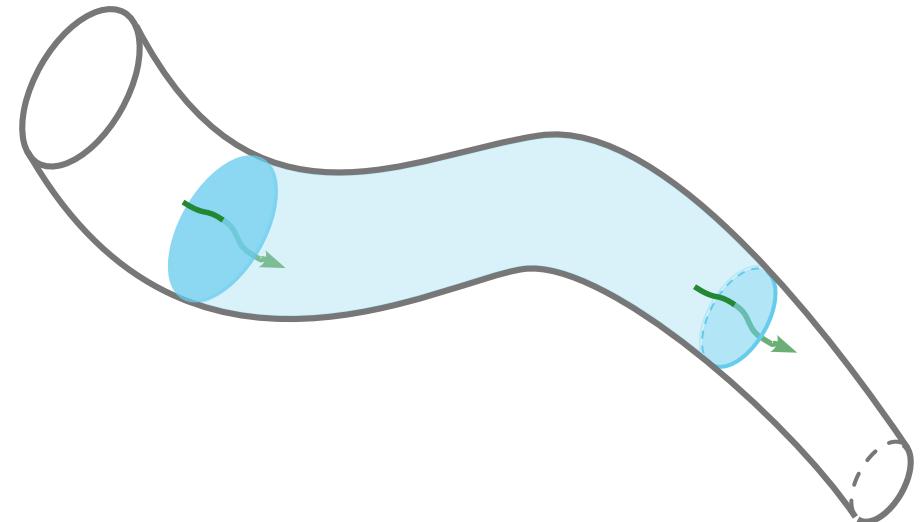
‘Bodies’  
‘Properties’ of bodies

“momentum of the tennis ball”  
“energy of the tennis ball”

...

## *Multi-physics*

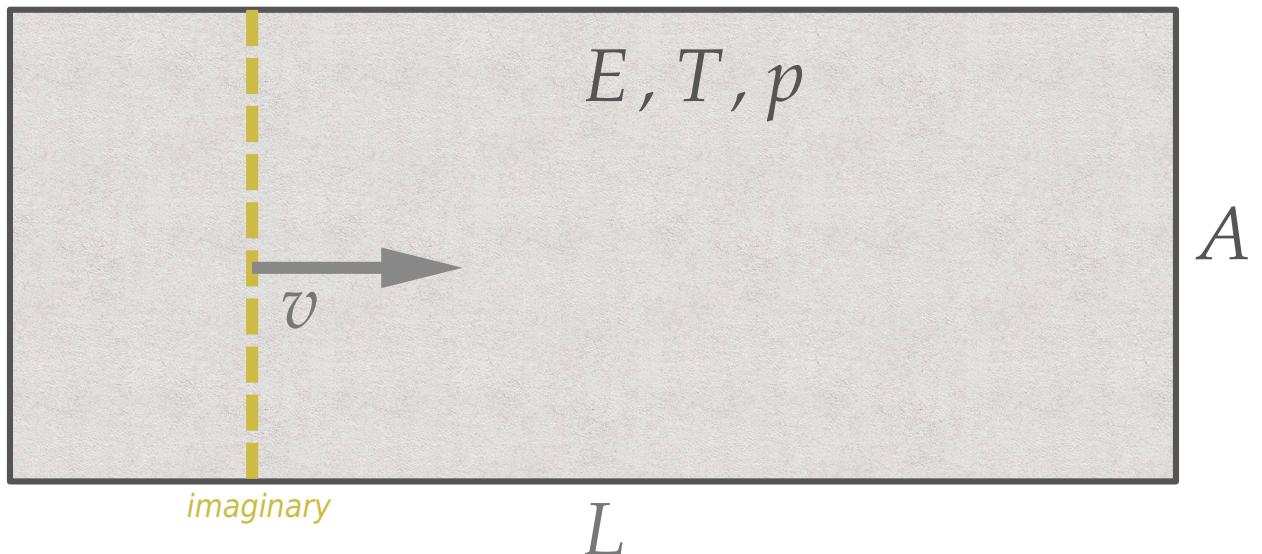
*fluid mechanics  
building engineering  
electromagnetics  
aerospace engineering  
thermochemistry*

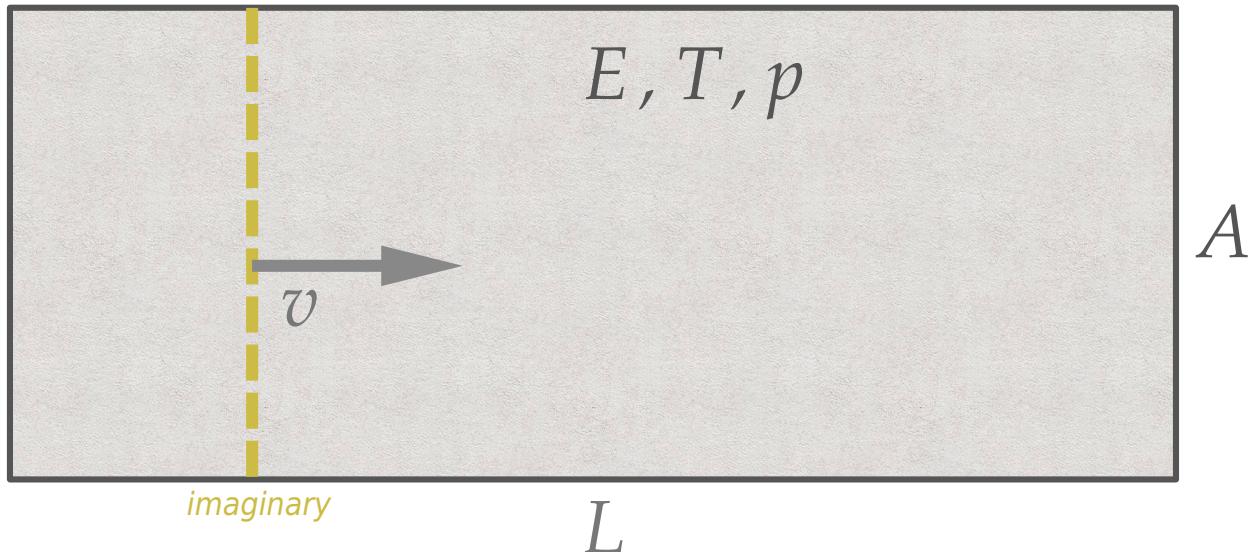


‘Control volumes’  
‘Contents’, ‘fluxes’, ...

“momentum flux through surface”  
“energy within volume”

...





how much is the flux of energy through the surface?

# Large Language Models are redefining ‘knowledge’ and ‘skills’



GPT UIO

New chat

Recent See all conversations →

For the follo... Save Edit Delete

P Voltaic Cell Breakdown  
GPT-4 Omni base

P For the following reaction, explain the structure of the corresponding voltaic cell, including the anode, cathode, and the flow of electrons. Balance the equation and calculate  $E^\circ_{\text{cell}}$ . Give a brief answer and don't use latex macros:  
 $\text{Zn(s)} + \text{Ag}^+(\text{aq}) \rightarrow \text{Ag(s)} + \text{Zn}^{2+}(\text{aq})$

C The balanced equation for the reaction is:  
 $\text{Zn(s)} + 2\text{Ag}^+(\text{aq}) \rightarrow 2\text{Ag(s)} + \text{Zn}^{2+}(\text{aq})$

Voltaic Cell Structure:

- Anode: Zinc (Zn) electrode, where Zn(s) is oxidized to Zn<sup>2+</sup>(aq).
- Cathode: Silver (Ag) electrode, where Ag<sup>+</sup>(aq) is reduced to Ag(s).
- Electron Flow: Electrons flow from the anode (Zn) to the cathode (Ag) through the external circuit.

Standard Electrode Potentials:

- $E^\circ(\text{Ag}/\text{Ag}) = +0.80 \text{ V}$
- $E^\circ(\text{Zn}^{2+}/\text{Zn}) = -0.76 \text{ V}$

Calculate  $E^\circ_{\text{cell}}$ :  $E^\circ_{\text{cell}} = E^\circ_{\text{cathode}} - E^\circ_{\text{anode}} = 0.80 \text{ V} - (-0.76 \text{ V}) = 1.56 \text{ V}$

Send a message

Generated text might contain errors or inaccuracies. Read more about limitations on our guidance pages.

For the following reaction, explain the structure of the corresponding voltaic cell, including the anode, cathode, and the flow of electrons. Balance the equation and calculate  $E^\circ_{\text{cell}}$ . Give a brief answer and don't use latex macros:



First, let's balance the given equation. The balanced reaction is:  $\text{Zn(s)} + 2\text{Ag}^+(\text{aq}) \rightarrow 2\text{Ag(s)} + \text{Zn}^{2+}(\text{aq})$ .

In a voltaic cell, the anode is where oxidation occurs and the cathode is where reduction occurs. For this reaction:

- Anode:  $\text{Zn(s)} \rightarrow \text{Zn}^{2+}(\text{aq}) + 2e^-$ .
- Cathode:  $2\text{Ag}^+(\text{aq}) + 2e^- \rightarrow 2\text{Ag(s)}$ .

The electrons flow from the anode to the cathode.

To calculate the standard cell potential ( $E^\circ_{\text{cell}}$ ), we need the standard electrode potentials for both half-reactions:

- $E^\circ$  for  $\text{Zn}^{2+}/\text{Zn}$  is -0.76 V.
- $E^\circ$  for  $\text{Ag}^+/\text{Ag}$  is +0.80 V.

The standard cell potential is calculated as:  $E^\circ_{\text{cell}} = E^\circ_{\text{cathode}} - E^\circ_{\text{anode}}$   $E^\circ_{\text{cell}} = 0.80 \text{ V} - (-0.76 \text{ V}) = 0.80 \text{ V} + 0.76 \text{ V} = 1.56 \text{ V}$ .

So, the structure of the voltaic cell includes:

- Anode: Zinc electrode ( $\text{Zn(s)}$ ).
- Cathode: Silver electrode ( $\text{Ag(s)}$ ).
- The salt bridge connects the two solutions to maintain charge balance.
- Electrons flow from the zinc electrode (anode) to the silver electrode (cathode).
- Ions move in the aqueous solutions:  $\text{Zn}^{2+}$  accumulates near the anode and  $\text{Ag}^+$  is reduced to  $\text{Ag}$  near the cathode.

Standard cell potential,  $E^\circ_{\text{cell}}$ , is 1.56 V.

*GPT-4 Omni*

*answer given in  
around 2 seconds:*

Tell me the definition of Standard Cell Potential

GPT-4 Omni

answer given in  
1 second:



The standard cell potential (denoted as  $E^\circ_{\text{cell}}$ ) is the measure of the electromotive force (EMF) or voltage of a voltaic cell when it operates under standard conditions. Standard conditions are defined as:

- A temperature of 25°C (298 K).
- A pressure of 1 atmosphere (1 atm) for any gases involved.
- Concentrations of 1 Molar (1 M) for all aqueous solutions.

$E^\circ_{\text{cell}}$  is calculated using the standard electrode potentials of the half-reactions involved in the cell. It is determined by subtracting the standard reduction potential of the anode (where oxidation occurs) from the standard reduction potential of the cathode (where reduction occurs).

Mathematically, it is expressed as:  $E^\circ_{\text{cell}} = E^\circ_{\text{cathode}} - E^\circ_{\text{anode}}$

A positive  $E^\circ_{\text{cell}}$  indicates that the cell reaction is spontaneous under standard conditions.

Tell me the definition of Standard Cell Potential

GPT-4 Omni

answer given in  
1 second:



The standard cell potential (denoted as  $E^\circ_{\text{cell}}$ ) is the measure of the electromotive force (EMF) or voltage of a voltaic cell when it operates under standard conditions. Standard conditions are defined as:

- A temperature of 25°C (298 K).
- A pressure of 1 atmosphere (1 atm) for any gases involved.
- Concentrations of 1 Molar (1 M) for all aqueous solutions.

$E^\circ_{\text{cell}}$  is calculated using the standard electrode potentials of the half-reactions involved in the cell. It is determined by subtracting the standard reduction potential of the anode (where oxidation occurs) from the standard reduction potential of the cathode (where reduction occurs).

Mathematically, it is expressed as:  $E^\circ_{\text{cell}} = E^\circ_{\text{cathode}} - E^\circ_{\text{anode}}$

A positive  $E^\circ_{\text{cell}}$  indicates that the cell reaction is spontaneous under standard conditions.

*Isn't this the kind of 'knowledge' and 'skills' that we're effectively giving to, and testing on, our students?*

In the popular treatise, whatever shreds of the science are allowed to appear, are exhibited in an exceedingly diffuse and attenuated form, apparently with the hope that the mental faculties of the reader [...] may insensibly become saturated with scientific phraseology [...]. In this way, by simple reading, the student may become possessed of the phrases of the science without having been put to the trouble of thinking a single thought about it. The loss implied in such an acquisition can be estimated only by those who have been compelled to unlearn a science that they might at length begin to learn it.

*J. Clerk Maxwell, 1878*

In the popular treatise, whatever shreds of the science are allowed to appear, are exhibited in an exceedingly diffuse and attenuated form, apparently with the hope that the mental faculties of the reader [...] may insensibly become saturated with scientific phraseology [...]. In this way, by simple reading, the student may become possessed of the phrases of the science without having been put to the trouble of thinking a single thought about it. The loss implied in such an acquisition can be estimated only by those who have been compelled to unlearn a science that they might at length begin to learn it.

*J. Clerk Maxwell, 1878*

Do we, in our schools and colleges, foster the spirit of inquiry, of skepticism, of adventurous thinking, of acquiring experience and reflecting on it? Or do we place a premium on docility, giving major recognition to the ability of the student to return verbatim in examinations that which he has been fed?

*R. E. Gibson, 1968*

In the popular treatise, whatever shreds of the science are allowed to appear, are exhibited in an exceedingly diffuse and attenuated form, apparently with the hope that the mental faculties of the reader [...] may insensibly become saturated with scientific phraseology [...]. In this way, by simple reading, the student may become possessed of the phrases of the science without having been put to the trouble of thinking a single thought about it. The loss implied in such an acquisition can be estimated only by those who have been compelled to unlearn a science that they might at length begin to learn it.

*J. Clerk Maxwell, 1878*

Do we, in our schools and colleges, foster the spirit of inquiry, of skepticism, of adventurous thinking, of acquiring experience and reflecting on it? Or do we place a premium on docility, giving major recognition to the ability of the student to return verbatim in examinations that which he has been fed?

*R. E. Gibson, 1968*

Finally, I said that I couldn't see how anyone could be educated by this self-propagating system in which people pass exams, and teach others to pass exams, but nobody knows anything.

I don't know what's the matter with people: they don't learn by understanding; they learn by some other way – by rote, or something. Their knowledge is so fragile!

*R. P. Feynman, 1985*

# Numerical methods as opposed to analytic methods

```
! Relative vorticity
select case(vbc%bc_type)
case(BC_PARTIAL_SLIP)
    cff = vbc%alpha / (vbc%alpha + 3.0D0)
    if(decomp%p_b == -1) then
        do layer = 1, layers
            do j = decomp%l_j_min, decomp%l_j_max
                z_b(layer) = z_b(layer) + cff * (-3.5D0 * psi(1, j, layer) &
                    & + 4.0D0 * psi(2, j, layer) &
                    & - 0.5D0 * psi(3, j, layer))
            end do
        end do
    end if
    if(decomp%p_d == -1) then
        do layer = 1, layers
            do j = decomp%l_j_min, decomp%l_j_max
                z_d(layer) = z_d(layer) + cff * (-3.5D0 * psi(decomp%ii, j, layer) &
                    & + 4.0D0 * psi(decomp%ii - 1, j, layer) &
                    & - 0.5D0 * psi(decomp%ii - 2, j, layer))
            end do
        end do
    end if
case(BC_FREE_SLIP)
```

# Numerical methods as opposed to analytic methods

More and more important for our technologies

```
! Relative vorticity
select case(vbc%bc_type)
case(BC_PARTIAL_SLIP)
    cff = vbc%alpha / (vbc%alpha + 3.0D0)
    if(decomp%p_b == -1) then
        do layer = 1, layers
            do j = decomp%l_j_min, decomp%l_j_max
                z_b(layer) = z_b(layer) + cff * (-3.5D0 * psi(1, j, layer) &
                    & + 4.0D0 * psi(2, j, layer) &
                    & - 0.5D0 * psi(3, j, layer))
            end do
        end do
    end if
    if(decomp%p_d == -1) then
        do layer = 1, layers
            do j = decomp%l_j_min, decomp%l_j_max
                z_d(layer) = z_d(layer) + cff * (-3.5D0 * psi(decomp%ii, j, layer) &
                    & + 4.0D0 * psi(decomp%ii - 1, j, layer) &
                    & - 0.5D0 * psi(decomp%ii - 2, j, layer))
            end do
        end do
    end if
case(BC_FREE_SLIP)
```

# Numerical methods as opposed to analytic methods

More and more important for our technologies

Give **physical insights** complementary to those from analytic methods

```
! Relative vorticity
select case(vbc%bc_type)
case(BC_PARTIAL_SLIP)
    cff = vbc%alpha / (vbc%alpha + 3.0D0)
    if(decomp%p_b == -1) then
        do layer = 1, layers
            do j = decomp%l_j_min, decomp%l_j_max
                z_b(layer) = z_b(layer) + cff * (-3.5D0 * psi(1, j, layer) &
                    & + 4.0D0 * psi(2, j, layer) &
                    & - 0.5D0 * psi(3, j, layer))
            end do
        end do
    end if
    if(decomp%p_d == -1) then
        do layer = 1, layers
            do j = decomp%l_j_min, decomp%l_j_max
                z_d(layer) = z_d(layer) + cff * (-3.5D0 * psi(decomp%ii, j, layer) &
                    & + 4.0D0 * psi(decomp%ii - 1, j, layer) &
                    & - 0.5D0 * psi(decomp%ii - 2, j, layer))
            end do
        end do
    end if
case(BC_FREE_SLIP)
```

# Numerical methods

## as opposed to analytic methods

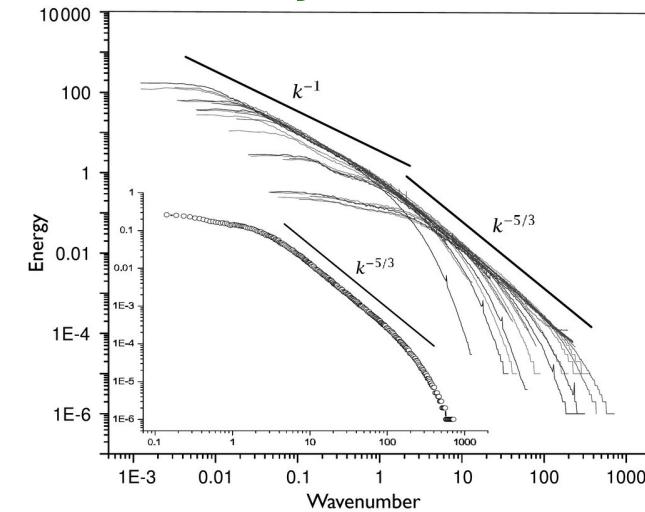
More and more important for our technologies

Give **physical insights** complementary to those from analytic methods

```

! Relative vorticity
select case(vbc%bc_type)
case(BC_PARTIAL_SLIP)
  cff = vbc%alpha / (vbc%alpha + 3.0D0)
  if(decomp%p_b == -1) then
    do layer = 1, layers
      do j = decomp%l_j_min, decomp%l_j_max
        z_b(layer) = z_b(layer) + cff * (-3.5D0 * psi(1, j, layer) &
                                         & + 4.0D0 * psi(2, j, layer) &
                                         & - 0.5D0 * psi(3, j, layer))
      end do
    end do
  end if
end if
if(decomp%p_d == -1) then
  do layer = 1, layers
    do j = decomp%l_j_min, decomp%l_j_max
      z_d(layer) = z_d(layer) + cff * (-3.5D0 * psi(decomp%ii, j, layer) &
                                         & + 4.0D0 * psi(decomp%ii - 1, j, layer) &
                                         & - 0.5D0 * psi(decomp%ii - 2, j, layer))
    end do
  end do
end if
case(BC_FREE_SLIP)

```



**Fig. 8.4** The energy spectrum of 3D turbulence measured in some experiments at the Princeton Superpipe facility.<sup>6</sup> The outer plot shows the spectra from a large number of experiments at different Reynolds numbers up to  $10^6$ , with the magnitude of their spectra appropriately rescaled. Smaller scales show a good  $-5/3$  spectrum, whereas at larger scales the eddies feel the effects of the pipe wall and the spectra are a little shallower. The inner plot shows the spectrum in the centre of the pipe in a single experiment at  $Re \approx 10^6$ .

# Numerical methods

## as opposed to analytic methods

- ⌚ More and more important for our technologies
- ⌚ Give **physical insights** complementary to those from analytic methods
- ⌚ Often only way in ‘multiphysics’ problems

```

! Relative vorticity
select case(vbc%bc_type)
case(BC_PARTIAL_SLIP)
    cff = vbc%alpha / (vbc%alpha + 3.0D0)
    if(decomp%p_b == -1) then
        do layer = 1, layers
            do j = decomp%l_j_min, decomp%l_j_max
                z_b(layer) = z_b(layer) + cff * (-3.5D0 * psi(1, j, layer) &
                                            & + 4.0D0 * psi(2, j, layer) &
                                            & - 0.5D0 * psi(3, j, layer))
            end do
        end do
    end if
    if(decomp%p_d == -1) then
        do layer = 1, layers
            do j = decomp%l_j_min, decomp%l_j_max
                z_d(layer) = z_d(layer) + cff * (-3.5D0 * psi(decomp%ii, j, layer) &
                                            & + 4.0D0 * psi(decomp%ii - 1, j, layer) &
                                            & - 0.5D0 * psi(decomp%ii - 2, j, layer))
            end do
        end do
    end if
case(BC_FREE_SLIP)

```

# Numerical methods

## as opposed to analytic methods

- ⌚ More and more important for our technologies
- ⌚ Give **physical insights** complementary to those from analytic methods
- ⌚ Often only way in ‘multiphysics’ problems
- ⌚ Of interest to DATA students

```

! Relative vorticity
select case(vbc%bc_type)
case(BC_PARTIAL_SLIP)
cff = vbc%alpha / (vbc%alpha + 3.0D0)
if(decomp%p_b == -1) then
do layer = 1, layers
  do j = decomp%l_j_min, decomp%l_j_max
    z_b(layer) = z_b(layer) + cff * (-3.5D0 * psi(1, j, layer) &
      & + 4.0D0 * psi(2, j, layer) &
      & - 0.5D0 * psi(3, j, layer))
  end do
end if
if(decomp%p_d == -1) then
do layer = 1, layers
  do j = decomp%l_j_min, decomp%l_j_max
    z_d(layer) = z_d(layer) + cff * (-3.5D0 * psi(decomp%ii, j, layer) &
      & + 4.0D0 * psi(decomp%ii - 1, j, layer) &
      & - 0.5D0 * psi(decomp%ii - 2, j, layer))
  end do
end if
case(BC_FREE_SLIP)

```

# Numerical methods

## as opposed to analytic methods

- ⌚ More and more important for our technologies
- ⌚ Give **physical insights** complementary to those from analytic methods
- ⌚ Often only way in ‘multiphysics’ problems
- ⌚ Of interest to DATA students

❓ *Help understanding hierarchy of physical laws!*

```

! Relative vorticity
select case(vbc%bc_type)
case(BC_PARTIAL_SLIP)
cff = vbc%alpha / (vbc%alpha + 3.0D0)
if(decomp%p_b == -1) then
do layer = 1, layers
  do j = decomp%l_j_min, decomp%l_j_max
    z_b(layer) = z_b(layer) + cff * (-3.5D0 * psi(1, j, layer) &
      & + 4.0D0 * psi(2, j, layer) &
      & - 0.5D0 * psi(3, j, layer))
  end do
end if
if(decomp%p_d == -1) then
do layer = 1, layers
  do j = decomp%l_j_min, decomp%l_j_max
    z_d(layer) = z_d(layer) + cff * (-3.5D0 * psi(decomp%ii, j, layer) &
      & + 4.0D0 * psi(decomp%ii - 1, j, layer) &
      & - 0.5D0 * psi(decomp%ii - 2, j, layer))
  end do
end if
case(BC_FREE_SLIP)

```

## *Today, what's the physics in everyday technologies?*

# Today, what's the physics in everyday technologies?

<https://www.gps.gov/technical/icwg/>  
 Official U.S. government information about the Global Positioning System (GPS) and related topics

Search

[Home](#)   [What's New](#)   [Systems](#)   [Applications](#)   [Governance](#)   [Multimedia](#)   **Support**

Home » Support » Technical Documentation » Interface Control Documents

*NOTE: The contents of this website have not been updated since February 2025 due to staffing shortages. Please bear with us as we work on a solution.*

**SUPPORT:**

- [Frequently Asked Questions](#)
- [Address, Route, & Map Problems](#)
- [Service Outages & Status Reports](#)
- [PNT Resilience](#)
- [Civil GPS Service](#)

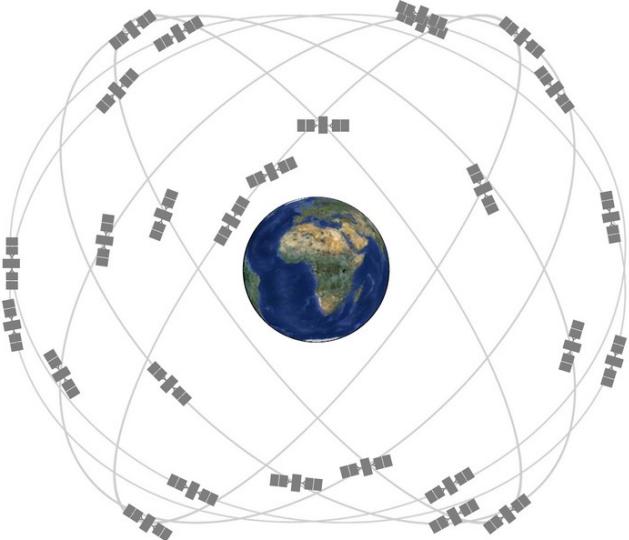
## Interface Control Documents

**UPDATED FEBRUARY 6, 2025**

The communication boundaries between the Global Positioning System and other systems, as well as within the GPS itself, are known as interfaces. Interface Control Documents (ICDs) are the formal means of establishing, defining, and controlling interfaces and for documenting detailed interface design information for the GPS program.

**On this page:**

- [New Revisions](#)
- [Current ICDs](#)
- [Interface Control](#)



# Today, what's the physics in everyday technologies?

# GPS.

Home

Home » Support » T

*NOTE: The contents  
as we work on a sol*

**SUPPORT:**

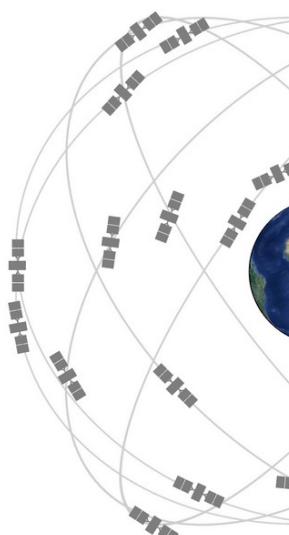
Frequently Asked  
Questions

Address, Route, &  
Map Problems

Service Outages &  
Status Reports

PNT Resilience

Civil GPS Service



## 20.3.3.3.3.1 User Algorithm for SV Clock Correction

The polynomial defined in the following allows the user to determine the effective SV PRN code phase offset referenced to the phase center of the antennas ( $\Delta t_{sv}$ ) with respect to GPS system time ( $t$ ) at the time of data transmission. The coefficients transmitted in subframe 1 describe the offset apparent to the dual-frequency user for the interval of time in which the parameters are transmitted. This estimated correction accounts for the deterministic SV clock error characteristics of bias, drift and aging, as well as for the SV implementation characteristics of group delay bias and mean differential group delay. Since these coefficients do not include corrections for relativistic effects, the user's equipment must determine the requisite relativistic correction. Accordingly, the offset given below includes a term to perform this function.

$$\Delta t_{sv} = a_{f0} + a_{f1}(t - t_{oc}) + a_{f2}(t - t_{oc})^2 + \Delta t_r \quad (2)$$

where

$a_{f0}$ ,  $a_{f1}$  and  $a_{f2}$  are the polynomial coefficients given in subframe 1,  $t_{oc}$  is the clock data reference time in seconds (reference paragraph 20.3.4.5), and  $\Delta t_r$  is the relativistic correction term (seconds) which is given by

$$\Delta t_r = F e \sqrt{A} \sin E_k$$

The orbit parameters ( $e$ ,  $\sqrt{A}$ ,  $E_k$ ) used here are described in discussions of data contained in subframes 2 and 3, while  $F$  is a constant whose value is

$$F = \frac{-2\sqrt{\mu}}{c^2} = -4.442807633 (10)^{-10} \frac{\text{sec}}{\sqrt{\text{meter}}},$$

where

$$\mu = 3.986005 \times 10^{14} \frac{\text{meters}^3}{\text{second}^2} = \text{value of Earth's universal gravitational parameters}$$

# IERS Reference Meridian

文 A 12 languages ▾

[Article](#) [Talk](#)

[Read](#) [Edit](#) [View history](#) [Tools](#) ▾

From Wikipedia, the free encyclopedia

*This article is about Earth's current international standard prime meridian. For the historical prime meridian, see [Prime meridian \(Greenwich\)](#).*

*For the general concept, see [prime meridian](#).*

The **IERS Reference Meridian**

(IRM), also called the

**International Reference**

**Meridian**, is the [prime](#)

[meridian \(0° longitude\)](#)

maintained by the [International](#)

[Earth Rotation and Reference](#)

[Systems Service \(IERS\)](#). It

passes about 5.3 [arcseconds](#)

east of [George Biddell Airy's](#)

1851 [transit circle](#), and thus it

differs slightly from the

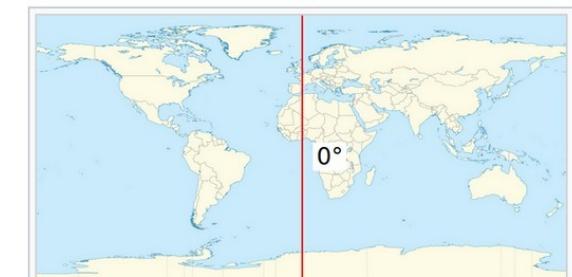
historical [Greenwich Meridian](#).

At the [latitude of the Royal](#)

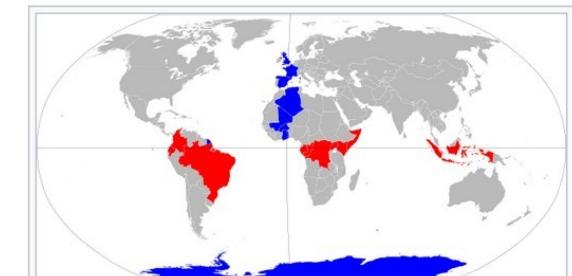
[Observatory, Greenwich](#) the

difference is 102 metres

(335 ft).<sup>[1][2][a]</sup>



Modern IERS Reference Meridian on Earth



Countries that touch the [Equator](#) (red) and that touch the [Prime Meridian](#) (blue)

It is the reference meridian of

the [Global Positioning System \(GPS\)](#) operated by the [United States Space Force](#), and of [WGS 84](#) and its two formal versions, the ideal [International](#)

[Terrestrial Reference System \(ITRS\)](#) and its realization, the [International](#)

[Terrestrial Reference Frame \(ITRF\)](#).

International Earth Rotation and Reference Systems Service (IERS)  
Service International de la Rotation Terrestre et des Systèmes de Référence

## IERS Technical Note No. 36

# IERS Conventions (2010)

Gérard Petit<sup>1</sup> and Brian Luzum<sup>2</sup> (eds.)

IERS Conventions Centre

<sup>1</sup> Bureau International des Poids et Mesures (BIPM)

<sup>2</sup> US Naval Observatory (USNO)

Talk

Read

Edit

View history

Tools ▾

Wikipedia, the free encyclopedia

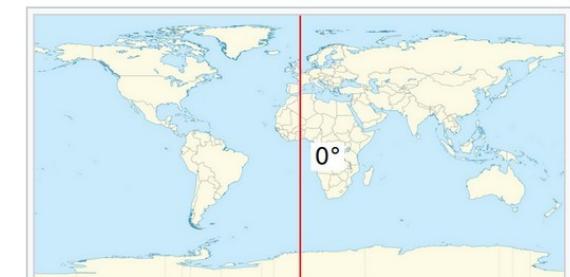
This article is about Earth's current international standard prime meridian. For the historical prime meridian, see [Prime meridian \(Greenwich\)](#).

For the general concept, see [prime meridian](#).

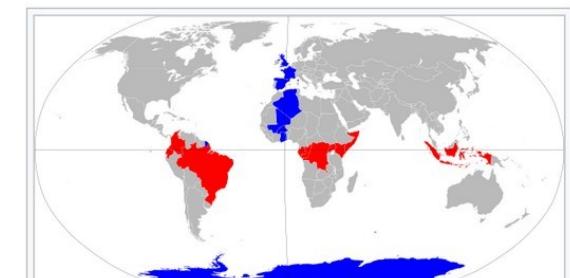
### IERS Reference Meridian

, also called the **national Reference Meridian**, is the [prime meridian](#) ( $0^\circ$  longitude) defined by the International Earth Rotation and Reference Systems Service (IERS). It is about 5.3 arcseconds of [George Biddell Airy's transit circle](#), and thus it is slightly from the historical [Greenwich Meridian](#). The latitude of the Royal Observatory, Greenwich, hence is 102 metres west. [1][2][a]

The reference meridian of the Global Positioning System (GPS) operated by the United States Space Force, and of WGS 84 and its two formal versions, the ideal International Terrestrial Reference System (ITRS) and its realization, the International Terrestrial Reference Frame (ITRF).



Modern IERS Reference Meridian on Earth



Countries that touch the Equator (red) and that touch the Prime Meridian (blue)

## 0 Introduction

This document is intended to define the standard reference systems realized by the International Earth Rotation and Reference Systems Service (IERS) and the models and procedures used for this purpose. It is a continuation of the series of documents begun with the Project MERIT (Monitor Earth Rotation and Intercompare the Techniques) Standards (Melbourne *et al.*, 1983) and continued with the IERS Standards (McCarthy, 1989; McCarthy, 1992) and IERS Conventions (McCarthy, 1996; McCarthy and Petit, 2004). The current issue of the IERS Conventions is called the IERS Conventions (2010).

The reference systems and procedures of the IERS are based on the resolutions of international scientific unions. The celestial system is based on IAU (International Astronomical Union) Resolution A4 (1991). It was officially initiated and named International Celestial Reference System (ICRS) by IAU Resolution B2 (1997) and its definition was further refined by IAU Resolution B1 (2000) and by IAU Resolution B3 (2009). The terrestrial system is based on IUGG (International Union of Geodesy and Geophysics) Resolution 2 (1991). It was officially endorsed as the International Terrestrial Reference System (ITRS) by IUGG Resolution 2 (2007). The transformation between celestial and terrestrial systems is based on IAU Resolution B1 (2000) and was complemented by IAU Resolutions B1 and B2 (2006). The definition of time coordinates and time transformations, the models for light propagation and the motion of massive bodies are based on IAU Resolution A4 (1991), further refined by IAU Resolution B1 (2000) and IAU Resolution B3 (2006). In some cases, the procedures used by the IERS, and the resulting conventional frames produced by the IERS, do not completely follow these resolutions. These cases are identified in this document and procedures to obtain results consistent with the resolutions are indicated. Following IAU resolutions, the IERS reference systems are defined in the framework of the General Relativity Theory (GRT). In a few cases, models are expressed in the parameterized post-Newtonian (PPN) formalism using parameters  $\beta$  and  $\gamma$  (equal to 1 in GRT). These cases are identified with a note.

## 0 Introduction

This document is intended to define the standard reference systems realized by the International Earth Rotation and Reference Systems Service (IERS) and the models and procedures used for this purpose. It is a continuation of the series of documents begun with the Project MERIT (Monitor Earth Rotation and Intercompare the Techniques) Standards (Melbourne *et al.*, 1983) and continued with the IERS Standards (McCarthy, 1989; McCarthy, 1992) and IERS Conventions (McCarthy, 1996; McCarthy and Petit, 2004). The current issue of the IERS Conventions is called the IERS Conventions (2010).

The reference systems and procedures of the IERS are based on the resolutions of international scientific unions. The celestial system is based on IAU (International Astronomical Union) Resolution A4 (1991). It was officially initiated and named International Celestial Reference System (ICRS) by IAU Resolution B2 (1997) and its definition was further refined by IAU Resolution B1 (2000) and by IAU Resolution B3 (2009). The terrestrial system is based on IUGG (International Union of Geodesy and Geophysics) Resolution 2 (1991). It was officially endorsed as the International Terrestrial Reference System (ITRS) by IUGG Resolution 2 (2007). The transformation between celestial and terrestrial systems is based on IAU Resolution B1 (2000) and was complemented by IAU Resolutions B1 and B2 (2006). The definition of time coordinates and time transformations, the models for light propagation and the motion of massive bodies are based on IAU Resolution A4 (1991), further refined by IAU Resolution B1 (2000) and IAU Resolution B3 (2006). In some cases, the procedures used by the IERS, and the resulting conventional frames produced by the IERS, do not completely follow these resolutions. These cases are identified in this document and procedures to obtain results consistent with the resolutions are indicated. Following IAU resolutions, the IERS reference systems are defined in the framework of the General Relativity Theory (GRT). In a few cases, models are expressed in the parameterized post-Newtonian (PPN) formalism using parameters  $\beta$  and  $\gamma$  (equal to 1 in GRT). These cases are identified with a note.

**IERS Reference Meridian** 12 languages

From Wikipedia, the free encyclopedia

This article is about Earth's current international standard prime meridian. For the historical prime meridian, see [Prime meridian \(Greenwich\)](#). For the general concept, see [prime meridian](#).

The **IERS Reference Meridian** (IRM), also called the **International Reference Meridian**, is the prime meridian ( $0^\circ$  longitude) maintained by the International Earth Rotation and Reference Systems Service (IERS). It passes about 5.3 arcseconds east of George Biddell Airy's 1851 transit circle, and thus it differs slightly from the historical Greenwich Meridian. At the latitude of the Royal Observatory Greenwich the difference is 102 metres (335 ft).<sup>[1][2][3]</sup>

It is the reference meridian of the Global Positioning System (GPS) operated by the United States Space Force, and of WGS 84 and its two formal versions, the ideal International Terrestrial Reference System (ITRS) and its realization, the International Terrestrial Reference Frame (ITRF).

**Modern IERS Reference Meridian on Earth**

Countries that touch the Equator (red) and that touch the Prime Meridian (blue)

# IAU Commission C.A3 Fundamental Standards

Home » Res

Home

Previous page

## The IAU 2000-2012 Resolutions on Reference Systems

The following gives information on the International Astronomical Union (IAU) and International Union of Geodesy and Geophysics (IUGG) resolutions that relate to reference systems, and in particular those after the IAU 1997 adoption of the International Celestial Reference System and Frame (ICRS/ICRF).

The following table summarises the particular resolutions indicating their purpose. While the sections below give more details of the resolutions and links to the IAU and related documents. Unless specified all resolutions are IAU resolutions.

Aim of the IAU / IUGG Resolutions - to deliver consistency with IAS accuracy				
Year	IAU / IUGG Resolutions			
2000 / IUGG 2003	<b>B1.3</b> Definition of BCRS and the GCRS <b>B1.5</b> Extended relativistic framework for time transformation	<b>B1.6</b> IAU 2000 precession-nutation model	<b>B1.7</b> Definition of CIP <b>B1.8</b> Definition and use of CEO and TEO	<b>B1.9</b> Re-definition of Terrestrial Time (TT)
2006 / IUGG 2007	IUGG Resolution 2 Definition of GTRS and ITRS as a specific GTRS	<b>B1</b> Adoption of the P03 precession model and definition of the ecliptic	<b>B2</b> Supplement to the IAU 2000 Resolutions: <b>Rec 1</b> Harmonizing <i>intermediate</i> to the pole and the origin <b>Rec 2</b> Default orientation of the BCRS/GCRS	<b>B3</b> Re-definition of Dynamical Barycentric Time (TDB)
2009 / IUGG 2011	<b>B2</b> Adoption of the IAU 2009 System of Astronomical Constants	<b>B3</b> Adoption of ICRF2	IUGG Resolution 3 adoption of ICRF2	
2012	<b>B2</b> Re-definition of the astronomical unit of length			
2015	<b>B3</b> Adoption of conversion constants for nominal units			
2018 / IUGG 2019	<b>B1</b> Adoption of the ITRS	<b>B2</b> Adoption of ICRF3	IUGG Resolution 2 recommending the ITRF	
2021 / IUGG	<b>B2</b> Recommendation for improvement and consistency for the Earth's rotation models	<b>B3</b> Adoption of Gaia optical reference frame (Gaia-CRF3)	IUGG	

THE ASTRONOMICAL JOURNAL, 126:2687–2706, 2003 December  
© 2003. The American Astronomical Society. All rights reserved. Printed in U.S.A.

## THE IAU 2000 RESOLUTIONS FOR ASTROMETRY, CELESTIAL MECHANICS, AND METROLOGY IN THE RELATIVISTIC FRAMEWORK: EXPLANATORY SUPPLEMENT

M. SOFFEL,<sup>1</sup> S. A. KLIONER,<sup>1</sup> G. PETIT,<sup>2</sup> P. WOLF,<sup>2</sup> S. M. KOPEIKIN,<sup>3</sup> P. BRETAGNON,<sup>4</sup> V. A. BRUMBERG,<sup>5</sup> N. CAPITAINE,<sup>6</sup> T. DAMOUR,<sup>7</sup> T. FUKUSHIMA,<sup>8</sup> B. GUINOT,<sup>6</sup> T.-Y. HUANG,<sup>9</sup> L. LINDEGREN,<sup>10</sup> C. MA,<sup>11</sup> K. NORDTVEDT,<sup>12</sup> J. C. RIES,<sup>13</sup> P. K. SEIDELMANN,<sup>14</sup> D. VOKROUHlický,<sup>15</sup> C. M. WILL,<sup>16</sup> AND C. XU<sup>17</sup>

*Received 2002 August 9; accepted 2003 July 2*

### ABSTRACT

We discuss the IAU resolutions B1.3, B1.4, B1.5, and B1.9 that were adopted during the 24th General Assembly in Manchester, 2000, and provides details on and explanations for these resolutions. It is explained why they present significant progress over the corresponding IAU 1991 resolutions and why they are necessary in the light of present accuracies in astrometry, celestial mechanics, and metrology. In fact, most of these resolutions are consistent with astronomical models and software already in use. The metric tensors and gravitational potentials of both the Barycentric Celestial Reference System and the Geocentric Celestial Reference System are defined and discussed. The necessity and relevance of the two celestial reference systems are explained. The transformations of coordinates and gravitational potentials are discussed. Potential coefficients parameterizing the post-Newtonian gravitational potentials are expounded. Simplified versions of the time transformations suitable for modern clock accuracies are elucidated. Various approximations used in the resolutions are explicated and justified. Some models (e.g., for higher spin moments) that serve the purpose of estimating orders of magnitude have actually never been published before.

*Key words:* astrometry — celestial mechanics — reference systems — time

Constants for nominal units

2018 / IUGG 2019	<b>B1</b> Adoption of the ITRS	<b>B2</b> Adoption of ICRF3	IUGG Resolution 2 recommending the ITRF
2021 / IUGG	<b>B2</b> Recommendation for improvement and consistency for the Earth's rotation models	<b>B3</b> Adoption of Gaia optical reference frame (Gaia-CRF3)	IUGG

THE ASTRONOMICAL JOURNAL, 126:2687–2706, 2003 December

© 2003. The American Astronomical Society. All rights reserved. Printed in U.S.A.

THE IAU 2000 R

## UNITED STATES NAVAL OBSERVATORY

### CIRCULAR NO. 179

M. SOFFEL,<sup>1</sup> S. A. U.S. Naval Observatory, Washington, D.C. 20392  
T. DAMOUR,<sup>7</sup> T.

2005 Oct 20

D METROLOGY IN  
NT

BERG,<sup>5</sup> N. CAPITAINE,<sup>6</sup>  
VEDT,<sup>12</sup> J. C. RIES,<sup>13</sup>

[https://aa.usno.navy.mil/publications/Circular\\_179](https://aa.usno.navy.mil/publications/Circular_179)

<https://doi.org/10.48550/arXiv.astro-ph/0602086>

We discuss the IAU Resolutions on Astronomical Reference Systems, Time Scales, and Earth Rotation Models. These resolutions are explained in the light of the IAU Assembly in 2000. It is shown why they provide a better reference system for the time scale and the rotation of the Earth than the previous ones. The resolutions are explained in the light of the IAU Assembly in 2000. It is shown why they provide a better reference system for the time scale and the rotation of the Earth than the previous ones.

*Key words:* astronomical reference systems, time scales, Earth rotation models

## The IAU Resolutions on Astronomical Reference Systems, Time Scales, and Earth Rotation Models

### Explanation and Implementation

he 24th General Assembly in 2000. It is explained why they are necessary. In fact, most of these new reference systems are based on the IAU Reference System. They are explained in the light of the IAU Assembly in 2000. It is shown why they provide a better reference system for the time scale and the rotation of the Earth than the previous ones. The new reference systems are explained in the light of the IAU Assembly in 2000. It is shown why they provide a better reference system for the time scale and the rotation of the Earth than the previous ones.

by

George H. Kaplan

2018 / IUGG 2019

constants

B1 Adopti

2021 / IUGG

B2 Recon

improvem

consistency for the Earth's

rotation models

optical reference frame  
(Gaia-CRF3)

IUGG

(Lebach et al. 1995) and  $\gamma = 0.99994 \pm 0.00031$  (Eubanks et al. 1997). The current accuracy of modern optical astrometry, as represented by the *Hipparcos Catalogue*, is about 1 mas, which gave a determination of  $\gamma$  at the level of  $0.997 \pm 0.003$  (Froeschlé, Mignard, & Arenou 1997). Future astrometric missions such as *SIM* and especially *GAIA* will push the accuracy to the level of a few microarcseconds, and the expected accuracy of determinations of  $\gamma$  will be  $10^{-6}$  to  $10^{-7}$ . The accuracy of 1  $\mu$ as should be compared with the maximal possible light deflection due to various parts of the gravitational field: the post-Newtonian effect of 1."75 due to the mass of the Sun, 240  $\mu$ as caused by the oblateness of

Jupiter,  $J_2$  (10  $\mu$ as due to Jupiter), and the post-Newtonian effect of 11  $\mu$ as due to the Sun's quadrupole moment. This illustrates how complicated the theory of gravity becomes at such high accuracy if one does not take into account the corrections formulated in a self-consistent relativistic theory.

Another problem worth mentioning is the realization of the second (the unit of proper time) in terms of the second magnitude in the last few years by means of cooled atomic clocks (Lemonde 2001; references therein) and its realization in terms of the second. This should be compared with  $U_E/c^2 \approx 7 \times 10^{-10}$ , which gives the relativistic effects produced by the motion of the Earth in the vicinity of its surface. Cooled atomic clocks in microgravities can achieve a further improvement by at least a factor of 10. At present, several clock experiments are planned, such as the Atomic Clock Comparison project (Lemonde et al. 2001).

lead to clock experiments in solar orbits, such as the *Solar System Test* project. All of these experiments require a detailed account of many subtle relativistic effects.

Finally, we would like to mention the problem of geodetic precession and nutation (a relativistic effect that is discussed in more detail below; Misner, Thorne, & Wheeler 1973; Soffel 1989) and the description of Earth's rotation in a suitably chosen geocentric celestial reference system. Geodetic precession amounts to 1".9 per century, and geodetic nutation is dominated by an annual term with amplitude 0.15 mas. Since the geocentric reference system is chosen to be kinematically nonrotating, geodetic precession and nutation should be contained in the model describing the relation between the geocentric system and the International Terrestrial Reference System (ITRS). According to IAU Resolution B1.6 (2000), this relativistic precession-nutation model is indeed contained in the present IAU precession-nutation model.

These examples show clearly that high-precision modern astronomical observations can no longer be described by Newtonian theory but require Einstein's theory of gravity. The consequences of this are profound for the basic formalism to be used, since one often tends to express it in terms of "small relativistic corrections" to Newtonian theory. This can lead to misconceptions and mistakes. One central point is that in Newton's theory, globally preferred coordinate systems exist that have a direct physical meaning. In the Newtonian framework, idealized clocks show absolute time everywhere in the universe at all times, and global spatial inertial coordinates exist in which dynamical equations of motion show no inertial forces. This is no longer true in

GRT. Usually, spacetime coordinates have no direct physical meaning and it is essential to construct the observables as coordinate-independent quantities, that is, scalars, in mathematical language. This construction usually occurs in two steps: first one formulates a coordinate picture of the measurement procedure, and then one derives the observable out of it. This leads us to the problem of defining useful and adequate coordinate systems in astronomy. The underlying concept in relativistic modeling of astronomical observations is a relativistic four-dimensional *reference system*. By reference system, we mean a purely mathematical construction (a chart or a coordinate system) giving

These examples show clearly that high-precision modern astronomical observations can no longer be described by Newtonian theory but require Einstein's theory of gravity. The consequences of this are profound for the basic formalism to be used, since one often tends to express it in terms of "small relativistic corrections" to Newtonian theory. This can lead to misconceptions and mistakes. One central point

and  $x^\alpha + dx^\alpha$  according to the rule

$$\begin{aligned} ds^2 &= g_{\alpha\beta}(t, x^i) dx^\alpha dx^\beta \\ &\equiv g_{00} c^2 dt^2 + 2g_{0i} c dt dx^i + g_{ij} dx^i dx^j , \end{aligned} \quad (1)$$

where Einstein's summation convention (summation over repeated indices) is implied. The metric tensor allows one to derive translational and rotational equations of motion of bodies, to describe the propagation of light, and to model the process of observation. Examples of such modeling include relating the observed (proper) time of an observer to the coordinate time  $t$ , and relating the angles between two incident light rays as observed by that observer to the corresponding coordinate directions. All of these components can be combined into a single relativistic model for a particular kind of observation. Such a model contains a certain set of parameters describing various properties of the objects participating in the process of observation. These parameters should be determined from observations. Many of these parameters crucially depend upon the reference system used to formulate the model of observations (e.g., the initial positions and velocities of certain bodies). Some other parameters might not depend at all upon the reference system (e.g., the speed of light in vacuum). On the other hand, according to the principle of covariance, different reference systems covering the region of spacetime under consideration are mathematically equivalent in the sense that any such system can be used to model the observations. This freedom to choose the reference system can be used to simplify the models or to make the resulting parameters more physically adequate.

THE IAU 2000 RESOLUTIONS FOR ASTROMETRY, CELESTIAL MECHANICS, AND METROLOGY IN THE RELATIVISTIC FRAMEWORK: EXPLANATORY SUPPLEMENT

M. SOFFEL,<sup>1</sup> S. A. KLIONER,<sup>1</sup> G. PETIT,<sup>2</sup> P. WOLF,<sup>2</sup> S. M. KOPEIKIN,<sup>3</sup> P. BRETAGNON,<sup>4</sup> V. A. BRUMBERG,<sup>5</sup> N. CAPITAINE,<sup>6</sup> T. DAMOUR,<sup>7</sup> T. FUKUSHIMA,<sup>8</sup> B. GUINOT,<sup>6</sup> T.-Y. HUANG,<sup>9</sup> L. LINDEGREN,<sup>10</sup> C. MA,<sup>11</sup> K. NORDTVEIT,<sup>12</sup> J. C. RIES,<sup>13</sup> P. K. SEIDELMANN,<sup>14</sup> D. VOKROUHlický,<sup>15</sup> C. M. WILL,<sup>16</sup> AND C. XU<sup>17</sup>

Received 2002 August 9; accepted 2003 July 2

#### ABSTRACT

We discuss the IAU resolutions B1.3, B1.4, B1.5, and B1.9 that were adopted during the 24th General Assembly in Manchester, 2000, and provides details on and explanations for these resolutions. It is explained why they present significant progress over the corresponding IAU 1991 resolutions and why they are necessary in the light of present accuracies in astrometry, celestial mechanics, and metrology. In fact, most of these resolutions are consistent with astronomical models and software already in use. The metric tensors and gravitational potentials of both the Barycentric Celestial Reference System and the Geocentric Celestial Reference System are defined and discussed. The necessity and relevance of the two celestial reference systems are explained. The transformations of coordinates and gravitational potentials are discussed. Potential coefficients parameterizing the post-Newtonian gravitational potentials are expounded. Simplified versions of the time transformations suitable for modern clock accuracies are elucidated. Various approximations used in the resolutions are explicated and justified. Some models (e.g., for higher spin moments) that serve the purpose of estimating orders of magnitude have actually never been published before.

*Key words:* astrometry — celestial mechanics — reference systems — time

With the harmonic gauge condition, the post-Newtonian Einstein field equations take the form

$$\left( -\frac{1}{c^2} \frac{\partial^2}{\partial t^2} + \nabla^2 \right) w = -4\pi G\sigma + O(c^{-4}), \quad (10)$$

$$\nabla^2 w^i = -4\pi G\sigma^i + O(c^{-2}). \quad (11)$$

Here  $\sigma$  and  $\sigma^i$  are the gravitational mass and mass current density, respectively. Mathematically they are related to the *energy-momentum tensor*  $T^{\mu\nu}$  by

$$\sigma = \frac{1}{c^2} (T^{00} + T^{ss}), \quad \sigma^i = \frac{1}{c} T^{0i}. \quad (12)$$

### 3.2. The Barycentric Celestial Reference System

Resolution B1.3 concerns the definition of the Barycentric Celestial Reference System and the Geocentric Celestial Reference System. The BCRS is defined with coordinates  $(ct, x^i) = x^\mu$ , where  $t = \text{TCB}$ . The BCRS is a particular version of the barycentric reference system of the solar system. The resolution recommends that the metric tensor of the BCRS be written in the form

$$\begin{aligned} g_{00} &= -1 + \frac{2w}{c^2} - \frac{2w^2}{c^4} + O(c^{-5}), \\ g_{0i} &= -\frac{4}{c^3} w^i + O(c^{-5}), \\ g_{ij} &= \delta_{ij} \left( 1 + \frac{2}{c^2} w \right) + O(c^{-4}). \end{aligned} \quad (8)$$

nonrotating geocentric reference system. Such a rotation has several components, often referred to as geodetic, Lense-Thirring, and Thomas precessions:

$$\boldsymbol{\Omega}_{\text{iner}} = \boldsymbol{\Omega}_{\text{GP}} + \boldsymbol{\Omega}_{\text{LTP}} + \boldsymbol{\Omega}_{\text{TP}} \quad (24)$$

with

$$\begin{aligned} \boldsymbol{\Omega}_{\text{GP}} &= -\frac{3}{2c^2} \boldsymbol{v}_E \times \nabla w_{\text{ext}}(\boldsymbol{x}_E), \\ \boldsymbol{\Omega}_{\text{LTP}} &= -\frac{2}{c^2} \nabla \times \boldsymbol{w}_{\text{ext}}(\boldsymbol{x}_E), \\ \boldsymbol{\Omega}_{\text{TP}} &= -\frac{1}{2c^2} \boldsymbol{v}_E \times \boldsymbol{Q}, \end{aligned} \quad (25)$$

in obvious notation. As a relativistic precession, the geodetic precession  $\boldsymbol{\Omega}_{\text{GP}}$  is proportional to  $1/c^2$ . It is also



From O'Neill, Ian J (US 1821) <ian.j.oneill@jpl.nasa.gov> 



To Piero.Giovanni.Luca.Porta-Mana@hvl.no <Piero.Giovanni.Luca.Porta-Mana@hvl.no> 

240412, 21:33

Cc Cofield, Calla E (US 1821) <calla.e.cofield@jpl.nasa.gov> 

Subject Re: [EXTERNAL] Educational inquiry about the use of relativity at JPL and NASA 

Hi Luca,

I was able to get a response from Ryan Park, the Group Supervisor of JPL's Solar System Dynamics Group:

"Yes, NASA/JPL include relativistic effects when we plan or calculate trajectories for Earth, Moon, and beyond. The same PPN (parameterized post-Newtonian) metric is used to calculate and plan spacecraft dynamics. For example, if we don't include the relativistic effect, GPS orbits will be not as good as what we have now. 😊"



From O'Neill, Ian J (US 1821) <ian.j.oneill@jpl.nasa.gov> 



To Piero.Giovanni.Luca.Porta-Mana@hvl.no <Piero.Giovanni.Luca.Porta-Mana@hvl.no> 

240412, 21:33

Cc Cofield, Calla E (US 1821) <calla.e.cofield@jpl.nasa.gov> 

Subject Re: [EXTERNAL] Educational inquiry about the use of relativity at JPL and NASA 

Hi Luca,

I was able to get a response from Ryan Park, the Group Supervisor of JPL's Solar System Dynamics Group:

"Yes, NASA/JPL include relativistic effects when we plan or calculate trajectories for Earth, Moon, and beyond. The same PPN (parameterized post-Newtonian) metric is used to calculate and plan spacecraft dynamics. For example, if we don't include the relativistic effect, GPS orbits will be not as good as what we have now. 😊"

From O'Neill, Ian J (US 1821) <ian.j.oneill@jpl.nasa.gov> 



To Piero.Giovanni.Luca.Porta-Mana@hvl.no <Piero.Giovanni.Luca.Porta-Mana@hvl.no> 

240412, 21:42

Cc Cofield, Calla E (US 1821) <calla.e.cofield@jpl.nasa.gov> 

Subject Re: [EXTERNAL] Educational inquiry about the use of relativity at JPL and NASA 

I also got a response from Paul Chodas, JPL's director for the Center of Near Earth Object Studies:

"Further to what Ryan said, we use the same dynamical models for navigating in cis-lunar or geocentric space as we do for interplanetary missions: the physics doesn't change between the two regimes, and the same software is used for navigating in both regimes."

It seems the professor has already found the key document by Moyer, which I would have referenced myself. In fact, I used the relativistic expressions in Moyer's earlier internal JPL document when I coded up the dynamical models used in our Small Body software, back in the early '90s, and the same Moyer expressions were used in JPL navigation software for a couple decades before that (back at least to the '70s)."

# Formulation for Observed and Computed Values of Deep Space Network Data Types for Navigation

---

**Theodore D. Moyer**

Jet Propulsion Laboratory  
California Institute of Technology

Formulation for  
Observed and Computed Values of  
Deep Space Network Data Types  
for Navigation  
(JPL Publication 00-7)

October 2000

The research described in this publication was carried out at the  
Jet Propulsion Laboratory, California Institute of Technology,  
under a contract with the National Aeronautics and Space Administration.



Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

$$\begin{aligned} \mathbf{g} = & -\frac{GM_E}{c^2 r^3} \left[ \left( 4 \frac{GM_E}{r} - (\dot{\mathbf{X}} \cdot \dot{\mathbf{X}}) \right) \mathbf{X} + 4(\mathbf{X} \cdot \dot{\mathbf{X}}) \dot{\mathbf{X}} \right] \\ & + 2(\boldsymbol{\Omega}_{GP} \times \dot{\mathbf{X}}) + 2 \frac{GM_E}{c^2 r^3} \\ & \times \left\{ \frac{3}{r^2} (\mathbf{X} \times \dot{\mathbf{X}})(\mathbf{X} \cdot \mathbf{J}) + (\dot{\mathbf{X}} \times \mathbf{J}) \right\}. \end{aligned}$$

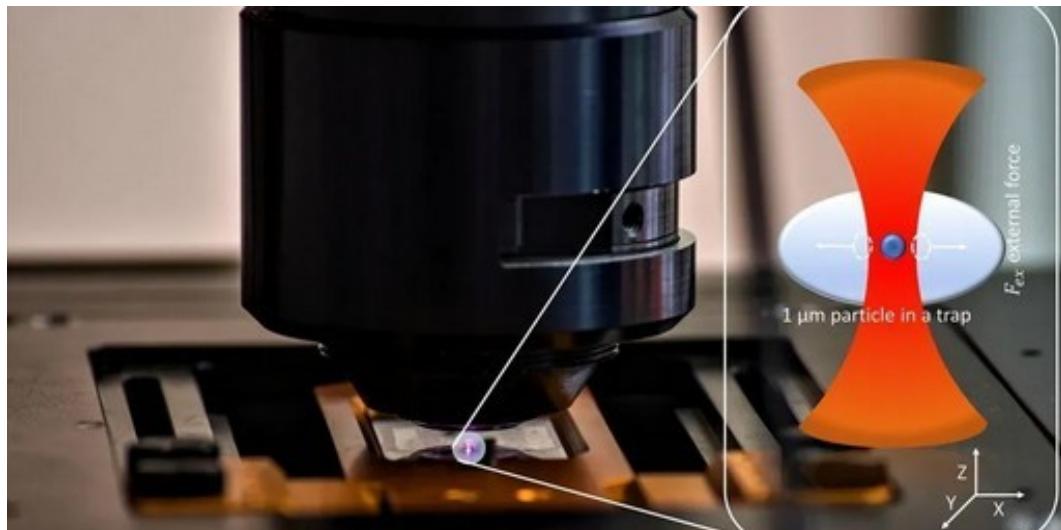
$$P = m \, v$$

full formula, used for instance by NASA  
for motion of satellites, spacecrafts, Moon, planets, ...

$$P = m v + \frac{1}{c^2} \Phi + \frac{1}{c^2} m v \left( \frac{1}{2} v^2 + E/V + 3 g \right) + \dots$$

full formula, used for instance by NASA  
for motion of satellites, spacecrafts, Moon, planets, ...

$$P = m v + \frac{1}{c^2} \Phi + \frac{1}{c^2} m v (\frac{1}{2} v^2 + E/V + 3 g) + \dots$$



Optical tweezers

<https://www.youtube.com/watch?v=mBE6xboXeHM>



Solar sails

<https://www.nasa.gov/mission/acs3/>

$$p = \epsilon_0 E \times B$$

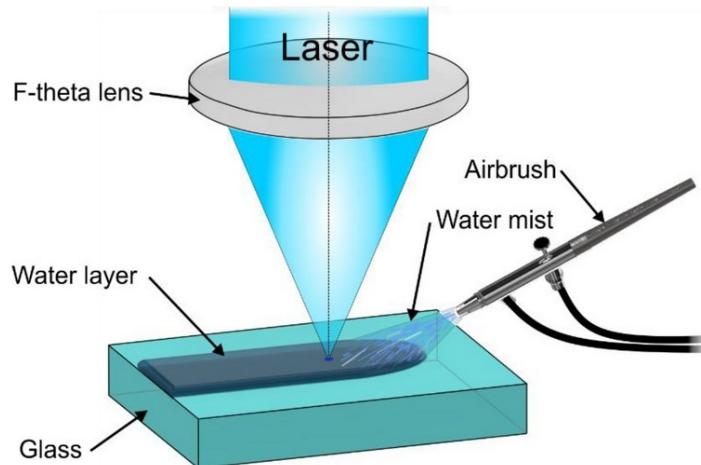
## Colloquium: Momentum of an electromagnetic wave in dielectric media

Robert N. C. Pfeifer,\* Timo A. Nieminen,<sup>†</sup> Norman R. Heckenberg,<sup>‡</sup>  
and Halina Rubinsztein-Dunlop<sup>§</sup>

*Centre for Biophotonics and Laser Science, School of Physical Sciences, The University of Queensland, Brisbane, QLD 4072, Australia*

(Published 1 October 2007)

Almost 100 years ago, two different expressions were proposed for the energy-momentum tensor of an electromagnetic wave in a dielectric. Minkowski's tensor predicted an increase in the linear momentum of the wave on entering a dielectric medium, whereas Abraham's tensor predicted its decrease. Theoretical arguments were advanced in favor of both sides, and experiments proved incapable of distinguishing between the two. Yet more forms were proposed, each with their advocates who considered the form that they were proposing to be the one true tensor. This paper reviews the debate and its eventual conclusion: that no electromagnetic wave energy-momentum tensor is complete on its own. When the appropriate accompanying energy-momentum tensor for the material medium is also considered, experimental predictions of all various proposed tensors will always be the same, and the preferred form is therefore effectively a matter of personal choice.



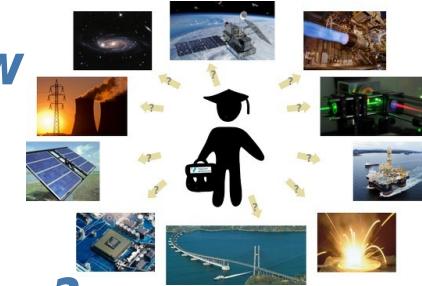
$$p = [\rho_0(c^2 + \epsilon_i) + \phi]\gamma^2 \frac{\mathbf{v}}{c} + \epsilon_0 \mathbf{E} \times \mathbf{B} + \frac{1}{c\alpha} \mathbf{P} \times \left( \frac{\mathbf{v}}{c} \times \mathbf{P} \right)$$

$$+ \frac{1}{c\beta} \mathbf{M} \times \left( \frac{\mathbf{v}}{c} \times \mathbf{M} \right) - \frac{1}{c} \mathbf{B} \times \left( \frac{\mathbf{v}}{c} \times \mathbf{M} \right)$$

$$+ \frac{1}{c^2} \mathbf{E} \times \mathbf{M},$$

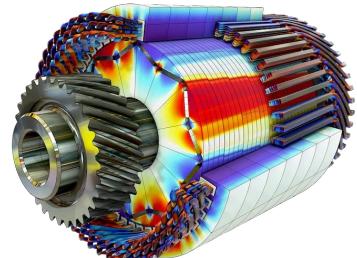
1

# Consider all possible career paths a student might follow



2

# Intro-physics course meaningful for all study programmes?



3

# 'Multiphysics'

GPT UIO

For the following reaction, explain the structure of the corresponding voltaic cell, including the anode, cathode, and the flow of electrons. Balance the equation and calculate  $E^\circ_{cell}$ . Give a brief answer and do not use latex macros:  $Zn(s) + Ag^+(aq) \rightarrow Ag(s) + Zn^{2+}(aq)$

The balanced equation for the reaction is:

$$Zn(s) + 2Ag^+(aq) \rightarrow 2Ag(s) + Zn^{2+}(aq)$$

Voltaic Cell Structure:

- Anode: Zinc (Zn) electrode, where Zn(s) is oxidized to  $Zn^{2+}(aq)$ .
- Cathode: Silver (Ag) electrode, where  $Ag^+(aq)$  is reduced to Ag(s).
- Electron Flow: Electrons flow from the anode (Zn) to the cathode (Ag) through the external circuit.

Standard Electrode Potentials:

- $E^\circ(Ag+/Ag) = +0.80 V$
- $E^\circ(Zn/Zn^{2+}) = -0.76 V$

Calculate  $E^\circ_{cell}$ :  $E^\circ_{cell} = E^\circ_{cathode} - E^\circ_{anode} = 0.80 V - (-0.76 V) = 1.56 V$

Pend a message

Generated text might contain errors or inaccuracies. Read more about limitations on our guidance pages.

4

# Large Language Models are redefining 'knowledge' and 'skills'

```

! Relative vorticity
select case(vbc%bc_type)
  case(BC_PARTIAL_SLIP)
    cff = vbc%alpha / (vbc%alpha + 3.000)
    if(decomp%p_b == -1) then
      do layer = 1, layers
        do j = decompl_j_min, decompl_j_max
          z_b(layer) = z_b(layer) + cff * (-3.500 * psi(1, j, layer) &
            & + 4.000 * psi(2, j, layer) &
            & - 0.500 * psi(3, j, layer))
        end do
      end do
    end if
    if(decomp%d == -1) then
      do layer = 1, layers
        do j = decompl_j_min, decompl_j_max
          z_d(layer) = z_d(layer) + cff * (-3.500 * psi(decomp%ii, j, layer) &
            & + 4.000 * psi(decomp%ii - 1, j, layer) &
            & - 0.500 * psi(decomp%ii - 2, j, layer))
        end do
      end do
    end if
  case(BC_FREE_SLIP)

```

5

# Numerical methods

IERS Reference Meridian

This article is about Earth's current international standard prime meridian. For the historical prime meridian, see Prime meridian (disambiguation). For the general concept, see prime meridian.

The IERS Reference Meridian (IRM), also called the International Reference Meridian, is the prime meridian ( $0^\circ$  longitude) maintained by the International Earth Rotation and Reference Systems Service (IERS). It passes about 5.3 km east of George Best.

1881 transit circle surveys set it almost exactly to the Royal Observatory Greenwich, at the Royal Observatory Greenwich, which the difference is 102 metres (335 ft) (NAD83).

It is the reference meridian of the Global Positioning System (GPS) operated by the United States Space Force, and its WGS 84 and its two formal versions, the International Terrestrial Reference System (ITRS) and its realization, the International Terrestrial Reference Frame (ITRF).

General relativity

6

# Today, what's the physics in everyday technologies?

7

...

**MECHANICS**

<b>1</b>	Units, Physical Quantities, and Vectors	1
<b>2</b>	Motion Along a Straight Line	34
<b>3</b>	Motion in Two or Three Dimensions	67
<b>4</b>	Newton's Laws of Motion	101
<b>5</b>	Applying Newton's Laws	130
<b>6</b>	Work and Kinetic Energy	172
<b>7</b>	Potential Energy and Energy Conservation	203
<b>8</b>	Momentum, Impulse, and Collisions	237
<b>9</b>	Rotation of Rigid Bodies	273
<b>10</b>	Dynamics of Rotational Motion	303
<b>11</b>	Equilibrium and Elasticity	339
<b>12</b>	Fluid Mechanics	369
<b>13</b>	Gravitation	398
<b>14</b>	Periodic Motion	433

*Patchwork of recipes!  
Still adequate?  
Are the students learning a method?*

**WAVES/AcouSTICS**

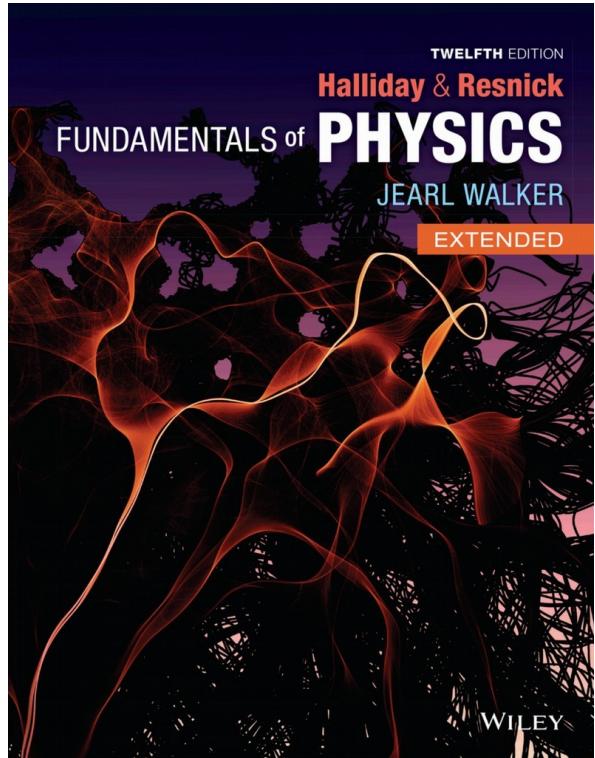
<b>15</b>	Mechanical Waves	468
<b>16</b>	Sound and Hearing	505

**THERMODYNAMICS**

<b>17</b>	Temperature and Heat	545
<b>18</b>	Thermal Properties of Matter	584
<b>19</b>	The First Law of Thermodynamics	618
<b>20</b>	The Second Law of Thermodynamics	647

**ELECTROMAGNETISM**

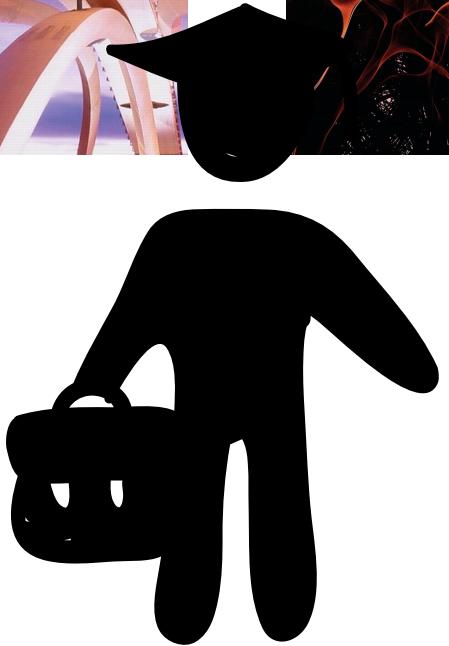
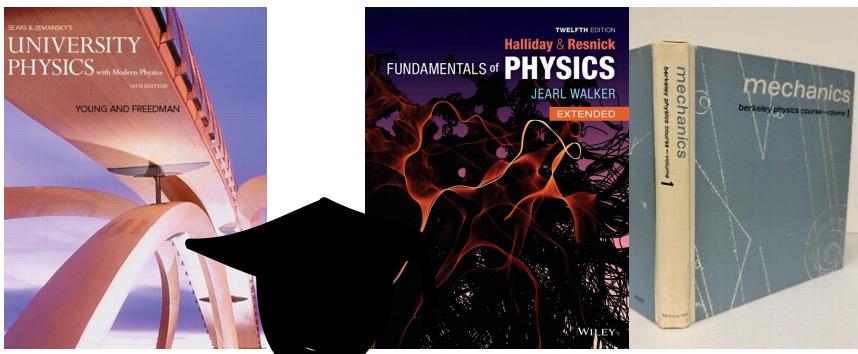
<b>21</b>	Electric Charge and Electric Field	683
<b>22</b>	Gauss's Law	722
<b>23</b>	Electric Potential	752
<b>24</b>	Capacitance and Dielectrics	785
<b>25</b>	Current, Resistance, and Electromotive Force	816

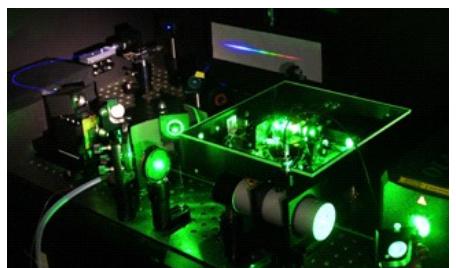
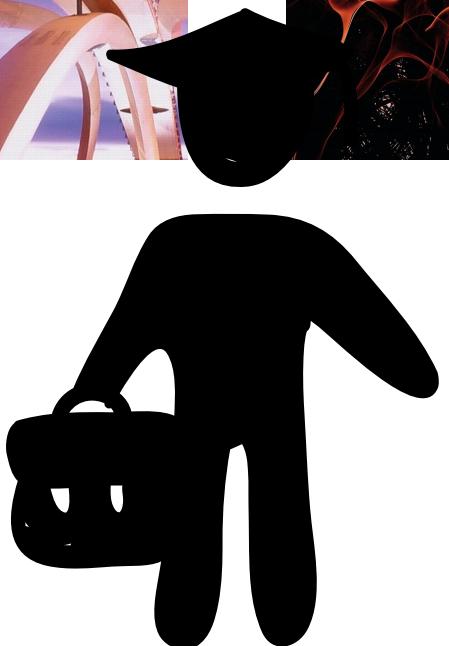
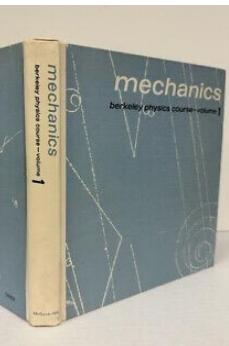
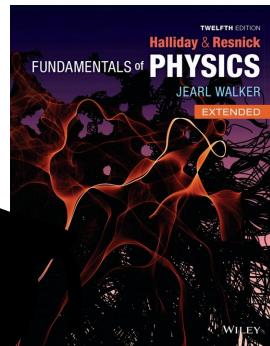
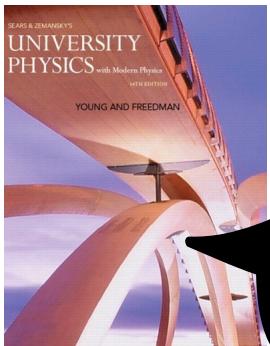


## BRIEF CONTENTS

### VOLUME 1

- 1** Measurement
- 2** Motion Along a Straight Line
- 3** Vectors
- 4** Motion in Two and Three Dimensions
- 5** Force and Motion—I
- 6** Force and Motion—II
- 7** Kinetic Energy and Work
- 8** Potential Energy and Conservation of Energy
- 9** Center of Mass and Linear Momentum
- 10** Rotation
- 11** Rolling, Torque, and Angular Momentum
- 12** Equilibrium and Elasticity
- 13** Gravitation
- 14** Fluids
- 15** Oscillations
- 16** Waves—I
- 17** Waves—II
- 18** Temperature, Heat, and the First Law  
of Thermodynamics
- 19** The Kinetic Theory of Gases
- 20** Entropy and the Second Law of  
Thermodynamics

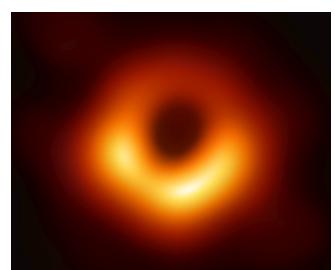




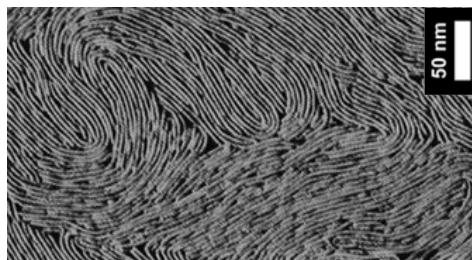
Quantum lasers  
Quantum communication



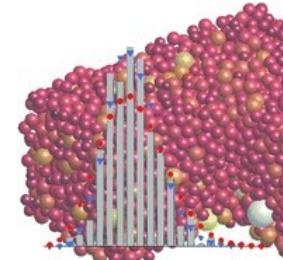
Plasma physics



General relativity  
QFT



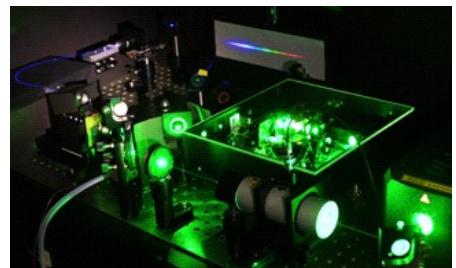
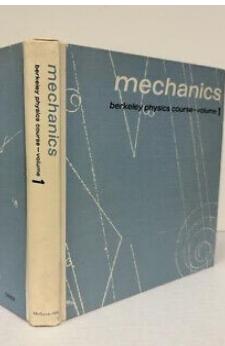
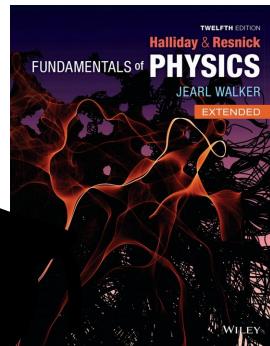
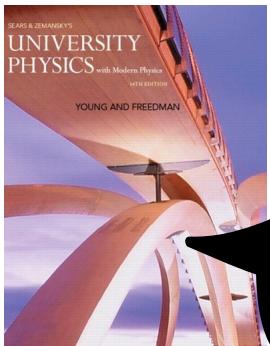
Continuum thermomechanics  
Polymer physics



Statistical mechanics  
neurosciences, medicine



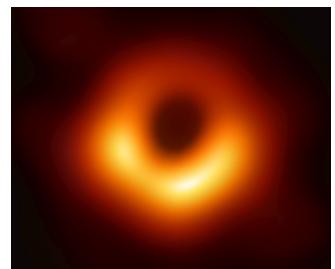
Fluid mechanics  
Ocean & atm. modelling



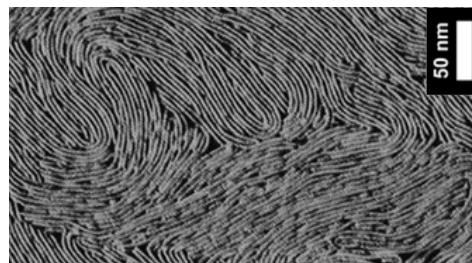
Quantum lasers  
Quantum communication



Plasma physics



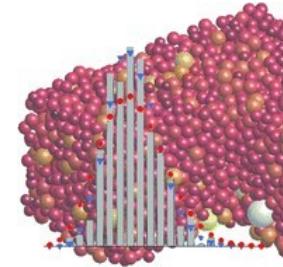
General relativity  
QFT



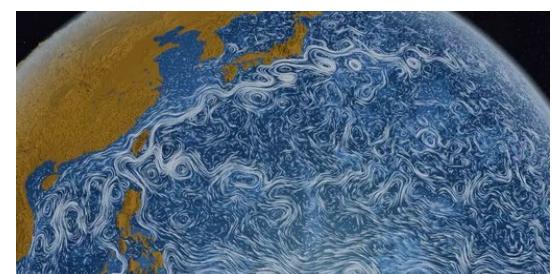
Continuum thermomechanics  
Polymer physics



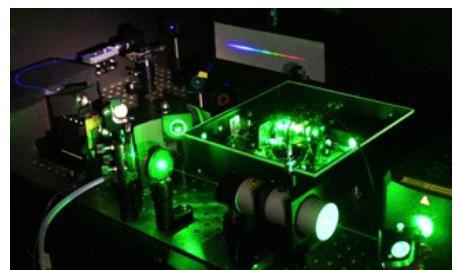
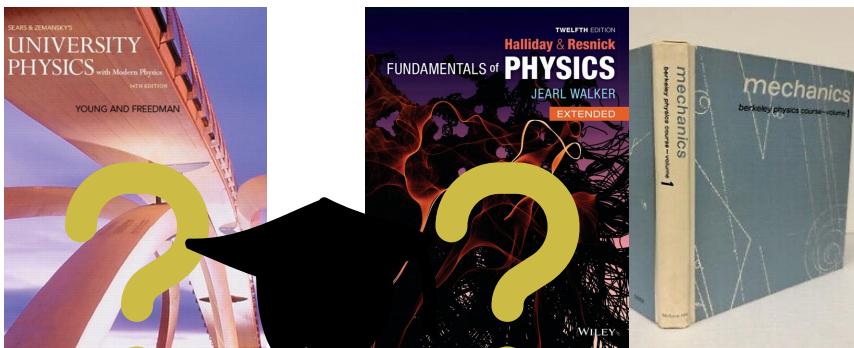
# Applied Computational



Statistical mechanics  
neurosciences, medicine



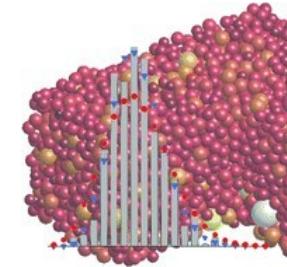
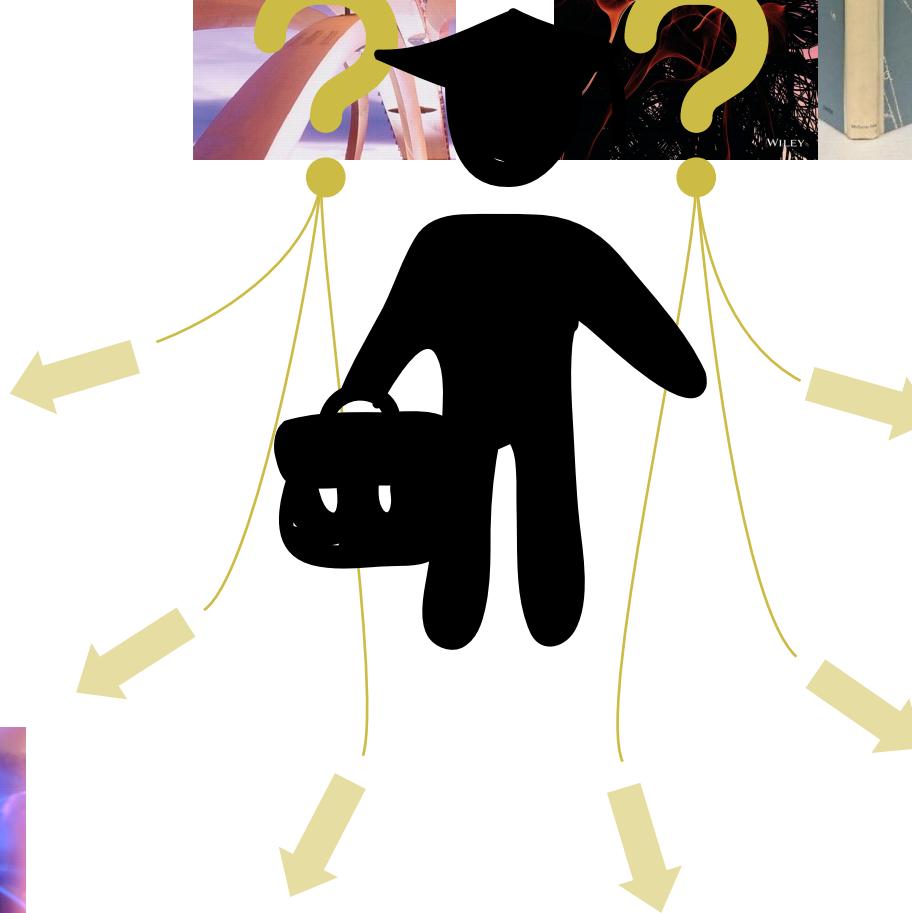
Fluid mechanics  
Ocean & atm. modelling



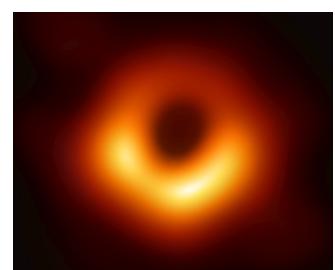
Quantum lasers  
Quantum communication



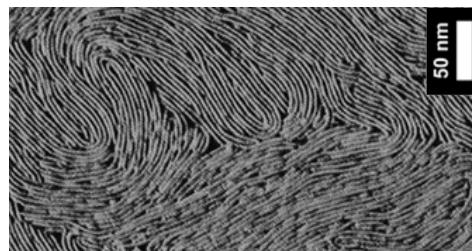
Plasma physics



Statistical mechanics  
neurosciences, medicine



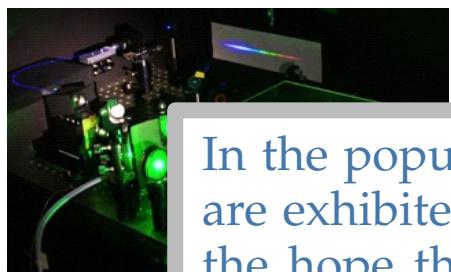
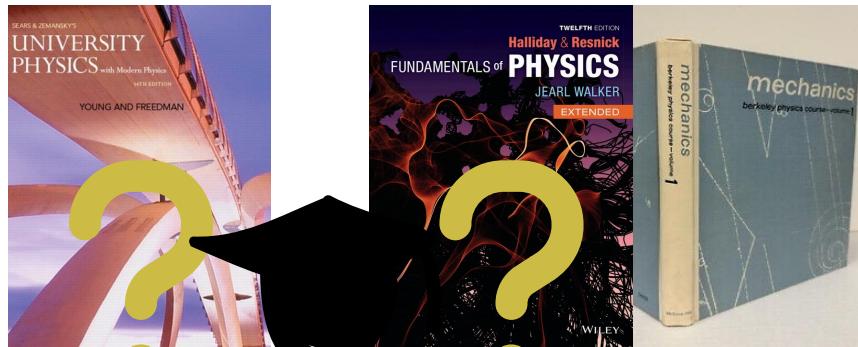
General relativity  
QFT



Continuum thermomechanics  
Polymer physics



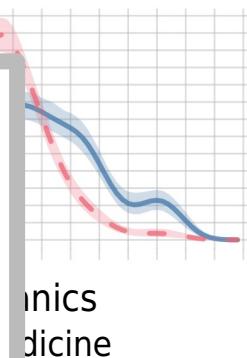
Fluid mechanics  
Ocean & atm. modelling



Quantum

In the popular treatise, whatever shreds of the science are allowed to appear, are exhibited in an exceedingly diffuse and attenuated form, apparently with the hope that the mental faculties of the reader [...] may insensibly become saturated with scientific phraseology [...]. In this way, by simple reading, the student may become possessed of the phrases of the science without having been put to the trouble of thinking a single thought about it. The loss implied in such an acquisition can be estimated only by those who have been compelled to unlearn a science that they might at length begin to learn it.

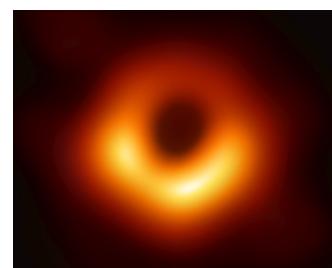
*J. Clerk Maxwell, 1878*



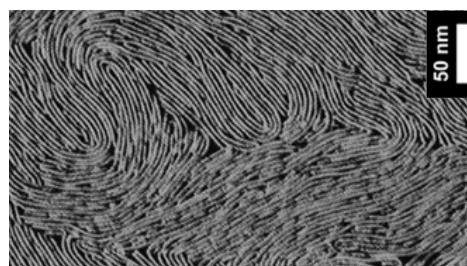
Physics  
medicine



Plasma physics



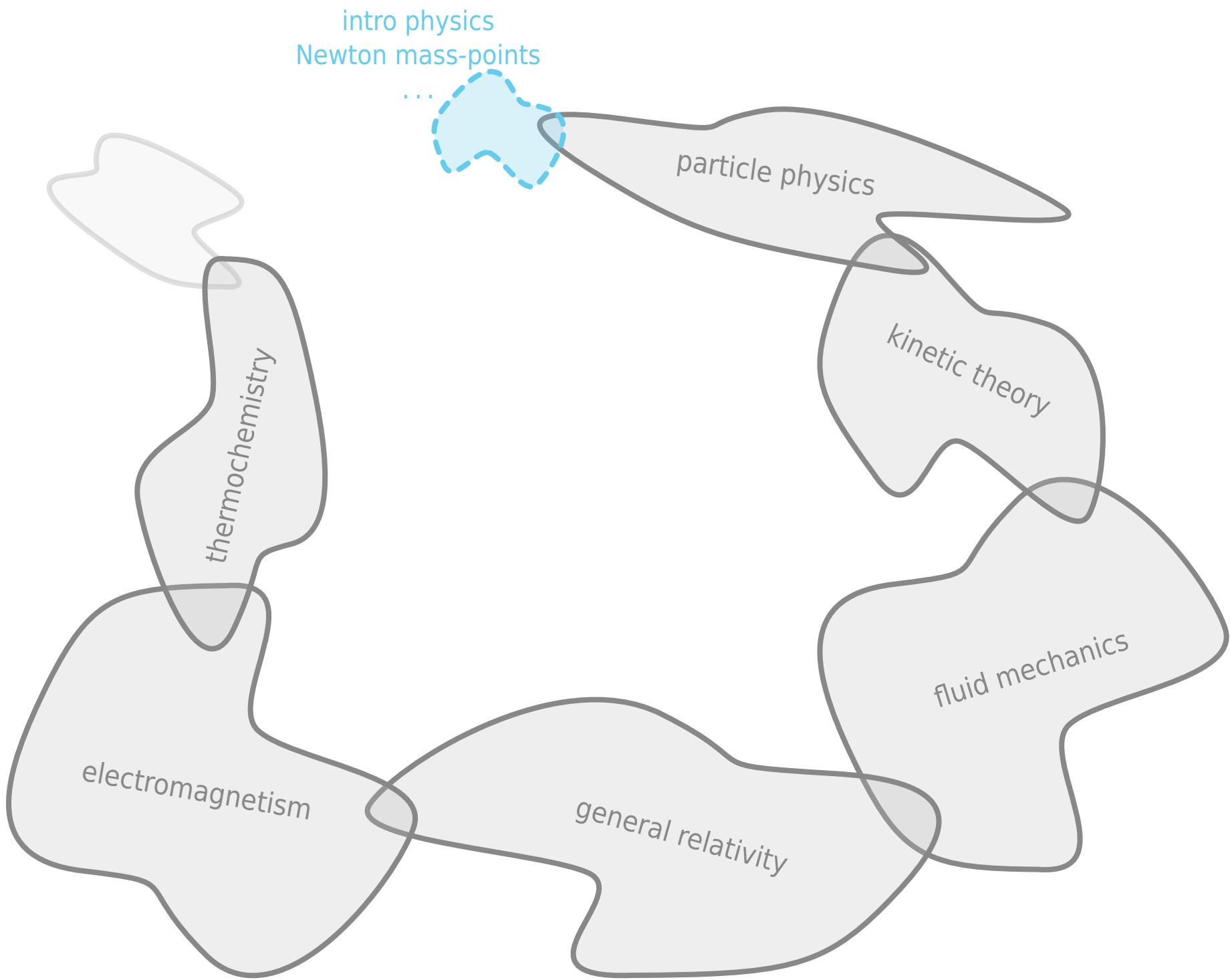
General relativity  
QFT

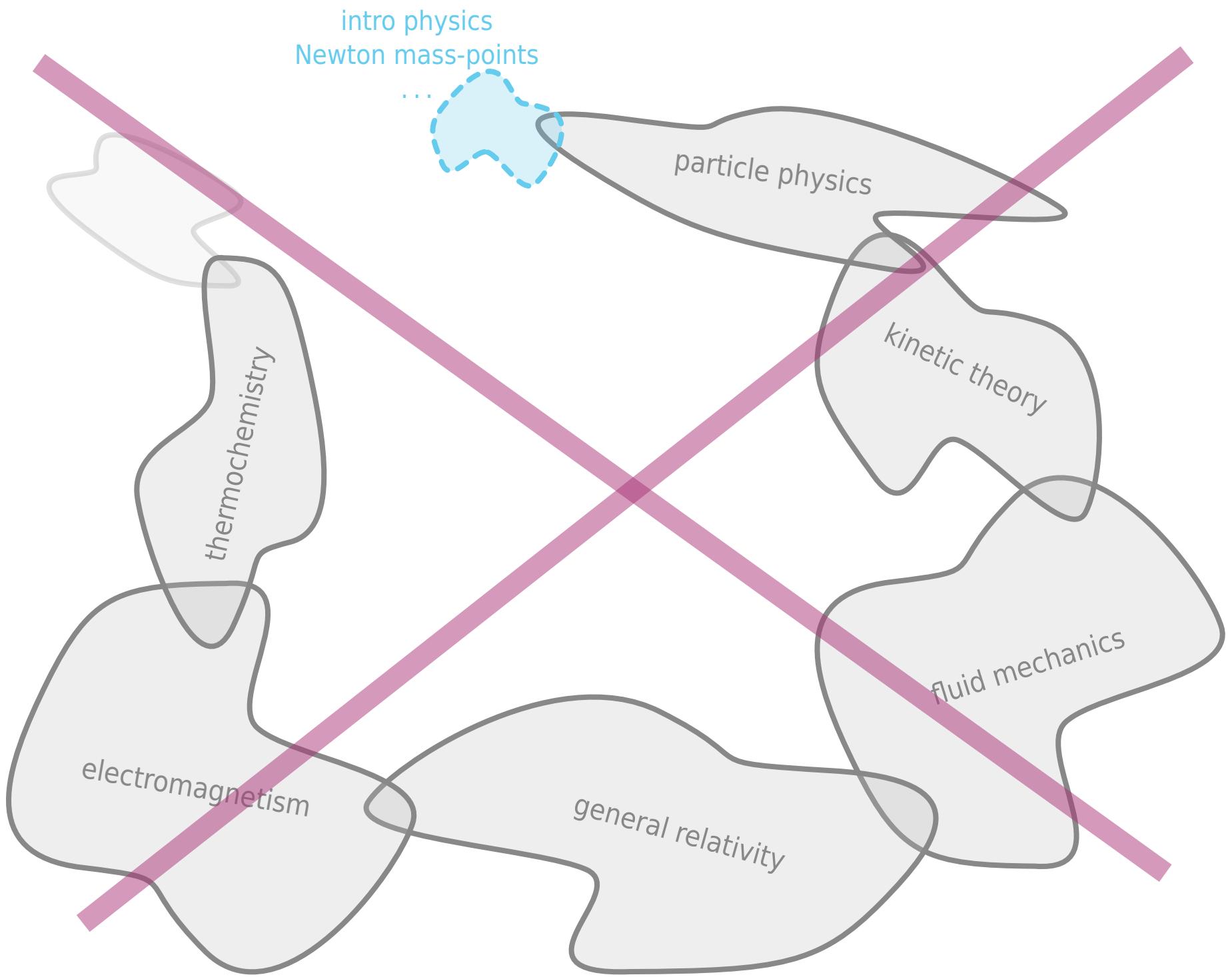


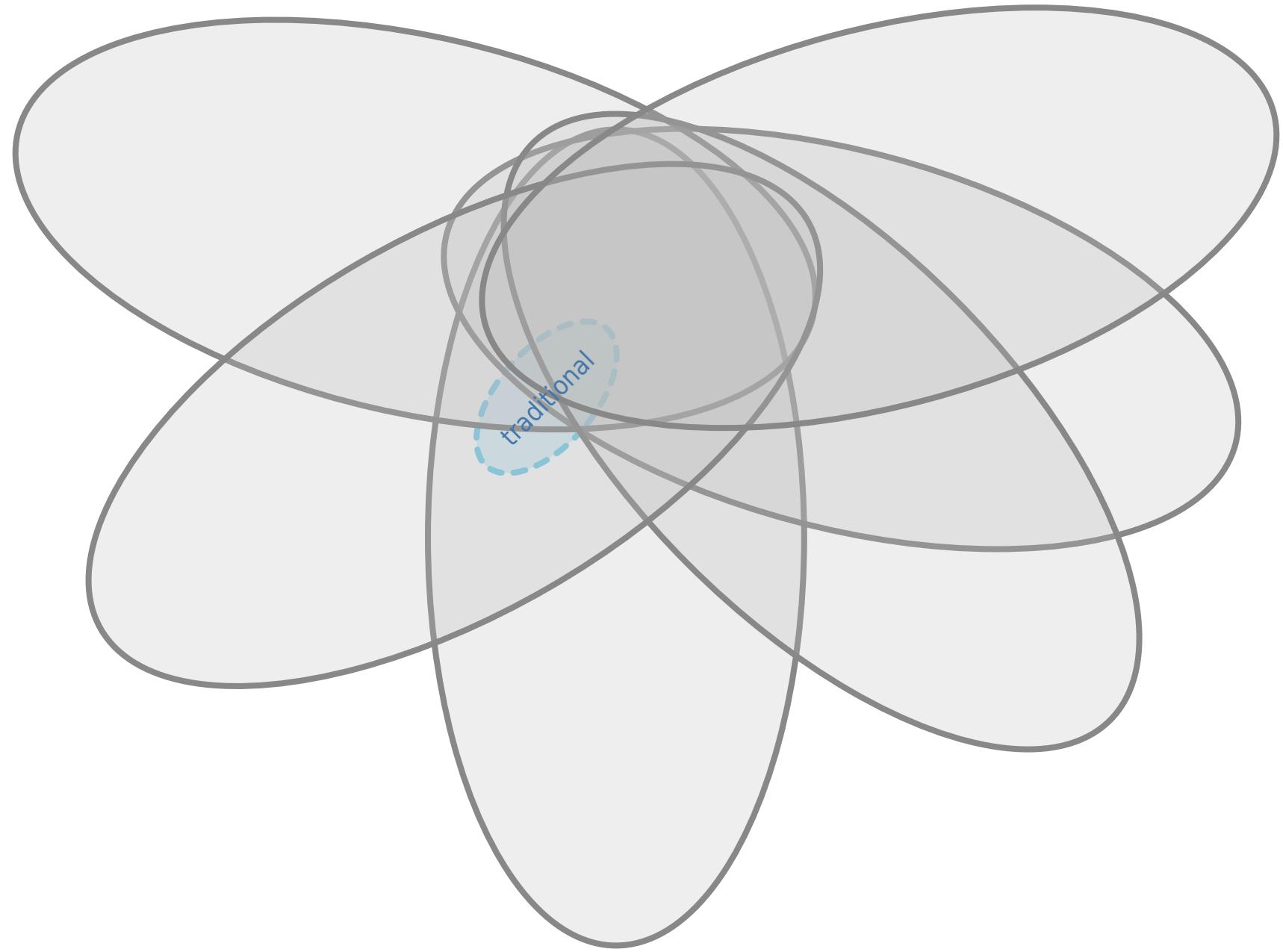
Continuum thermomechanics  
Polymer physics



Fluid mechanics  
Ocean & atm. modelling

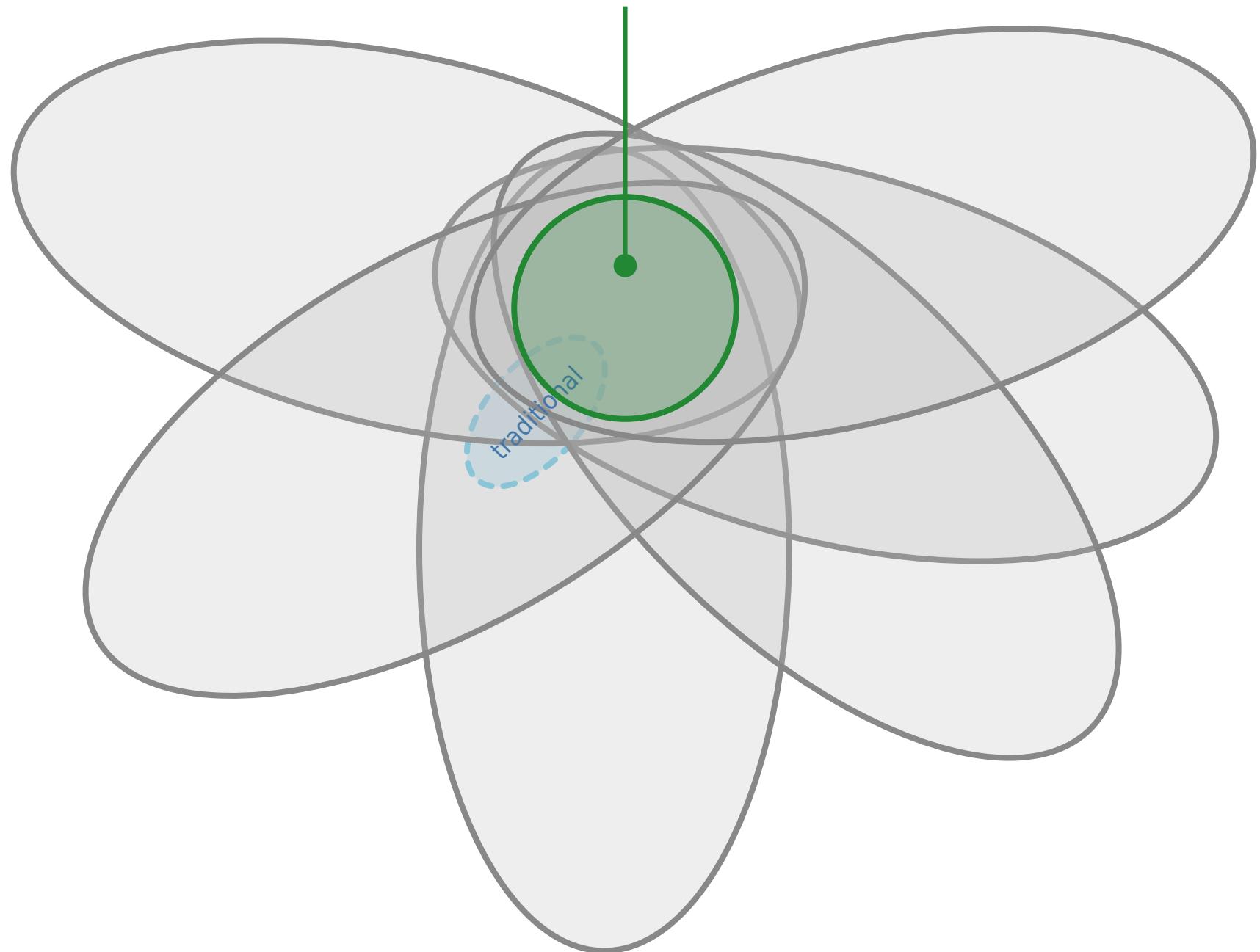






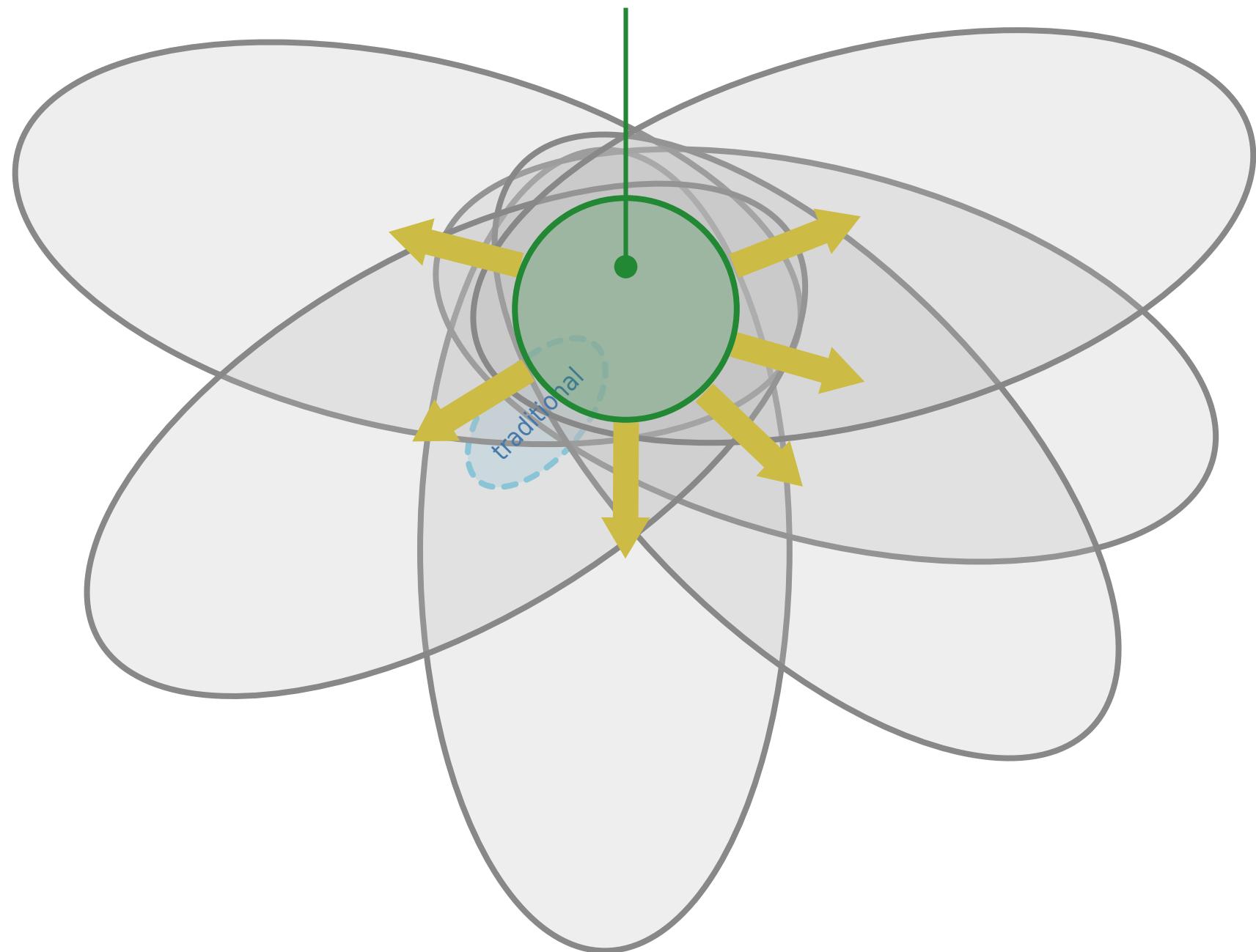
Common core of notions

Common core of  
*thinking framework*



## Common core of notions

## Common core of *thinking framework*

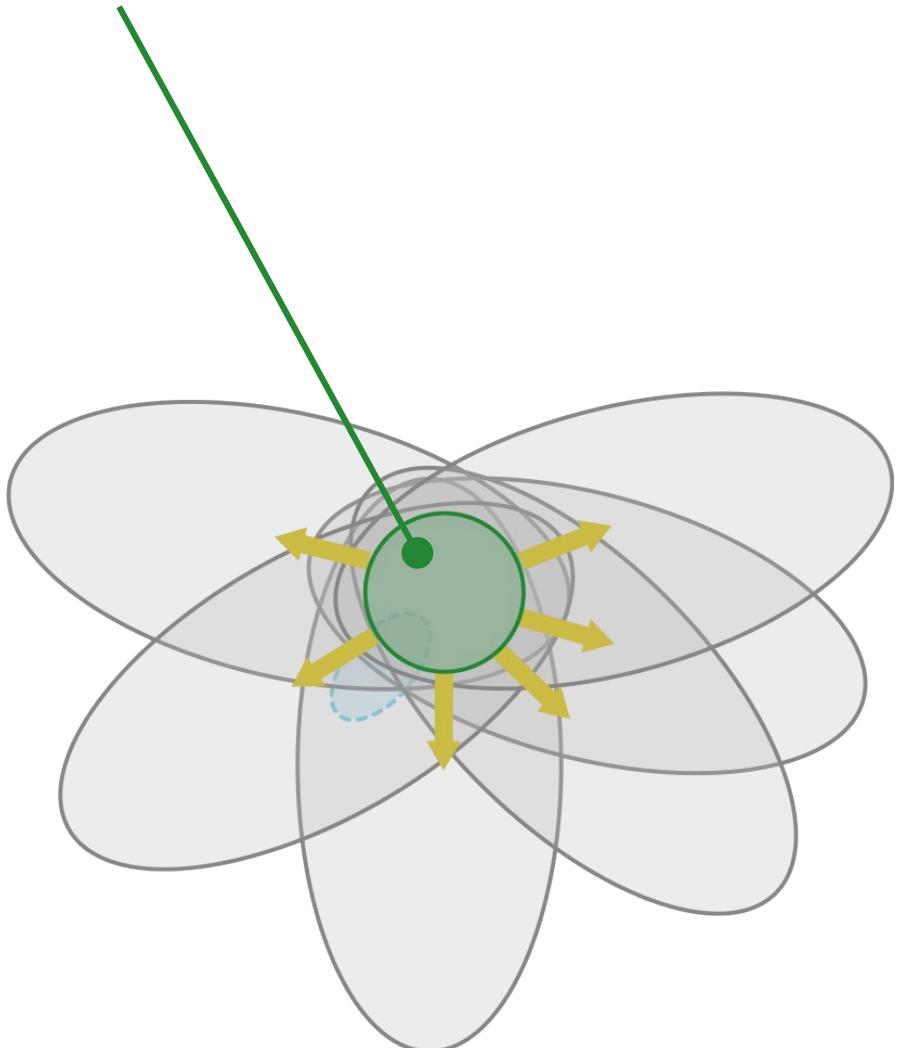


# Common to all physics disciplines

## Simple & intuitive

## Modular

## Immediate numerical application



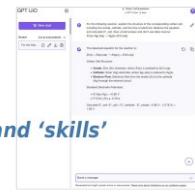
① Consider all possible career paths a student might follow



② Intro-physics course meaningful for all study programmes?



③ 'Multiphysics'



④ Large Language Models are redefining 'knowledge' and 'skills'



⑤ Numerical methods



⑥ Today, what's the physics in everyday technologies?

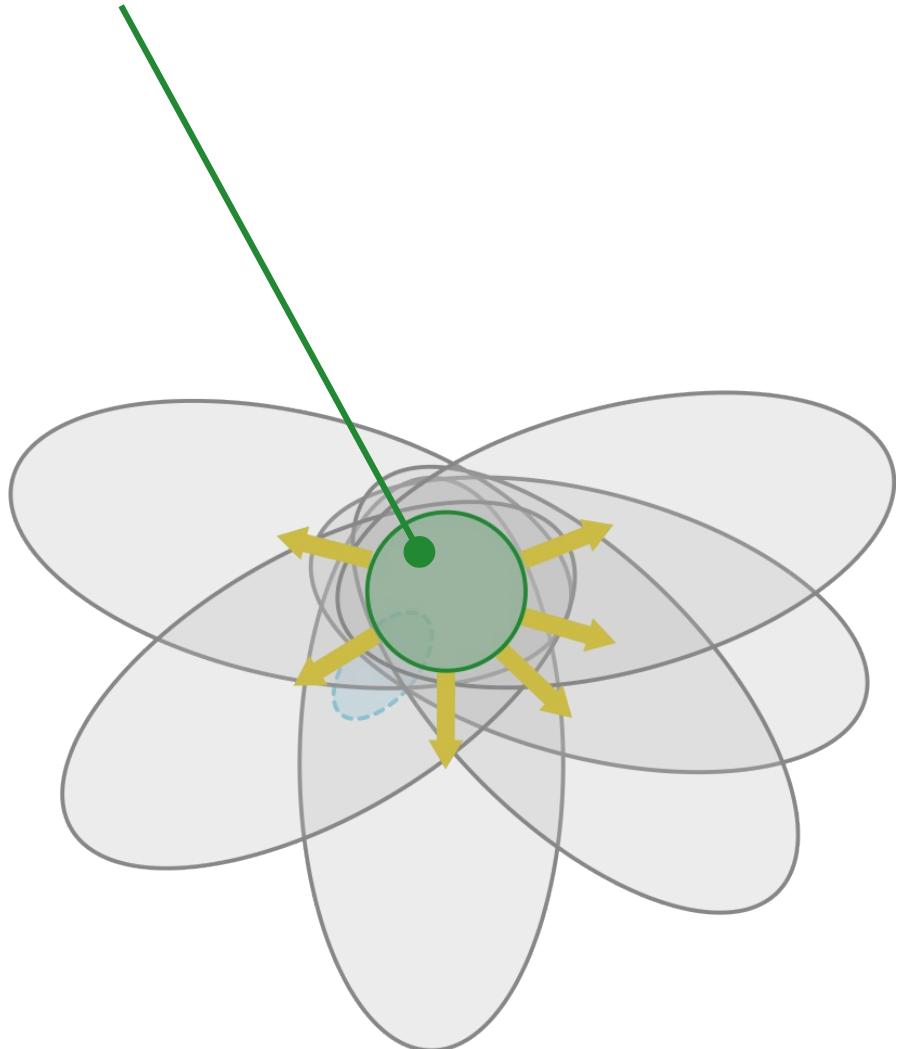
⑦ ...

# Common to all physics disciplines

## Simple & intuitive

## Modular

## Immediate numerical application



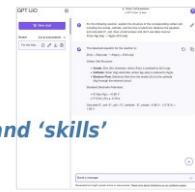
① Consider all possible career paths a student might follow



② Intro-physics course meaningful for all study programmes?



③ 'Multiphysics'



④ Large Language Models are redefining 'knowledge' and 'skills'



⑤ Numerical methods



⑥ Today, what's the physics in everyday technologies?

⑦ ...

I wish  
they had taught me  
this way of thinking  
from the start!



Ideas & current experiments  
for a different introductory-physics course  
at Western Norway University

## *Judging & evaluating possible changes in intro-physics: biases*

## ***Judging & evaluating possible changes in intro-physics: biases***

- ➊ Sceptical reaction?
  - Because of real physical or pedagogical motivations? Or...

## ***Judging & evaluating possible changes in intro-physics: biases***

### ➊ Sceptical reaction?

- Because of real physical or pedagogical motivations? Or...
- Because of questioning something you learned with many years of hard work?  
(a completely understandable and natural reaction!)

## ***Judging & evaluating possible changes in intro-physics: biases***

### **! Sceptical reaction?**

- Because of real physical or pedagogical motivations? Or...
- Because of questioning something you learned with many years of hard work?  
(a completely understandable and natural reaction!)

### **! Can we judge *unfamiliarity to students* based on *unfamiliarity to teachers*?**

## ***Judging & evaluating possible changes in intro-physics: biases***

### **! Sceptical reaction?**

- Because of real physical or pedagogical motivations? Or...
- Because of questioning something you learned with many years of hard work?  
(a completely understandable and natural reaction!)

### **! Can we judge *unfamiliarity to students* based on *unfamiliarity to teachers*?**

### **! Remember that *education shapes our world-view and what's intuitive***

- Ancient Greek or Roman wouldn't understand "I feel full of energy today"

## **Judging & evaluating possible changes in intro-physics: biases**

### ! Sceptical reaction?

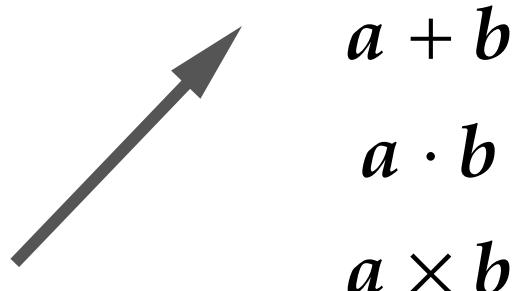
- Because of real physical or pedagogical motivations? Or...
- Because of questioning something you learned with many years of hard work?  
(a completely understandable and natural reaction!)

### ! Can we judge *unfamiliarity* to students based on *unfamiliarity* to teachers?

### ! Remember that *education shapes our world-view and what's intuitive*

- Ancient Greek or Roman wouldn't understand "I feel full of energy today"

### ! Remember the example from *vector calculus*



# Judging & evaluating possible changes in intro-physics: biases

## ! Sceptical reaction?

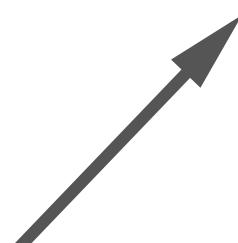
- Because of real physical or pedagogical motivations? Or...
- Because of questioning something you learned with many years of hard work?  
(a completely understandable and natural reaction!)

## ! Can we judge *unfamiliarity* to students based on *unfamiliarity* to teachers?

## ! Remember that *education shapes our world-view and what's intuitive*

- Ancient Greek or Roman wouldn't understand "I feel full of energy today"

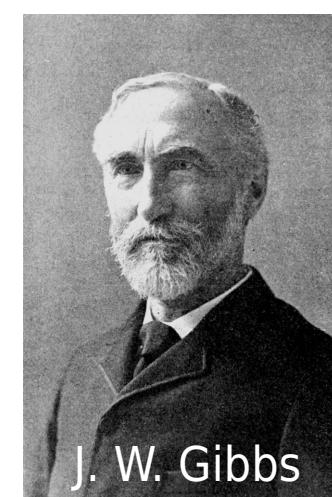
## ! Remember the example from *vector calculus*



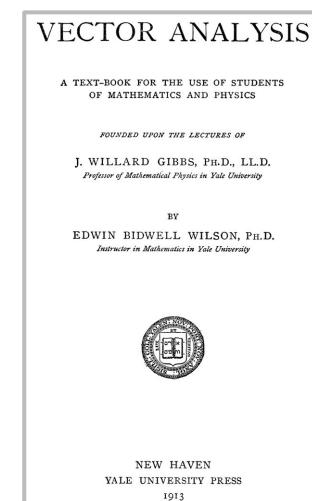
$$\mathbf{a} + \mathbf{b}$$

$$\mathbf{a} \cdot \mathbf{b}$$

$$\mathbf{a} \times \mathbf{b}$$



J. W. Gibbs



## ***Main features of the alternative perspective***

- 💡 Borrow & simplify concepts and viewpoint of continuum physics & fluid mechanics

## ***Main features of the alternative perspective***

- 💡 Borrow & simplify concepts and viewpoint of continuum physics & fluid mechanics
- ❗ Student must still be able to follow and understand traditional perspective & jargon!

## ***Main features of the alternative perspective***

⌚ Emphasis on *physical laws that apply in every discipline* vs *specific laws*

**seven  
universal  
balance laws**



Apply to all physical phenomena

Apply (unchanged) in all disciplines

Apply (unchanged) in Newton & non-Newton

Have the meaning of a 'budget'

**(countless)  
constitutive  
equations**



Each applies only to specific phenomena

Different in different disciplines

Different between Newton/non-Newton

Have a connective purpose

# Universal balance laws

balance of matter (mass)

$$\frac{dN}{dt} = J + \mathcal{A}$$

balance of momentum

$$\frac{dP}{dt} = F + G$$

balance of energy

$$\frac{dE}{dt} = \Phi + \mathcal{R}$$

balance of angular momentum

$$\frac{dL}{dt} = M + \mathcal{T}$$

conservation of magnetic flux

$$\frac{d\mathcal{B}}{dt} = -\mathcal{E}$$

conservation of electric charge

$$\frac{dQ}{dt} = \mathcal{I}$$

balance of entropy

$$\frac{dS}{dt} \geq \Pi$$

# Constitutive equations (examples)

momentum for matter  
(Newton approx)

$$P = mv$$

momentum for matter  
(special relativity)

$$P = \frac{m_0 v}{\sqrt{1 - v^2/c^2}}$$

momentum for electromagnetic field

$$\frac{P}{V} = \epsilon_0 E \times B$$

force for matter  
ideal gas

$$\frac{F}{A} = \frac{RNT}{V}$$

force for matter  
Hookean spring

$$F = -k(r_1 - r_2)$$

energy for matter

$$E = U + \frac{1}{2}mv^2 + mgz$$

energy for matter  
ideal gas

$$E = CNT$$

energy for electromagnetic field

$$\frac{E}{V} = \frac{1}{2}\epsilon_0 E^2 + \frac{1}{2\mu_0}B^2$$

energy flux  
Newton's law of cooling

$$\Phi = A h (T_1 - T_2)$$

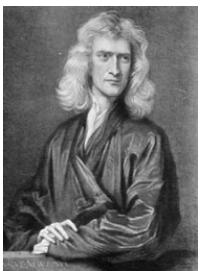


## Balance of momentum

$$\frac{d\mathbf{P}}{dt} = \mathbf{F} + \mathbf{G}$$

## Balance of momentum

$$\mathbf{P} = m \mathbf{v}$$



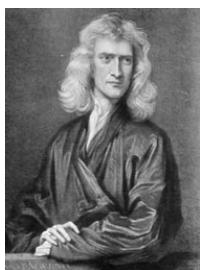
constitutive equation

$$\frac{d\mathbf{P}}{dt} = \mathbf{F} + \mathbf{G}$$

## Balance of momentum

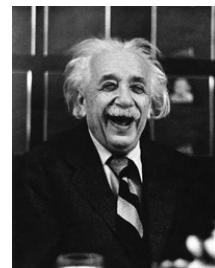
$$\frac{d\mathbf{P}}{dt} = \mathbf{F} + \mathbf{G}$$

$$\mathbf{P} = m \mathbf{v}$$



*constitutive equation*

$$\mathbf{P} = \frac{m_0 \mathbf{v}}{\sqrt{1 - \mathbf{v}^2/c^2}}$$



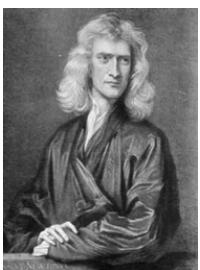
## Balance of momentum

$$\frac{d\mathbf{P}}{dt} = \mathbf{F} + \mathbf{G}$$

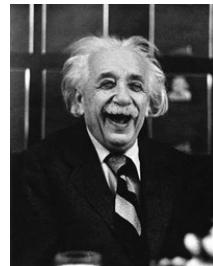
*constitutive equation*

$$\mathbf{P} = \frac{1}{V} \epsilon_0 \mathbf{E} \times \mathbf{B}$$

$$\mathbf{P} = m \mathbf{v}$$



$$\mathbf{P} = \frac{m_0 \mathbf{v}}{\sqrt{1 - \mathbf{v}^2/c^2}}$$



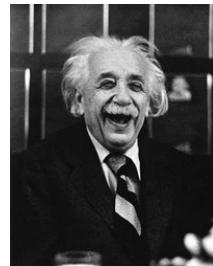
## Balance of momentum

$$\frac{d\mathbf{P}}{dt} = \mathbf{F} + \mathbf{G}$$

$$\mathbf{P} = m \mathbf{v}$$



$$\mathbf{P} = \frac{m_0 \mathbf{v}}{\sqrt{1 - \mathbf{v}^2/c^2}}$$

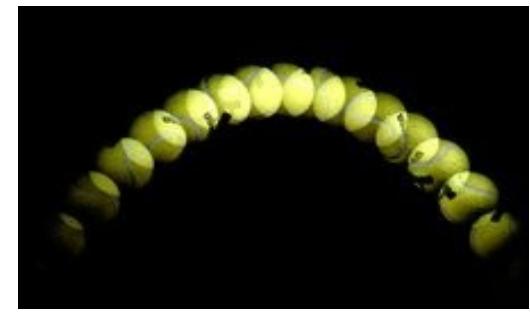


$$\mathbf{P} = \frac{1}{V} \epsilon_0 \mathbf{E} \times \mathbf{B}$$



## ***Main features of the alternative perspective***

- Code/simulation as a way to understand the universal/constitutive difference



$$\left\{ \begin{array}{l} \mathbf{P} = m\mathbf{v} \\ \frac{d\mathbf{P}}{dt} = \mathbf{F} \\ \frac{d\mathbf{r}}{dt} = \mathbf{v} \end{array} \right.$$

$$\left\{ \begin{array}{l} P = mv \\ \frac{dP}{dt} = F \\ \frac{dr}{dt} = v \end{array} \right. \Rightarrow m \frac{d^2r}{dt^2} = F \quad \rightarrow \text{solve analytically}$$



$$\left\{ \begin{array}{l} P = mv \\ \frac{dP}{dt} = F \\ \frac{dr}{dt} = v \end{array} \right.$$

$\Rightarrow$

$$m \frac{d^2r}{dt^2} = F \quad \rightarrow \text{solve analytically}$$



$$P = mv$$

$$\frac{dP}{dt} = F$$

$$\frac{dr}{dt} = v$$

$\Rightarrow$

$$m \frac{d^2r}{dt^2} = F \quad \rightarrow \text{solve analytically}$$





$$\left\{ \begin{array}{l} \mathbf{P} = m\mathbf{v} \\ \frac{d\mathbf{P}}{dt} = \mathbf{F} \\ \frac{d\mathbf{r}}{dt} = \mathbf{v} \end{array} \right.$$



$$\left\{ \begin{array}{l} P = mv \\ \frac{dP}{dt} = F \\ \frac{dr}{dt} = v \end{array} \right. \quad \begin{array}{l} P(t + \Delta t) \approx P(t) + F(t) \Delta t \\ r(t + \Delta t) \approx r(t) + v(t) \Delta t \end{array}$$



$$\left\{ \begin{array}{ll} P = mv & P = mv \\ \frac{dP}{dt} = F & P(t + \Delta t) \approx P(t) + F(t) \Delta t \\ \frac{dr}{dt} = v & r(t + \Delta t) \approx r(t) + v(t) \Delta t \end{array} \right.$$

$$\left\{ \begin{array}{l} P = mv \\ \frac{dP}{dt} = F \\ \frac{dr}{dt} = v \end{array} \right.$$

$$\xrightarrow{\hspace{1cm}}$$

$$P = mv$$

$$P(t + \Delta t) \approx P(t) + F(t) \Delta t$$

$$r(t + \Delta t) \approx r(t) + v(t) \Delta t$$

$$v = P/m$$



$$\left\{ \begin{array}{l} P = mv \\ \frac{dP}{dt} = F \\ \frac{dr}{dt} = v \end{array} \right.$$

$$P = mv$$

$$P(t + \Delta t) \approx P(t) + F(t) \Delta t$$

$$r(t + \Delta t) \approx r(t) + v(t) \Delta t$$

$$v = P/m$$



```

while t < t1
    %% find momentum with constitutive eq.
    P = m * v;

    %% step forward in time with balance laws
    t = t + dt;
    P = P + F * dt;
    r = r + v * dt;

    %% find velocity to repeat loop
    v = P / m;
end

```

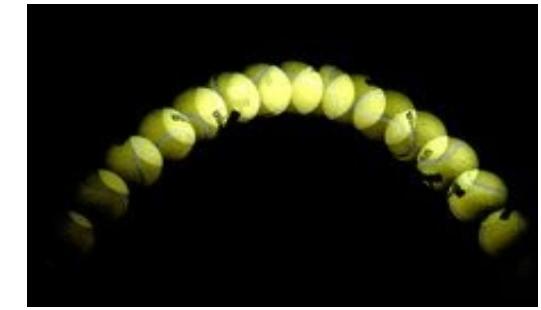
$$\left\{ \begin{array}{l} P = mv \\ \frac{dP}{dt} = F \\ \frac{dr}{dt} = v \end{array} \right.$$

$$P = mv$$

$$P(t + \Delta t) \approx P(t) + F(t) \Delta t$$

$$r(t + \Delta t) \approx r(t) + v(t) \Delta t$$

$$v = P/m$$



```

while t < t1
    %% find momentum with constitutive eq.
    P = m * v / sqrt(1 - norm(v)^2 / c^2);

    %% step forward in time with balance laws
    t = t + dt;
    P = P + F * dt;
    r = r + v * dt;

    %% find velocity to repeat loop
    v = P / sqrt(m^2 + norm(P)^2 / c^2);
end

```

$$\left\{ \begin{array}{l} P = mv \\ \frac{dP}{dt} = F \\ \frac{dr}{dt} = v \end{array} \right.$$

$$P = mv$$

$$P(t + \Delta t) \approx P(t) + F(t) \Delta t$$

$$r(t + \Delta t) \approx r(t) + v(t) \Delta t$$

$$v = P/m$$



```

while t < t1
    %% find momentum with constitutive eq.
    P = m * v / sqrt(1 - norm(v)^2 / c^2);

    %% step forward in time with balance laws
    t = t + dt;
    P = P + F * dt;
    r = r + v * dt;

    %% find velocity to repeat loop
    v = P / sqrt(m^2 + norm(P)^2 / c^2);
end

```



<https://octave.org>

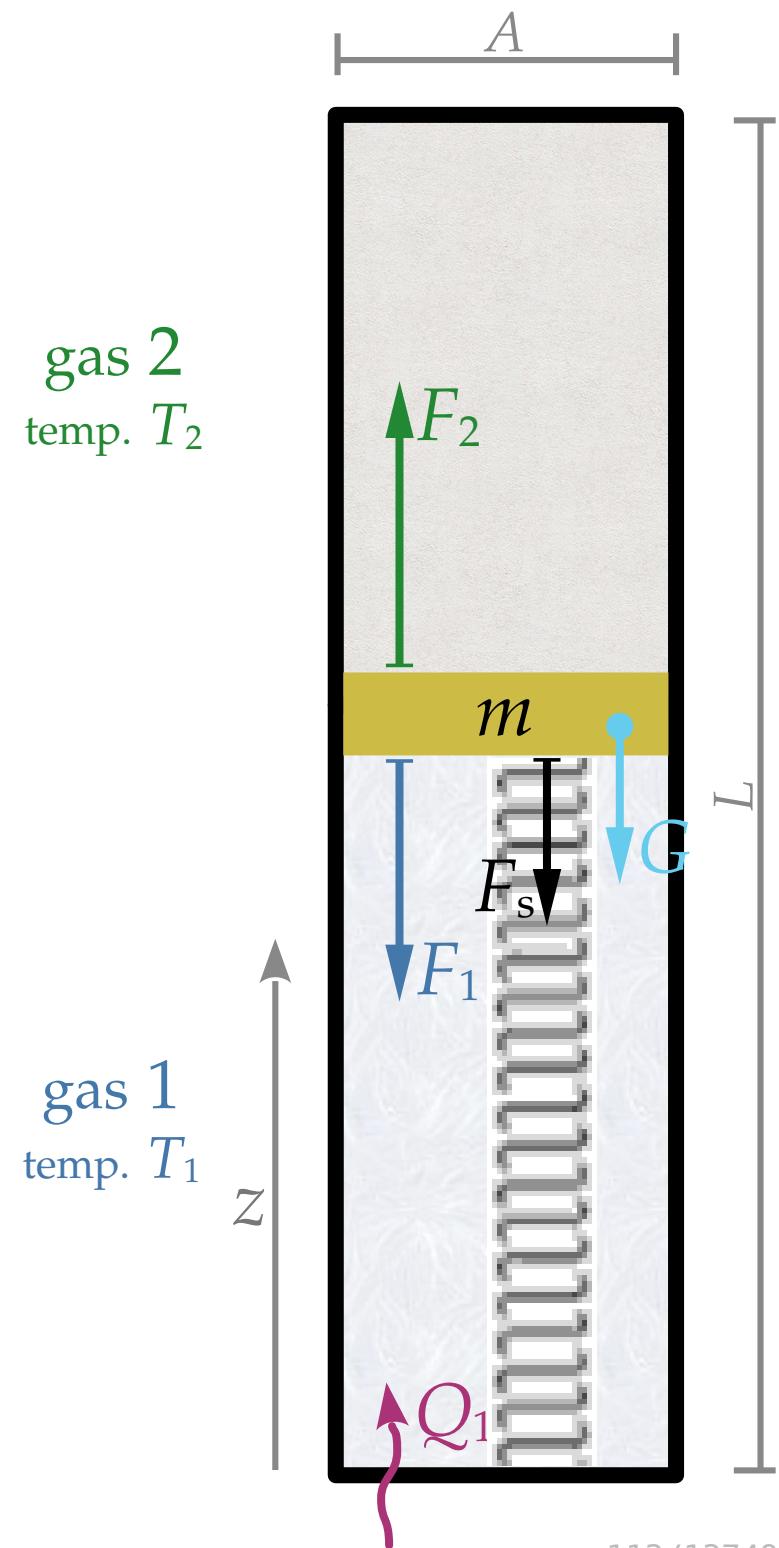


<https://python.org>

# 'Multiphysics'

two ideal gases (non-equilibrium)  
piston with mass & gravity  
Hookean spring  
heat flux

- mechanics + thermodynamics
- non-linear (no analytic solution)

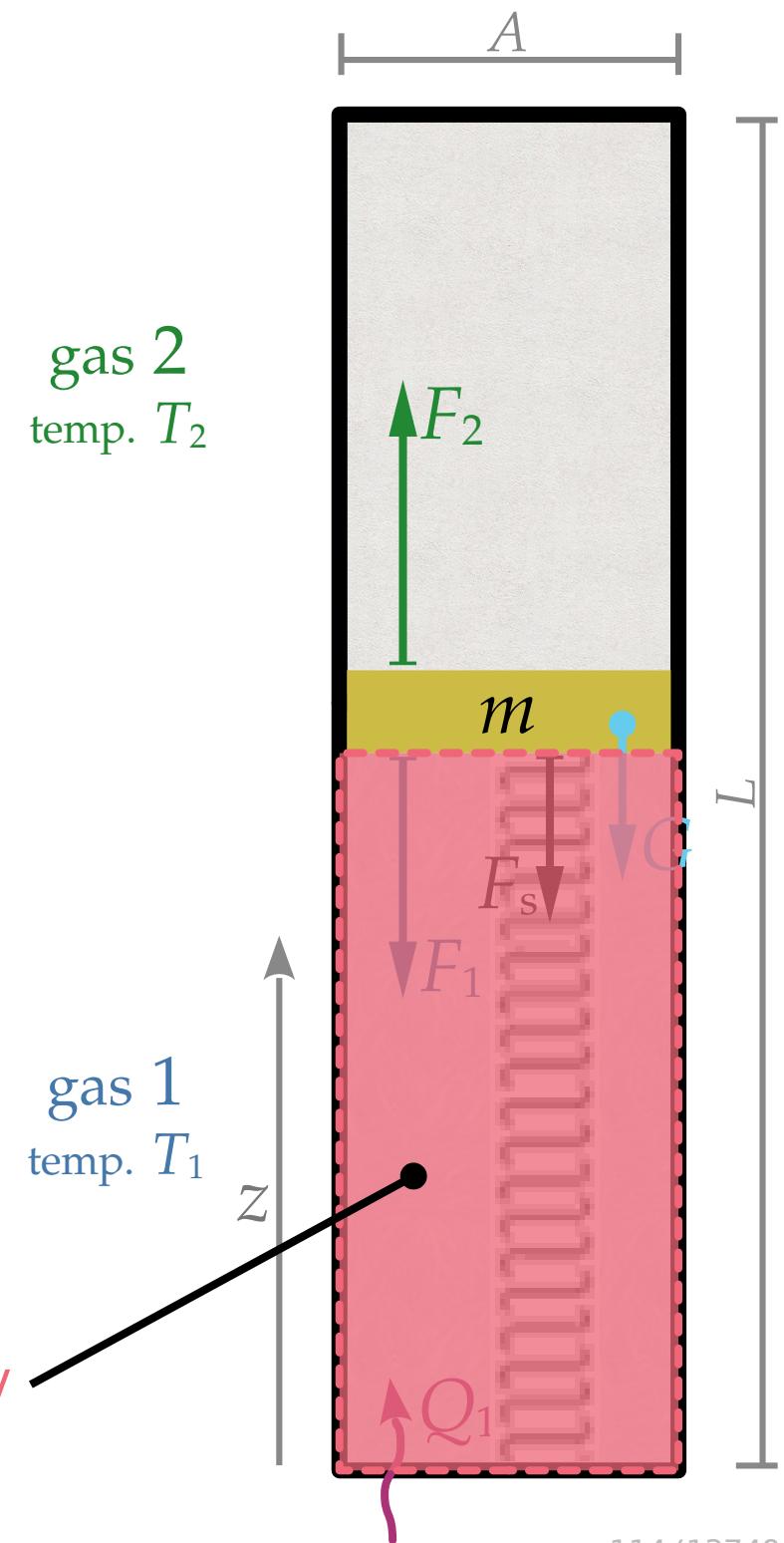


# 'Multiphysics'

two ideal gases (non-equilibrium)  
piston with mass & gravity  
Hookean spring  
heat flux

- mechanics + thermodynamics
- non-linear (no analytic solution)

balance of energy

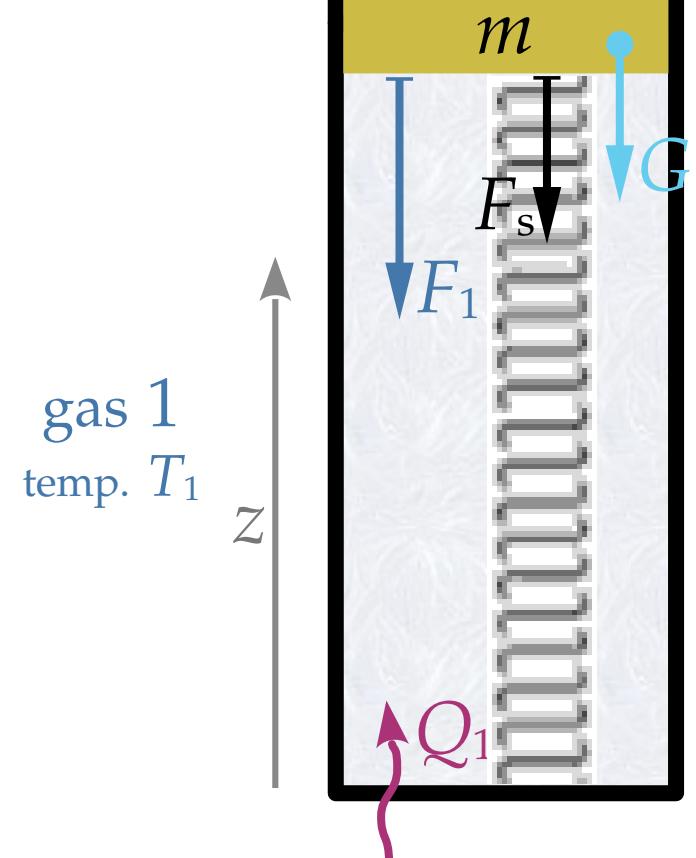


# 'Multiphysics'

two ideal gases (non-equilibrium)  
piston with mass & gravity  
Hookean spring  
heat flux

balance of energy

gas 2  
temp.  $T_2$



- mechanics + thermodynamics
- non-linear (no analytic solution)

# 'Multiphysics'

two ideal gases (non-equilibrium)  
piston with mass & gravity  
Hookean spring  
heat flux

- mechanics + thermodynamics
- non-linear (no analytic solution)

balance of momentum

gas 2  
temp.  $T_2$

$m$

$F_s$

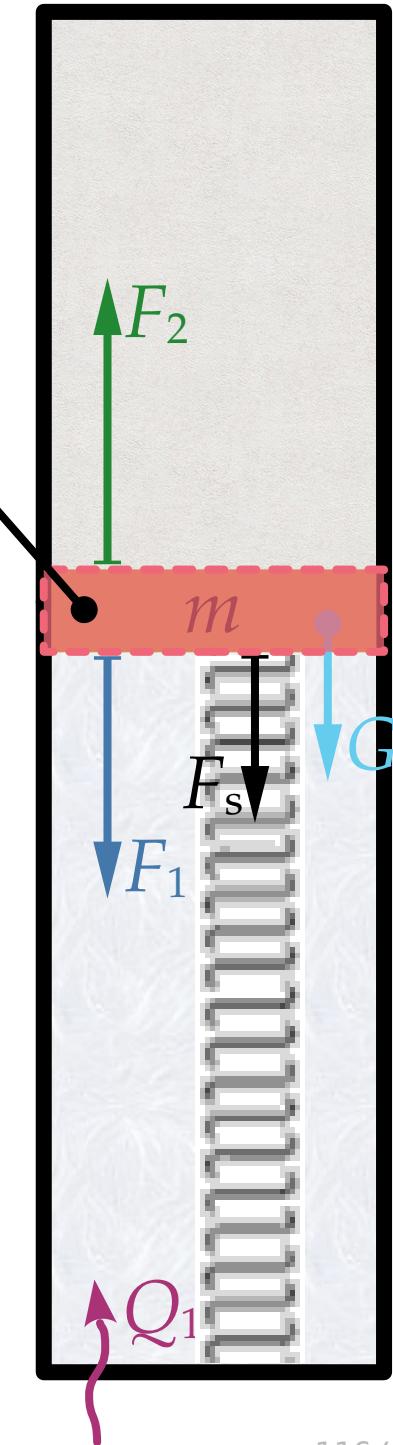
$F_1$

gas 1  
temp.  $T_1$

$Q_1$

$A$

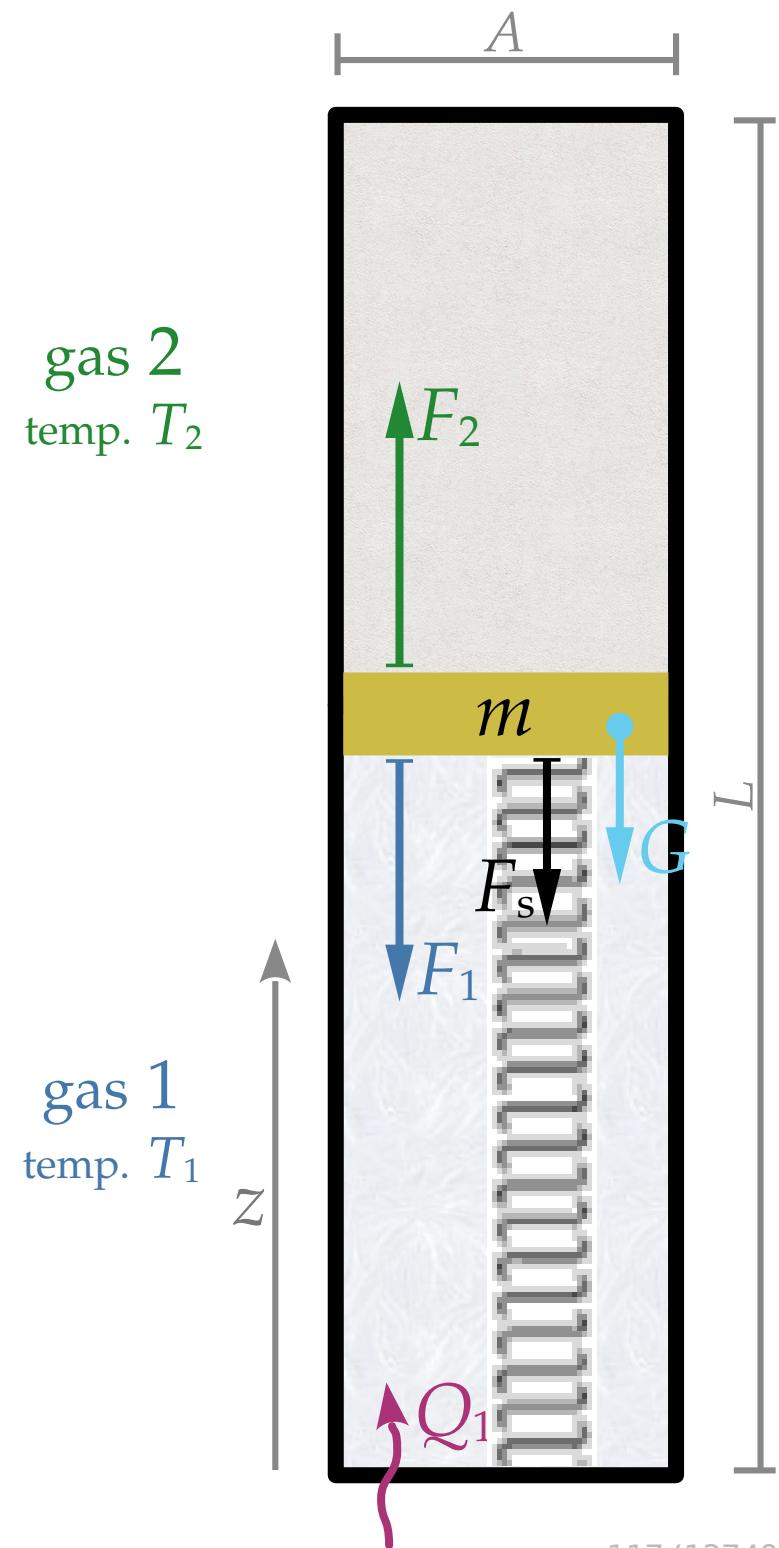
$L$



# 'Multiphysics'

two ideal gases (non-equilibrium)  
piston with mass & gravity  
Hookean spring  
heat flux

- mechanics + thermodynamics
- non-linear (no analytic solution)



```

while t < t1
    V1 = A * z;           % volume gas 1
    V2 = A * (L - z);   % volume gas 2

    %% constitutive relations
    F1 = R * N1 * T1 / z;      % ideal-gas law (force)
    F2 = -R * N2 * T2 / z;    % ideal-gas law (force)
    Fs = -k * z;              % Hooke's law (force)
    F = F1 + F2 + Fs;         % net force on piston
    P = m * v;                % Newton's formula for momentum

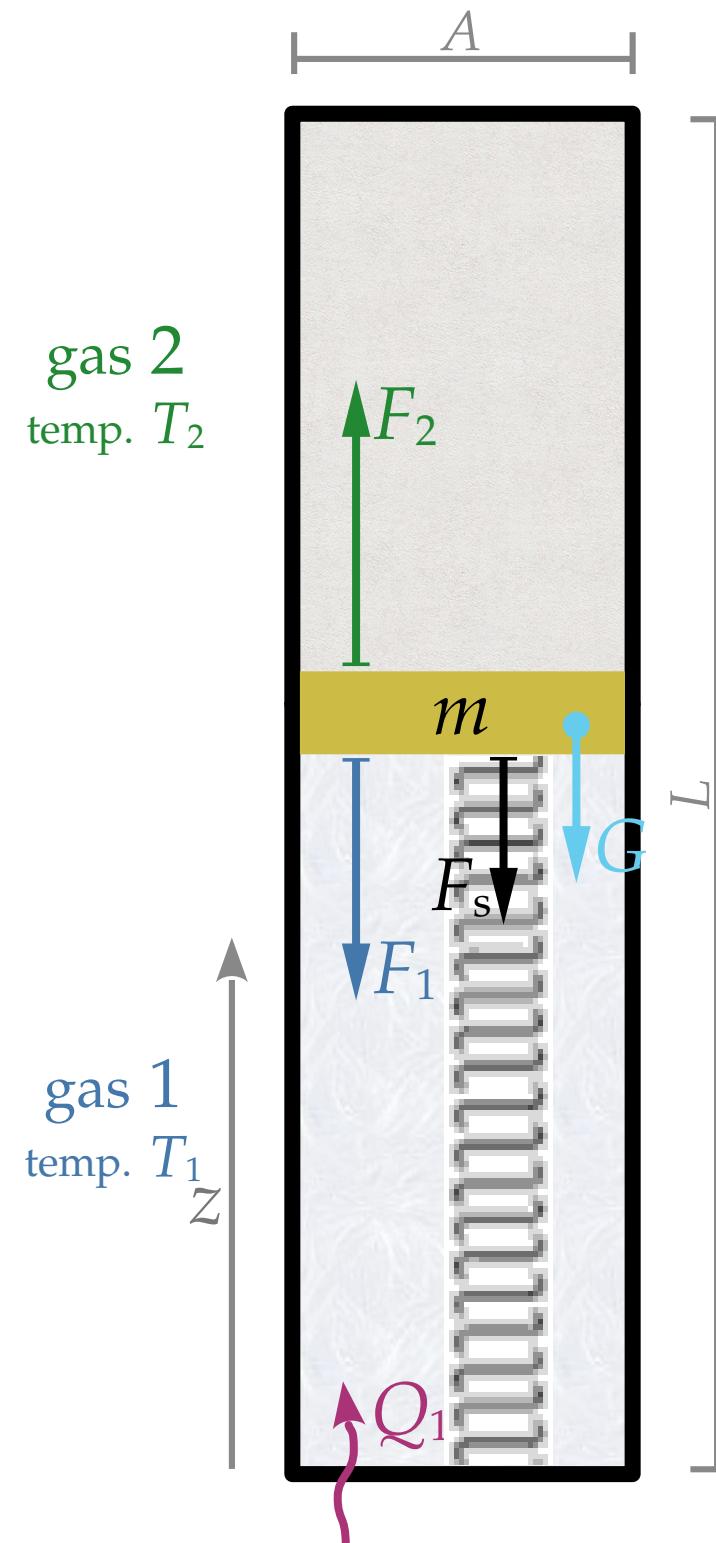
    Q1 = A * h * (Text - T1); % law of cooling gas 1
    Phi1 = Q1 - F1 * v;       % energy influx for gas 1
    E1 = C * N1 * T1;         % internal energy of ideal gas 1

    Phi2 = Q2 - F2 * v;       % energy influx for gas 2
    E2 = C * N2 * T2;         % internal energy of ideal gas 2

    %% step forward in time with balance laws
    t = t + dt;
    E1 = E1 + Phi1 * dt;     % energy balance gas 1
    E2 = E2 + Phi2 * dt;     % energy balance gas 2
    P = P + (F + G) * dt;   % momentum balance piston
    z = z + v * dt;          % update position piston

    %% constitutive relations
    T1 = E1 / (C * N1);    % temperature gas 1
    T2 = E2 / (C * N2);    % temperature gas 2
    v = P / m;               % velocity of piston
end

```



$A$

```

while t < t1
  V1 = A * z;           % volume gas 1
  V2 = A * (L - z);    % volume gas 2

```

```

%% constitut
F1 = R * N1
F2 = -R * N2
Fs = -k * z;
F = F1 + F2
P = m * v;

```

```

Q1 = A * h *
Phi1 = Q1 -
E1 = C * N1

```

```

Phi2 = Q2 -
E2 = C * N2

```

```

%% step forward
t = t + dt;
E1 = E1 + Phi1;
E2 = E2 + Phi2;
P = P + (F +
z = z + v *

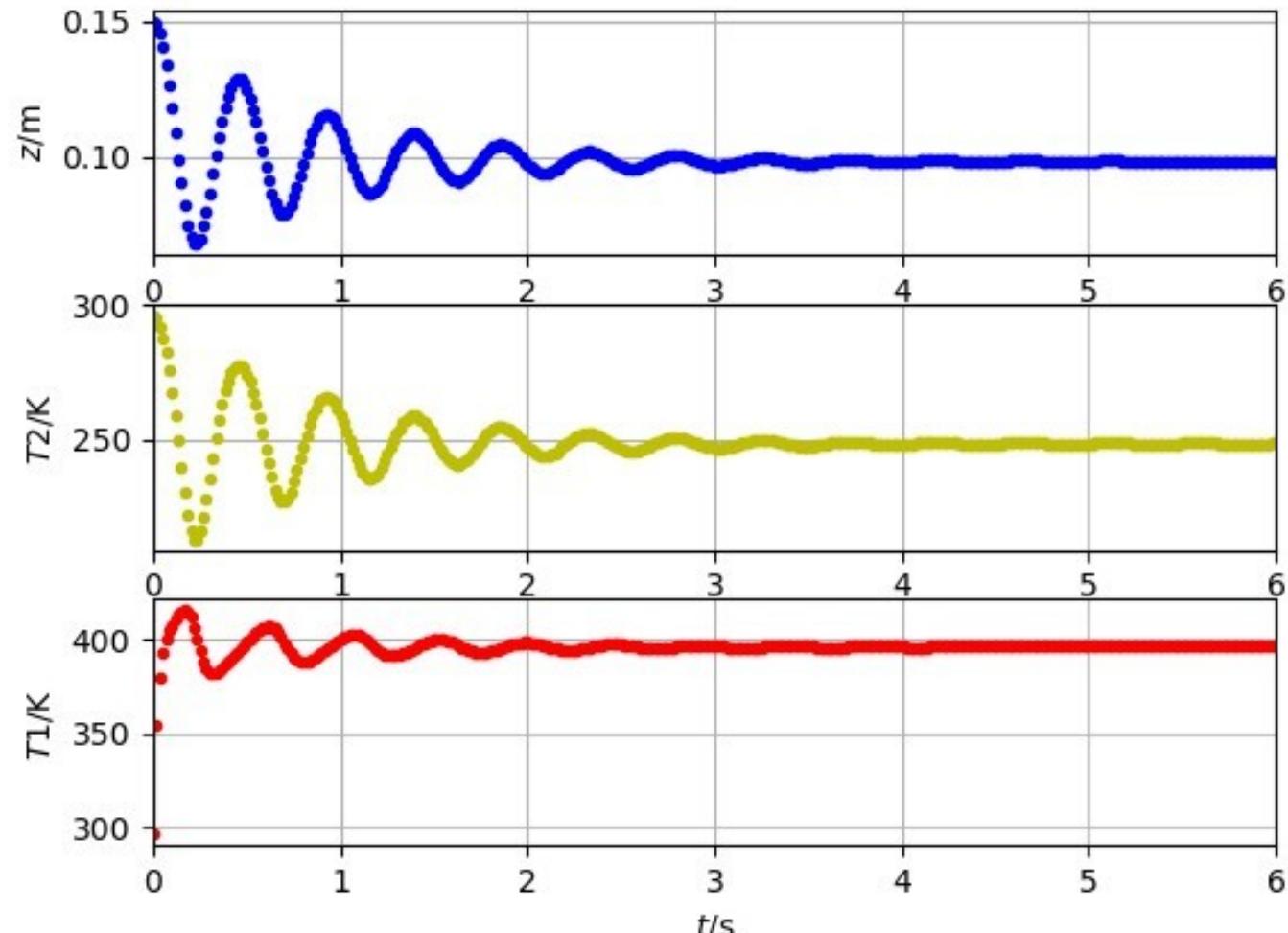
```

```

%% constitut
T1 = E1 / (C
T2 = E2 / (C
v = P / m;

```

end



$T_2$

$m$

$F_s$

$G$

$L$

$Q_1$

## **Main features of the alternative perspective**

- ⌚ Slightly different method of application: “control volume” vs “body”
  - simple and works universally
  - student is ready for fluid dynamics, building eng., chemistry, gen. relativity...
  
- ⌚ Emphasize identity between *force* and *momentum flux* (*flow rate, current*)
  - helps understanding viscosity, electromagnetism
  - student is ready for fluid dynamics, transport phenomena, high-en. physics

## ***Main features of the alternative perspective***

- ⌚ De-emphasis of “ $P = m v$ ”
- ⌚ Emphasize some modern understandings from relativity & quantum theory

## **Emphasize some modern understandings from relativity & quantum theory**

rate of increase of momentum  
(force, momentum flux)

$$\mathbf{F}$$

rate of increase of energy  
(energy flux)

$$Q + \mathbf{F} \cdot \mathbf{v}$$

*heat*    *mechanical power*  
*(work)*

## **Emphasize some modern understandings from relativity & quantum theory**

rate of increase of momentum  
(force, momentum flux)

$$\mathbf{F} + \frac{1}{c^2} \mathbf{Q} \mathbf{v} + \dots$$

rate of increase of energy  
(energy flux)

$$\mathbf{Q} + \mathbf{F} \cdot \mathbf{v} + \dots$$

*heat*    *mechanical power*  
*(work)*

## **Main features of the alternative perspective**



“Discuss” with LLM, *find errors in LLM’s reasoning*

## “Discuss” with LLM, find errors in LLM’s reasoning

This question was asked to ChatGPT:

“An amount of gas is at rest in a rectangular container with side area  $A$ . The total energy content of the gas is  $E$ ; the internal pressure is  $p$  and is the same throughout the gas. There is no heat flux in the gas. Consider an *imaginary* vertical control surface with area  $A$  moving with constant horizontal velocity  $u$  in the container, from the left side to the right side. How much is the flux of energy  $\Phi$  through this surface?”

ChatGPT answered this question by using the constitutive formula for the energy flux:

$$\Phi = Q + \mathbf{F} \cdot \mathbf{v}$$

together with  $F = p A$ , and said that the energy flux through the control surface is  $\Phi = p A u$ , because there's no heat flux  $Q$ . This answer is wrong!

Explain why ChatGPT cannot use the constitutive formula above in this case.  
*(Note: you do not need to find the correct formula. This oppgave can be answered in less than 40 words. Feel free to write more if you like, but only after you have focused on the other oppgaver.)*

**(a) Den følgende spørsmålsstillingen ble gitt til ChatGPT:**

*Consider a helicopter in space, with no air and no gravitational field. The tail rotor is missing. In an inertial coordinate system, is it possible to have a situation in which the main rotor is rotating with constant angular velocity, while the rest of the helicopter is not rotating?*

ChatGPTs svar var som følger:

No, it is not possible. In space, without air or a gravitational field, if the main rotor is rotating, it would exert a torque on the helicopter body due to conservation of angular momentum. This would cause the helicopter to rotate in the opposite direction to conserve angular momentum. Therefore, both the main rotor and the helicopter would end up rotating.

Men dette er faktisk feil. **Forklar hvorfor ChatGPTs svar er feil, og vis at situasjonen beskrevet over faktisk er tillatt.** Følg disse stegene:

If you have access to a large-language-model service, try feeding it one of our simulation scripts, and ask it to analyse what the different parts do.

- Does it correctly explain the purpose of the different blocks in the script?
- Does it recognize the difference between constitutive relations and balance laws, and their different roles in the time iteration?

It's possible that the large language model might offer you to “optimize” the script. Keep in mind that we're writing the scripts in order to understand the physics, rather than to be numerically efficient.

$$\frac{dE}{dt} = \Phi + \mathcal{R}$$

ING  
175  
174  
 $16\frac{2}{4}$



$$\frac{dP}{dt} = \mathbf{F} + \mathbf{G}$$



$$\frac{dL}{dt} = \mathbf{M} + \mathcal{T}$$



$$\frac{dN}{dt} = J$$

$$\frac{dQ}{dt} = I$$

$$\frac{d\mathcal{B}}{dt} = -\mathcal{E}$$

$$\frac{dS}{dt} \geq \Psi$$

# Judging & evaluating possible changes in intro-physics: biases

## ! Sceptical reaction?

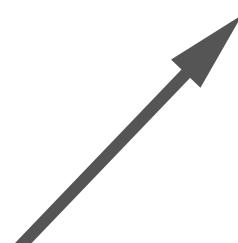
- Because of real physical or pedagogical motivations? Or...
- Because of questioning something you learned with many years of hard work?  
(a completely understandable and natural reaction!)

## ! Can we judge *unfamiliarity* to students based on *unfamiliarity* to teachers?

## ! Remember that *education shapes our world-view and what's intuitive*

- Ancient Greek or Roman wouldn't understand "I feel full of energy today"

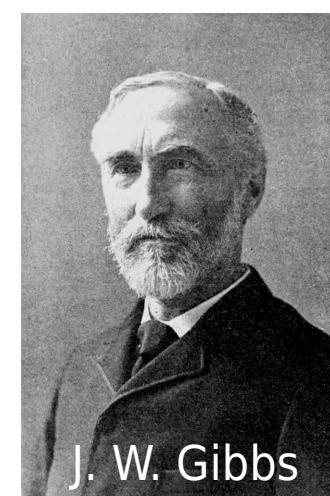
## ! Remember the example from *vector calculus*



$$\mathbf{a} + \mathbf{b}$$

$$\mathbf{a} \cdot \mathbf{b}$$

$$\mathbf{a} \times \mathbf{b}$$



J. W. Gibbs

