DIY: Mini Magnetically-Levitated Trains

Week 1: Introduction

MIT ESP – Summer HSSP 2023

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Source: https://commons.wikimedia.org/wiki/File:Transrapid.jpg

Brief Introduction

- B.S.E in Mechanical Engineering and Electrical Engineering from University of Michigan in 2021
- Current Mechanical Engineering Masters student working in the Precision Motion Control Laboratory with Prof. David Trumper
- Research interests include mechatronics systems and actuator development and control
- Hobbies: playing sports and enjoying outdoor activities (recently got into hiking and sailing…)

Today, we will cover…

- Course Syllabus
- Introduction to magnetically-levitated (maglev) trains
  - Motivation and basic working principles
  - Current maglev architectures and terminology
  - Parallels between maglev and linear actuators
- Break
- Physics (classical mechanics) Review
  - Vectors, dot product, cross product
  - Forces, work, energy, and power

Course Syllabus

- Objectives, expectations, class structure
- Schedule:
  1. Week 1: Introduction of Maglev Trains, Physics Review
  2. Week 2: Linear permanent-magnet motors
  3. Week 3: Linear induction motors
  4. Week 4: Tradeoffs between electromagnetic design and mechanical design
  5. Week 5: Tradeoffs between electromagnetic design and thermal design
  6. Week 6: Demonstration of a working mini maglev train prototype, Discussion on improvements
- Syllabus is posted online for your reference

Why do we care about Maglev Trains?

- Any differences you can think of?
  - Performance, cost, safety, etc…

Traditional

Source: https://www.wgbh.org/news/local-news/2021/04/04/for-greater-boston-a-new-commuter-rail-schedule-for-a-new-kind-of-commute

VS

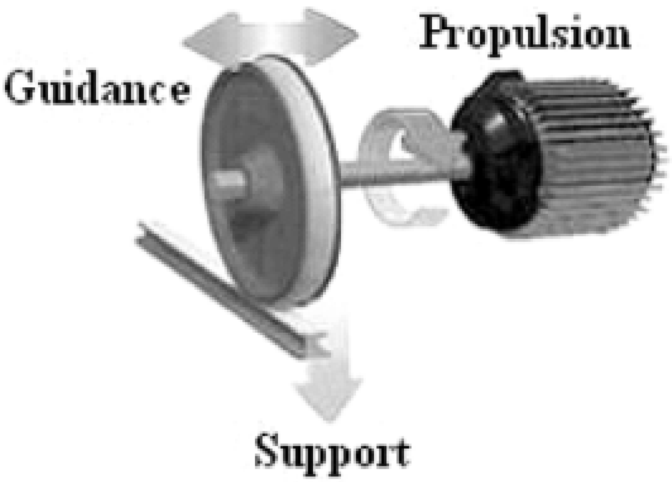
Maglev

Source: https://en.wikipedia.org/wiki/Transrapid#/media/File:Transrapid-emsland.jpg

Traditional vs. Maglev Trains

- Comparing working principles

Traditional: Diesel Engine



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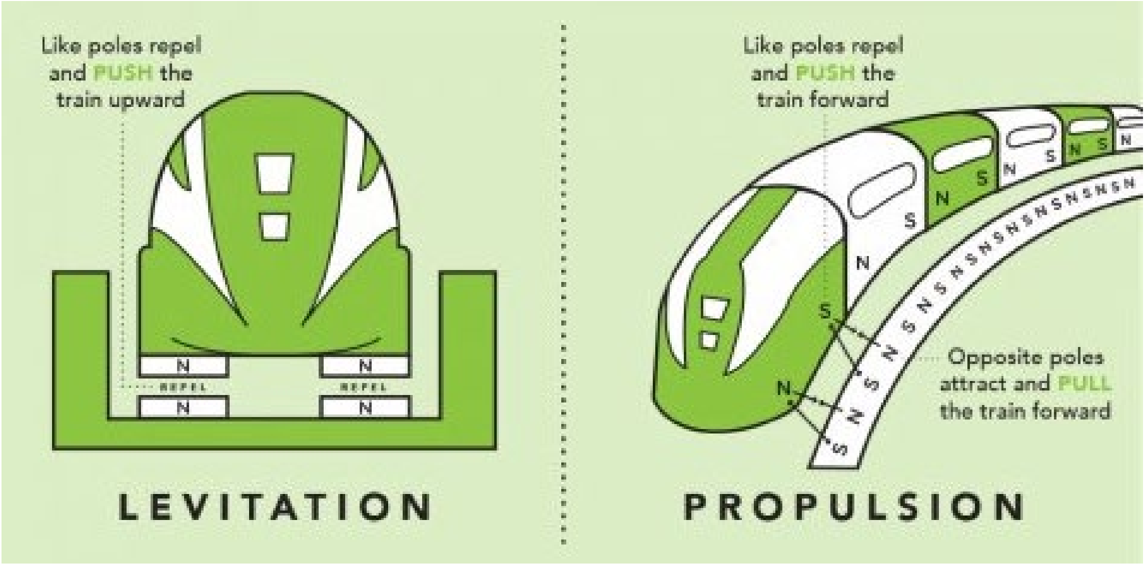
VS

Maglev: Electric power and Magnets



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Advantages of Maglev Trains

- No contact between train and track/guideway → minimal friction [1]
  - Faster speeds and accelerations
    - More than twice the speed of traditional trains [3]
    - 7 hours to go from NYC to LA [2]
  - Potentially less maintenance and operational costs
  - Smoother ride
  - Lower noise
- Lightweight and distributed load [1]
- Minimal risk of derailment due to constraining guideways [1]

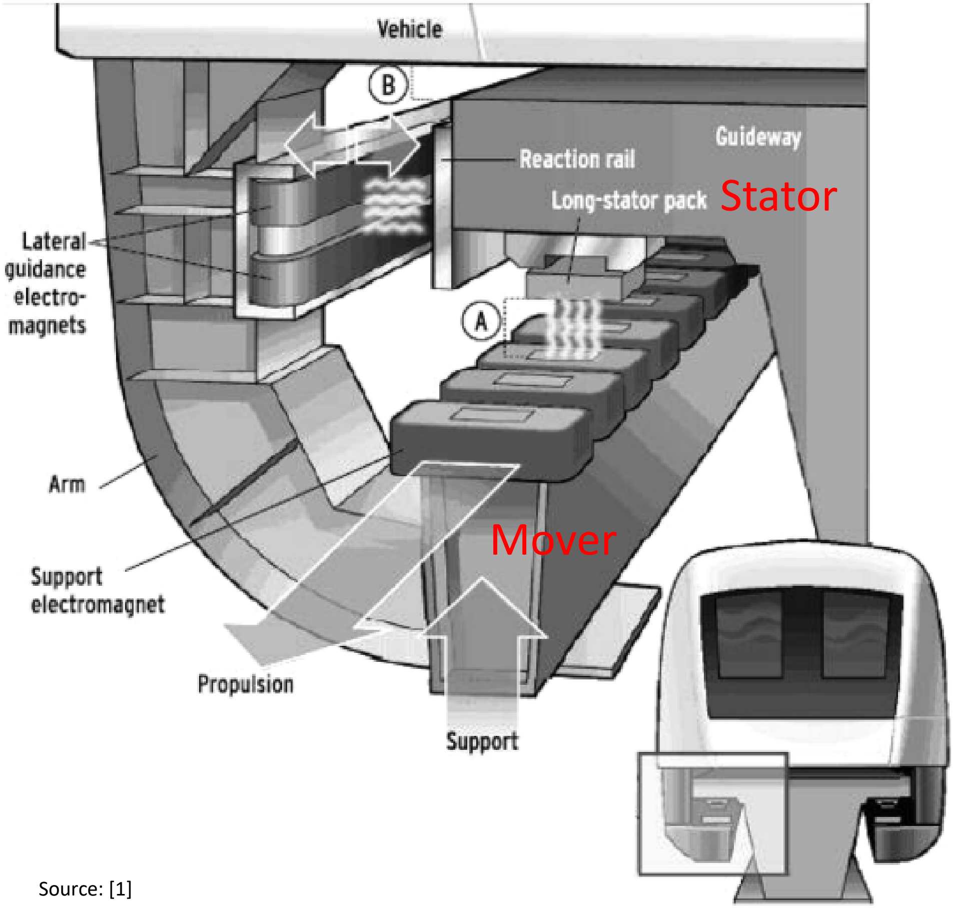
Disadvantages of Maglev Trains

- Infrastructure construction cost [1,3]
  - Up to 5 times as much as traditional trains
- Not suitable for freight transportation [1]
  - For heavy payloads, the power required by the maglev train may exceed reasonable limits
- Braking and accelerating are achieved by the same propulsion mechanism [1]
- Dependence on electric power supply reliability [4]
- Large magnetic fields → health concern [1]
  - However, there are ways to shield passengers from the magnetic fields

Any Questions So Far?

Maglev Working Principle: Magnetic Interactions between Mover and Stator

Full Maglev System Schematic



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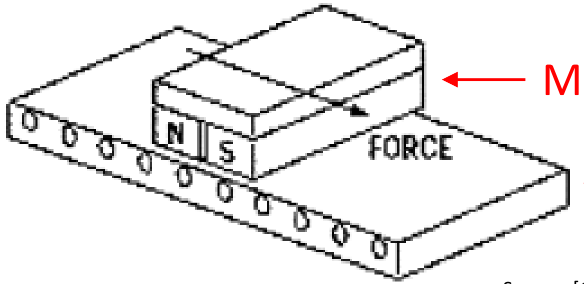
Simplified

Maglev Propulsion System Schematic



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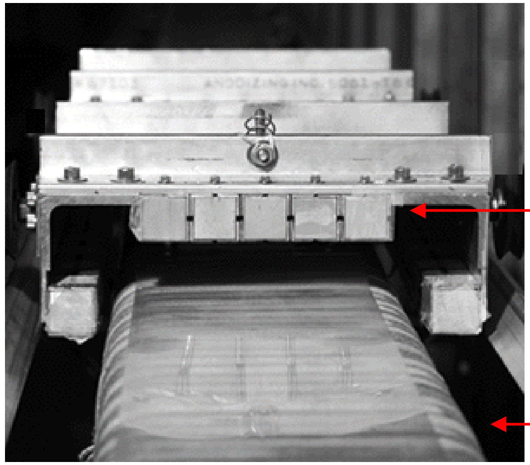
Maglev Propulsion System Implementation



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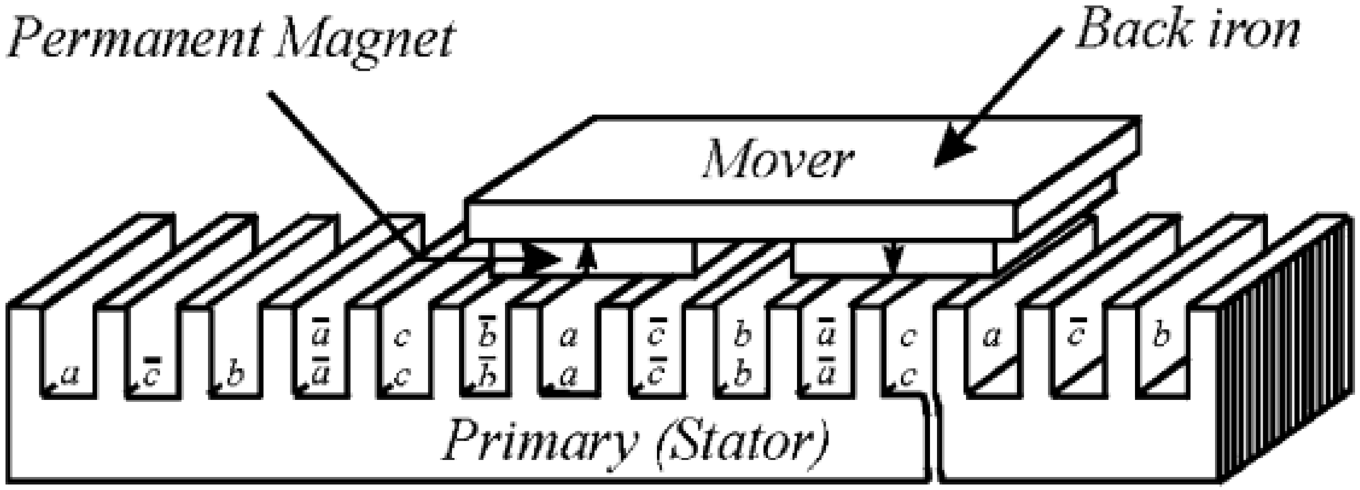
Mover and Stator: Components of a Linear Actuator

- Key takeaway: propulsion system of a maglev train = linear actuator
- We have many tools for designing and analyzing linear actuators!



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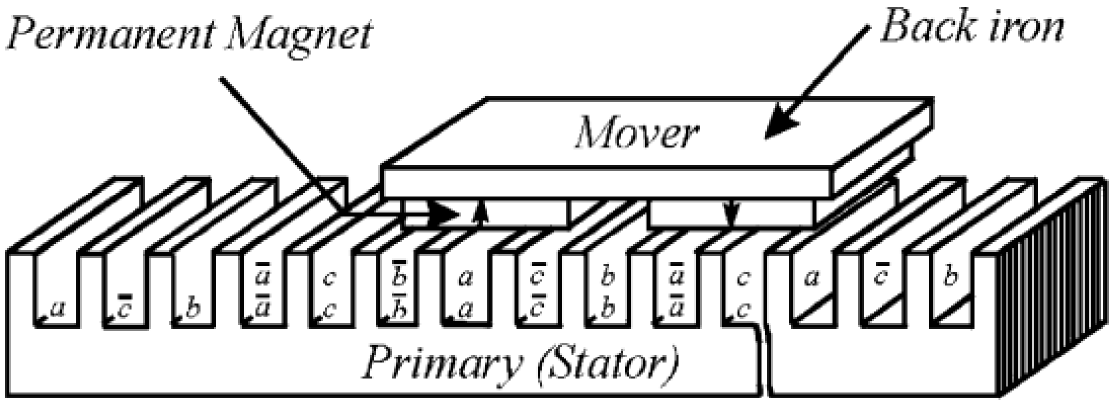
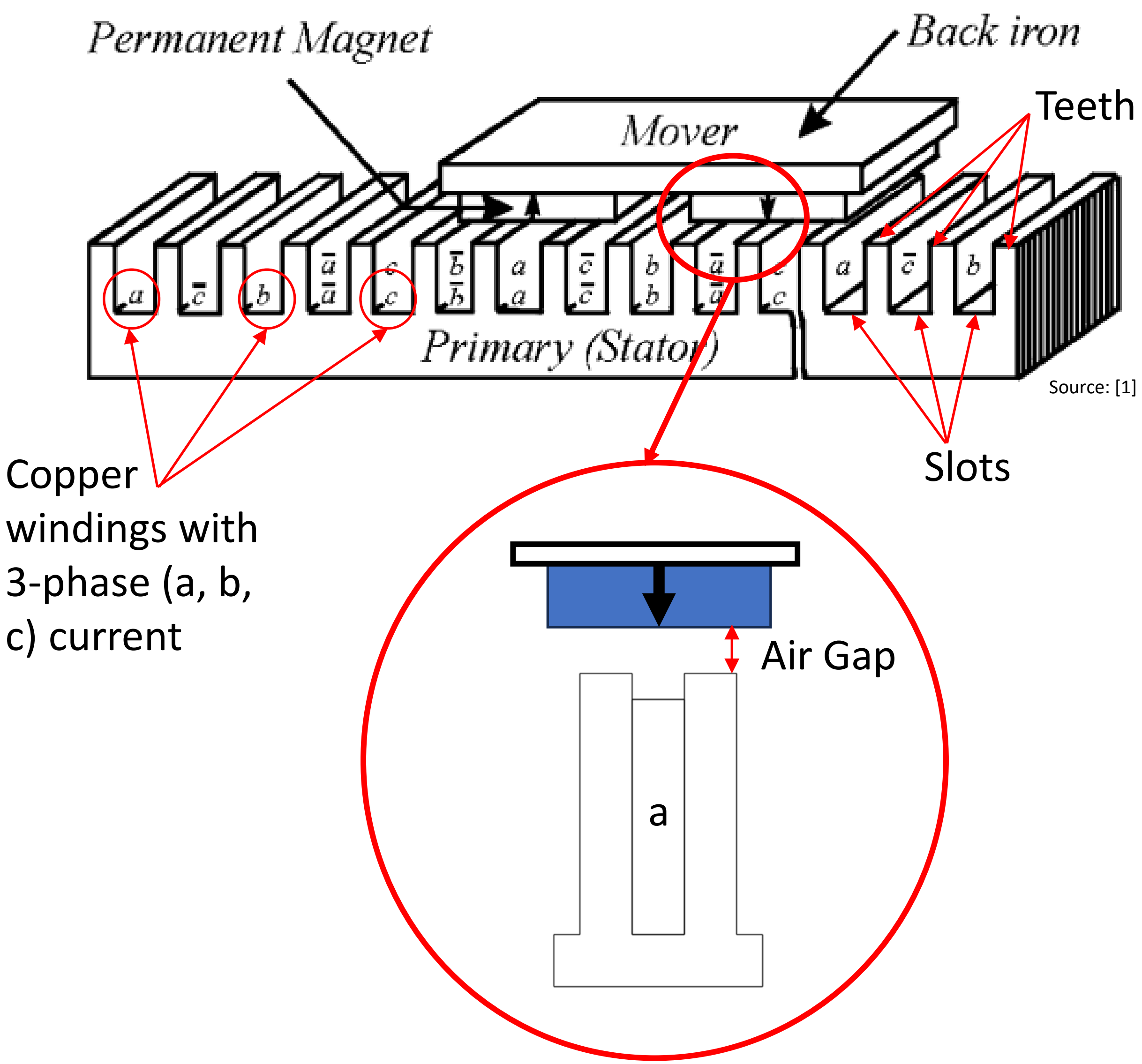
Linear Actuator (permanent magnet) Terminology and Definitions



Source: [1]

- Mover: the part of the actuator that moves and carries the payload
- Permanent Magnet: a special material that generates magnetic fields due to its internal structure
- Back iron: the part of the mover that prevents magnetic fields from straying out, and physically secures the permanent magnets in place
- Stator: the part of the actuator that is stationary and is attached to the part of the system that is stationary relative to the mover

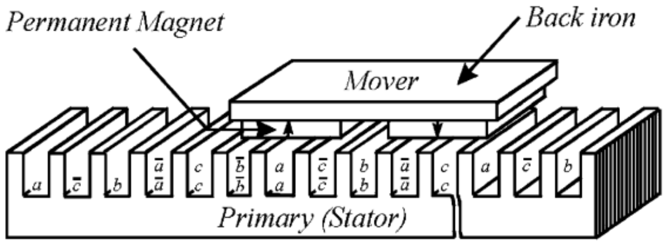
Linear Actuator (Permanent Magnet) Terminology and Definitions



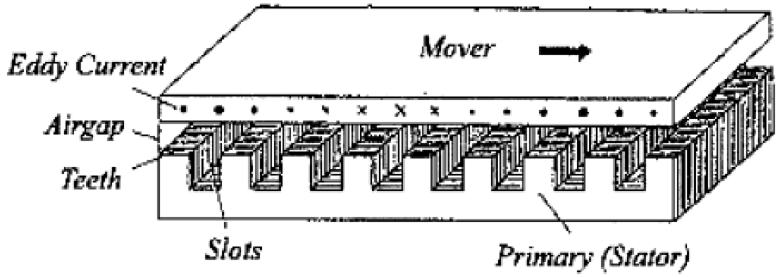
- Air Gap: Gap in between the permanent magnets of the mover and the teeth of the stator
- Teeth: Salient (or protruding) features of the stator
- Slots: Voids in between the teeth for winding copper wires
- Copper Windings: Responsible for generating the magnetic fields via currents (usually 3-phase currents) that will interact with the permanent magnets

Linear Actuator Architectures we will study in this class

- Linear Permanent Magnet Motors (LPMM)



- Linear Induction Motors (LIM)



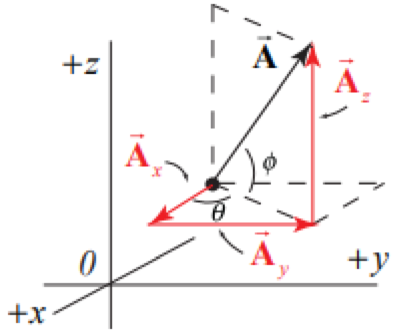
- Modifications of these architectures are implemented on actual maglev trains!

Any Questions So Far?

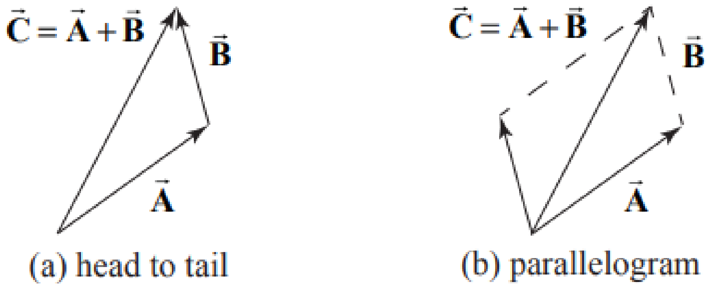
5 Minute Break

Vectors

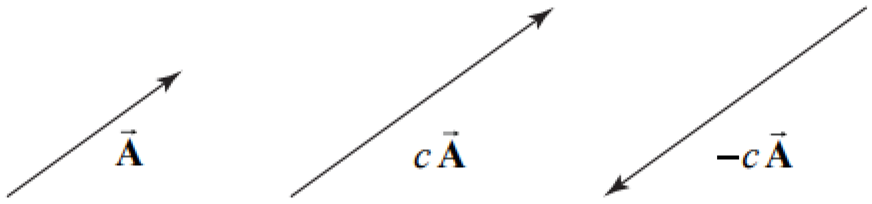
- Vector is a mathematical tool to describe a physical quantity that has both a scalar magnitude and a direction using components of a coordinate system (e.g. cartesian coordinate system, XYZ)
  - Examples of vector: velocity, force, temperature gradient



- Vector addition:



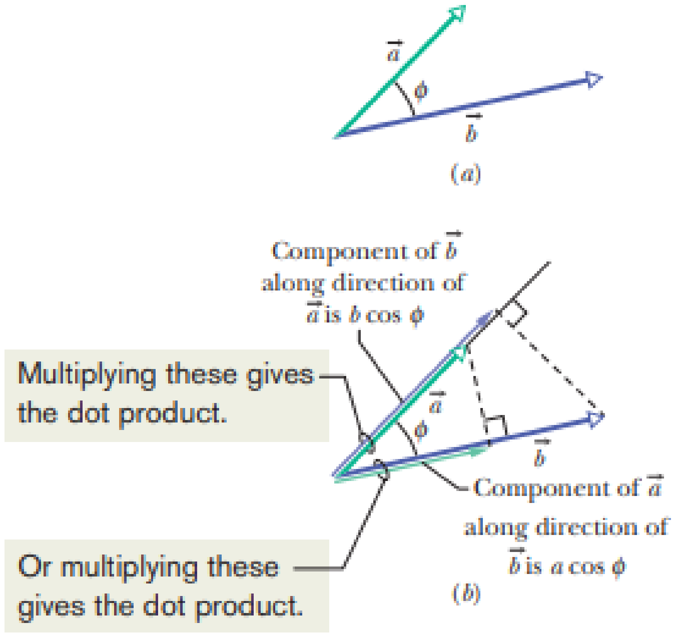
- Vector and scalar multiplication:



Adapted from: [6]

Dot products

- Physical interpretation of dot product is the magnitude of a vector projected onto another vector
  - OR, the component of a vector along the direction of another vector
- Mathematical definition of dot product: $\vec{a} \cdot \vec{b} = ab\cos(\phi)$



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Cross products

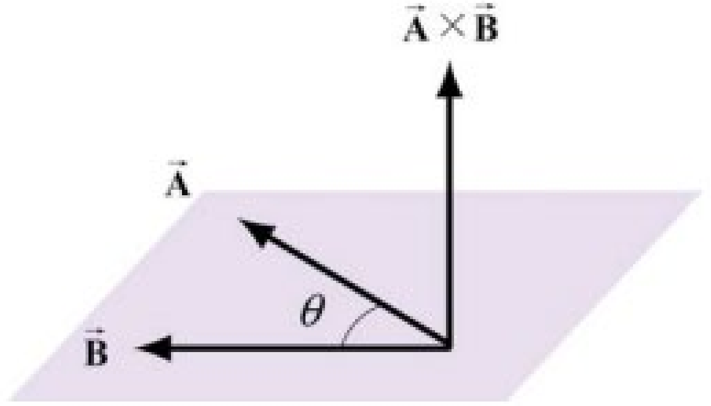
- Physical/geometric interpretation of cross product is the vector perpendicular to the plane constructed by two vectors
- Mathematical interpretation of cross product vector:

$$\vec{C} = \vec{A} \times \vec{B}$$

- Mathematical interpretation of cross product magnitude:

$$\left|\vec{C}\right| = \left|\vec{A}\right|\left|\vec{B}\right|\sin(\theta)$$

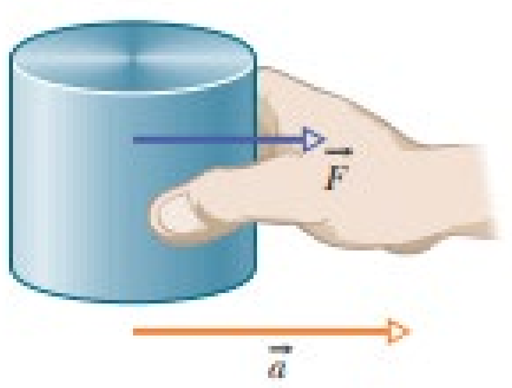
- Right-hand rule!



Adapted from: [6]

Forces

- Physical definition of force: an action taken on a body to change its current state
- Mathematical definition of force: $\vec{F} = m\vec{a}$, where *F* is the force vector, *m* is the mass, and *a* is the acceleration vector
- Units: Newtons $N = \frac{kg*m}{s^2}$
- Some examples of forces: gravity, springs, dampers, friction, etc.



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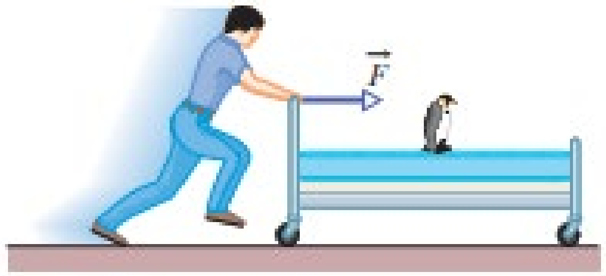
Adapted from: [6]

Work and Energy

- Physical definition of energy: a quantity describing the capacity of a body in any given state to do “useful” work
- Physical definition of work: the process of transferring energy from one body to another body
- Mathematical definition of work: $W = \vec{F} \cdot \vec{d}$
- Units of work and energy: Joules $\mathrm{J} = \frac{kg * m^2}{s^2}$



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Adapted from: [6]

Work, Energy, and Power

- In all systems, energy is conserved (even energy dissipation)
  - Energy dissipation is typically heat generation that doesn't contribute to useful work
- Energy conversion between electrical energy and mechanical energy is the fundamental physical principle that allows linear actuators to move
- Power (units in Watts $\mathrm{W} = \frac{J}{s}$) is the rate at which work is done (or dissipated), and allows for equations to be written to relate electrical and mechanical domains
  - Mechanical power: P=FV, where F is force and V is velocity
  - Electrical power: P = IE, where I is current and E is voltage

Any Questions So Far?

Key Takeaways

- Maglev trains have key advantages over traditional trains
- Maglev train propulsion systems can be modeled by linear actuators
- We will consider two linear actuator architectures: linear permanent magnet actuators and linear induction actuators
- Vectors and vector operations are important mathematical tools in developing equations to describe physical phenomena
- Power is a useful quantity for writing equations that relate mechanical and electrical domains. We use these equations to design linear actuators and observe tradeoffs

References

1. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1644911
2. https://www.energy.gov/articles/how-maglev-works
3. https://science.howstuffworks.com/transport/engines-equipment/maglev-train.htm
4. https://www.osti.gov/servlets/purl/791522
5. https://web.archive.org/web/20050313212121/http://www.skytran.net/press/sciam03.htm
6. https://ocw.mit.edu/courses/8-01sc-classical-mechanics-fall-2016/
7. Fundamentals of Physics, 10th ed. by Halliday, Walker, and Resnick
8. https://ocw.mit.edu/courses/6-007-electromagnetic-energy-from-motors-to-lasers-spring-2011/resources/mit6_007s11_lec02/