The Physics of Timekeeping

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A Quick introduction

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- Interests: Hiking, Swimming, Tabletop Games

What is time?

Time

- Time can be defined a few ways
  - The relation of the progression of events from the past to the present and beyond
  - What is measured by a clock
- Time is incredibly useful for us as humans
  - It lets us understand the relationship between two events
  - It can help us get context on why certain things are happening in the present
- Time is also important for physicists
  - It allows us to measure changes in things which can help us to model how the universe works

What are some quantities we need time to understand?

Time & Physics

- **As we mentioned, physicists use time to measure changes**
  - **Velocity is a measure of how something changes position with respect to time**

$$v = \frac{d}{\Delta t}$$

  - **Acceleration is a measure of how something changes velocity w.r.t time**

$$a = \frac{v}{\Delta t}$$

  - **Frequency is the number of times something happens in a stretch of time**

$$f = \frac{n}{\Delta t}$$

Measuring Time

- Time is measured using the second as its standard unit
  - All other measures of time are based off the second
    - 1 minute = 60 seconds, 1 hour = 60 minutes = 3600 seconds, etc.
  - The definition of one second has changed a few times but is currently based on atomic transitions of the cesium atom
- The best way to measure time is by using a clock
  - Clocks are devices that are specifically built to measure time accurately
  - Nearly all clocks have measures for minutes and hours but some also have seconds
    - In digital clocks, there can also be smaller increments of time included

A brief history of time(keeping)

What are some devices for measuring time?

Early Clocks

- One of the earliest form of clocks was the sundial/obelisk
  - The sun shining on the sundial/obelisk would create a shadow
  - The position of that shadow would then determine what time of day it was

- Another form of early clock was the candle clock
  - Candle clocks are candles with a set rate of burning
  - The amount of candle burned through was the amount of time that had passed

Early Clocks

- Hourglasses were another type of early clock that used grains of sand to keep time
    - A set amount of sand was put into the hourglass that would pour at a set rate
    - Once the sand in one half emptied into the other, an amount of time will have passed

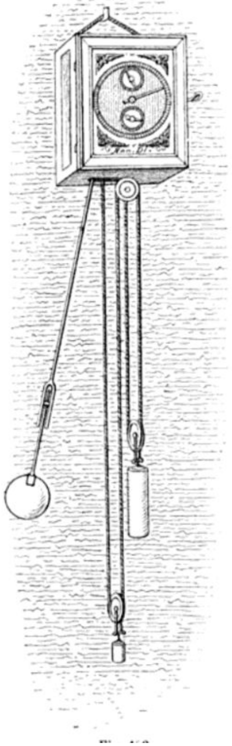
What are some problems with these clocks?

Problems with Early Clocks

- While early clocks were great for their time, they had a few drawbacks
  - Sundials required the presence of the sun to work
    - They also only work at the latitude they were built for
  - Candle clocks require very precise materials to work correctly
    - They are also time consuming to make and are single-use
  - Hourglasses can only measure a specific time accurately
    - Also, hourglasses must be flipped regularly to keep time beyond their intended make

Enter the Pendulum Clock

- In 1656, the pendulum clock was invented by Dutch scientist Christiaan Huygens
  - The pendulum clock uses the motion of a pendulum to keep time
  - The clock has a pendulum of a set length
  - Based on its length, the pendulum swings with a set period
  - The swinging of the pendulum moves a set of gears in the clock
  - These gears then drive the hands of the clock to tell time
  - This version of the clock was the most accurate to date
  - The motion of the pendulum can be described as simple harmonic motion



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How do we find the period of a pendulum?

a) $P = \sqrt{(length)}$

b) $P = \sqrt{(length/mass)}$

c) $P = \sqrt{(length/g)}$

d) $P = \sqrt{(length*mass)}$

How do we find the period of a pendulum?

a) P = √(length)

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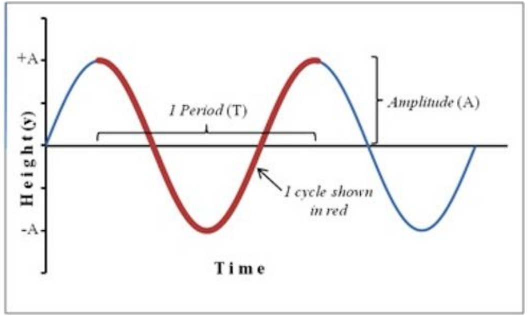
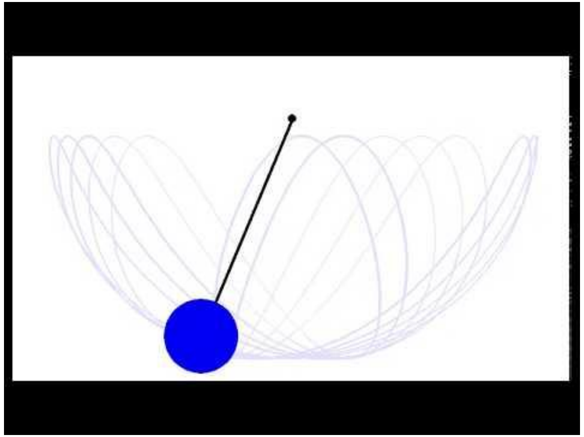
Problems at Sea

- While the pendulum clock was an amazing advancement in timing technology, it had its drawbacks
    - The pendulum clock is a 2-D oscillator
        - The pendulum moves along the x-axis and y-axis
    - Sailors attempted to use these clocks at sea
        - The motion of the boat turns them into 3-D oscillators
            - This makes them inaccurate as the period changes

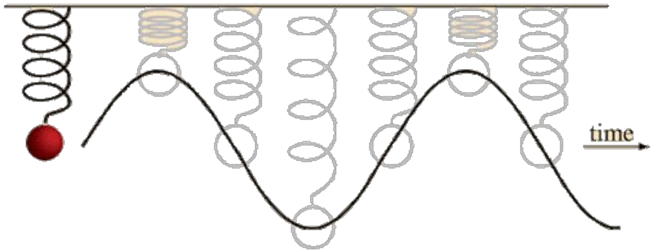




How do we go about fixing this?

Springs!

- Oscillators are still a great way to keep time
  - If we can’t use a pendulum, why not try a spring?
  - Springs with a mass on them will oscillate at a set frequency once started
    - However, just hanging a mass on a spring is no better than a pendulum
      - Why?



What is a possible issue with a mass on a spring approach?

a) The spring can become a 3D oscillator

b) The spring won't oscillate forever

c) The spring changes its period as it oscillates

d) Some combination of the above

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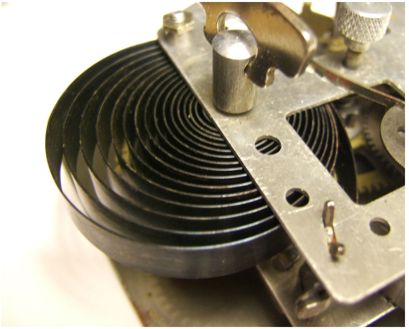
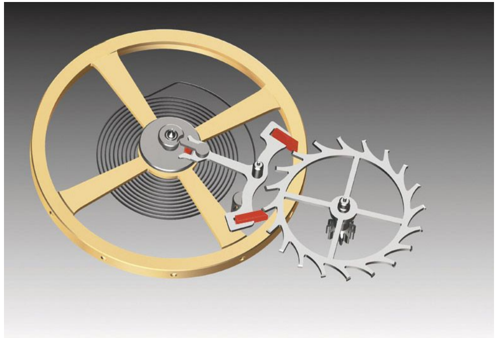
A New Solution - The Mainspring

- Since using a hanging spring isn't ideal, inventors came up with a new idea, a coiled spring
  - In the 15th century, clockmaker Peter Henlein developed the mainspring
  - The mainspring is a coiled spring inside the clock or watch
  - The spring is wound by the user and it will attempt to uncoil itself
    - In uncoiling, it imparts a force to other parts of the clock
    - This force can then drive gears which have a set ratio to turn the clock at the right pace



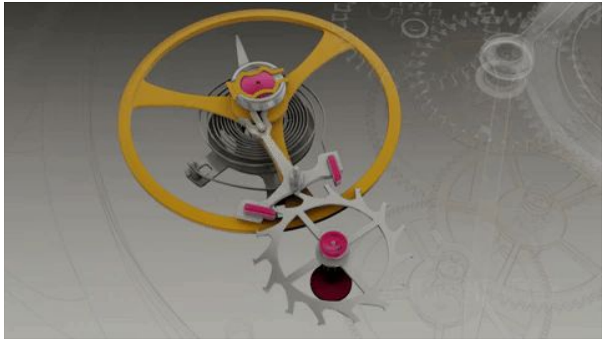
The Balance Spring & Escapement

- Using just the mainspring on its own proved to still be relatively inaccurate
  - Thus the balance spring was added
  - The balance spring is a second spring inside the watch that helps keep time more accurately
  - It is paired with something called the escapement which allows the clock to keep ticking



The Balance Spring & Escapement

- The escapement takes force from the mainspring and rotates
  - A fork attached to the balance wheel stops it from fully rotating
    - This then drives the balance wheel and coils the balance spring
  - The balance spring then uncoils to turn the fork the other way
    - This lets the next tooth of the escapement go
  - This repeats until the mainspring fully unwinds



The Mechanical Watch

- The combination of the mainspring, balance spring, and escapement help create the “heart” of the mechanical watch
  - These watches were more accurate than most clocks before them and were portable!
  - These even reduced the impact of motion on the accuracy of time
  - They were not without their drawbacks though
    - Certain interactions could still cause these watches to lose time

What are some possible physics phenomena that cause mechanical watches to lose time?

a) Heating up the watch

b) Energy loss

c) Magnets

d) None of the above

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How Mechanical Watches Lose Time

- There are a few ways that mechanical watches lose time
  - The main source is the loss of energy over time through various means
    - Friction of the components in the watch
    - Sound and heat generation by the components
    - The mainspring fully uncoiling
    - Drops in the force of the mainspring as it uncoils
  - Another source is heating up the watch
    - If the watch is heated up, the components can expand or warp
  - One other source of losing time is magnetism
    - If the watch was placed in a powerful enough magnetic field or became magnetized itself, it could throw off its timing

Demo

Oscillator Demo

- As we can see, like with the mainspring, the oscillating ruler will eventually lose energy and stop "ticking"
  - If this is the mainspring of a watch, that means we have to be constantly winding it or the clock will stop altogether
    - If you happened to forget to wind your watch, you might not have an accurate clock to compare it to for a while
  - So how do we go about avoiding this energy loss?

The Electromagnetic Watch

- One major leap in watch innovation was the introduction of electricity to watches
  - With the advent of small watch-sized batteries, electricity could be put onto a person's wrist
  - With this came designs for battery powered watches
  - One of the first designs was through the use of an electromagnet

The Electromagnetic Watch

- Watches that used an electromagnet became popular in the 60's
    - They worked by having a sort of metal tuning fork that would vibrate at a resonant frequency and propel the watch mechanism forward
        - When the tuning fork vibrates in one direction, a circuit is completed and an electromagnet, powered by the battery, is enabled
            - This then pushes the tuning fork away from the magnet
                - When the fork is pushed away the circuit is broken and the electromagnet turns off
                    - This then lets the fork move towards the magnet again due to a restoring force and the process repeats

Demo

What are some ways that the electromagnet watch could stop working?

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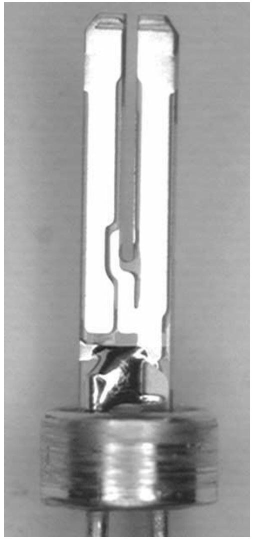
The Electromagnetic Watch

- There are a few ways the electromagnet watch could stop ticking
  - The first is if the battery dies
    - Once the battery is dead, the tuning fork simply oscillates like in the first demo until it runs out of energy
  - Another way this can happen is if the fork is not deflected far enough to oscillate back and trigger the circuit again

The Quartz Watch

- The electromagnet and tuning fork design was soon replaced with what most modern watches use today, quartz
  - Quartz watches, initially produced in 1969, make use of a small tuning fork made of quartz crystal
  - The tuning fork vibrates at a frequency of 32,768 Hz
    - This high frequency makes the watch *very* accurate
  - The main difference between the quartz watch and the electromagnet watch is how the two operate

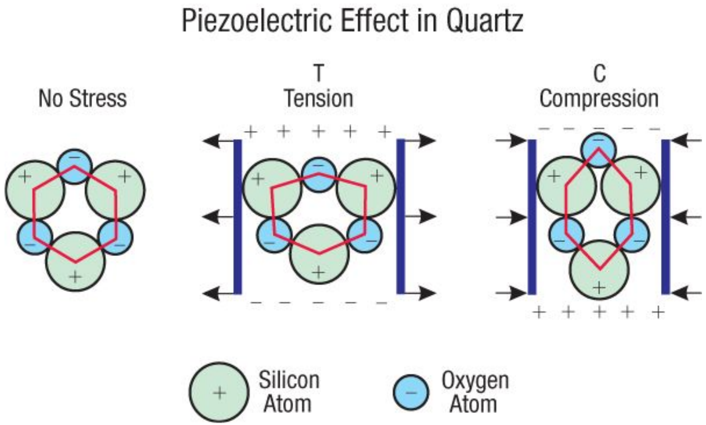


The Quartz Watch - Piezoelectric Effect

- **While the electromagnet watch uses a tuning fork driven by an electromagnet, the quartz watch makes use of the piezoelectric effect**
  - **Quartz has a unique property in that it is piezoelectric**
    - **This means that its structure allows it to generate or respond to energy**

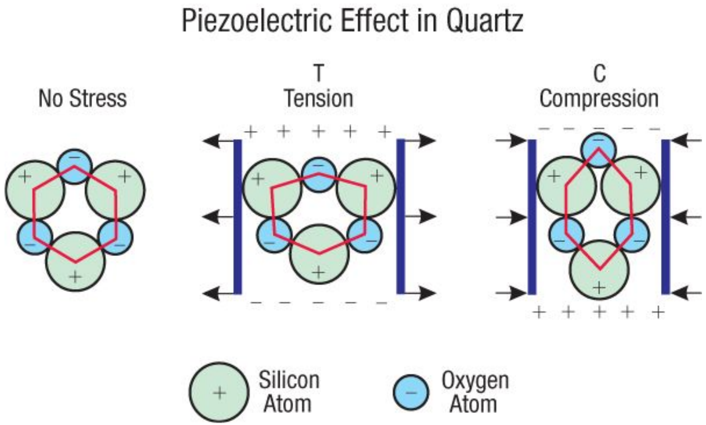
The Quartz Watch - Piezoelectric Effect

- **Quartz is made up of Silicon and Oxygen atoms arranged in a lattice**
  - **Silicon is slightly positively charged and oxygen is slightly negatively charged**
  - **When at rest in the lattice, the quartz is electrically neutral**
    - **But, if it is deformed by compression or tension, it creates an electric potential**



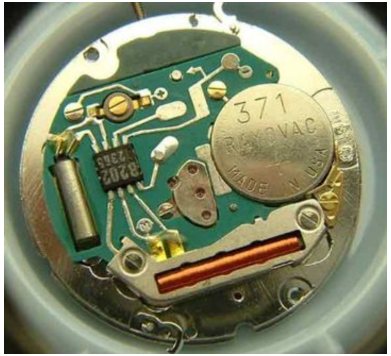
The Quartz Watch - Piezoelectric Effect

- **The reverse is also true of quartz in that if you pass electricity over it, it will deform**
  - **In the case of our quartz tuning forks, it will start to vibrate at its resonant frequency**



The Quartz Watch

- This is what makes up the mechanism behind quartz watches
  - An electrical pulse is sent from a battery to the quartz crystal
    - This causes the crystal to start vibrating at 32,768 Hz
  - An onboard microchip then counts the number of vibrations
    - On the 32,768th oscillation, it delivers a single pulse to move the second hand of the watch



The Quartz Watch

- The design of the quartz watch makes it incredibly precise
  - Since the frequency of the quartz is a power of 2 (2^{15}), it makes it much easier for the electronics to quickly distinguish when to pass a pulse to the watch
  - Additionally, quartz is not as heavily affected by magnets or heat compared to metallic watch components

What are some possible drawbacks of the quartz watch design?

a) If it gets hit, it will short circuit

b) It stops when the battery dies

c) Magnets

d) None of the above

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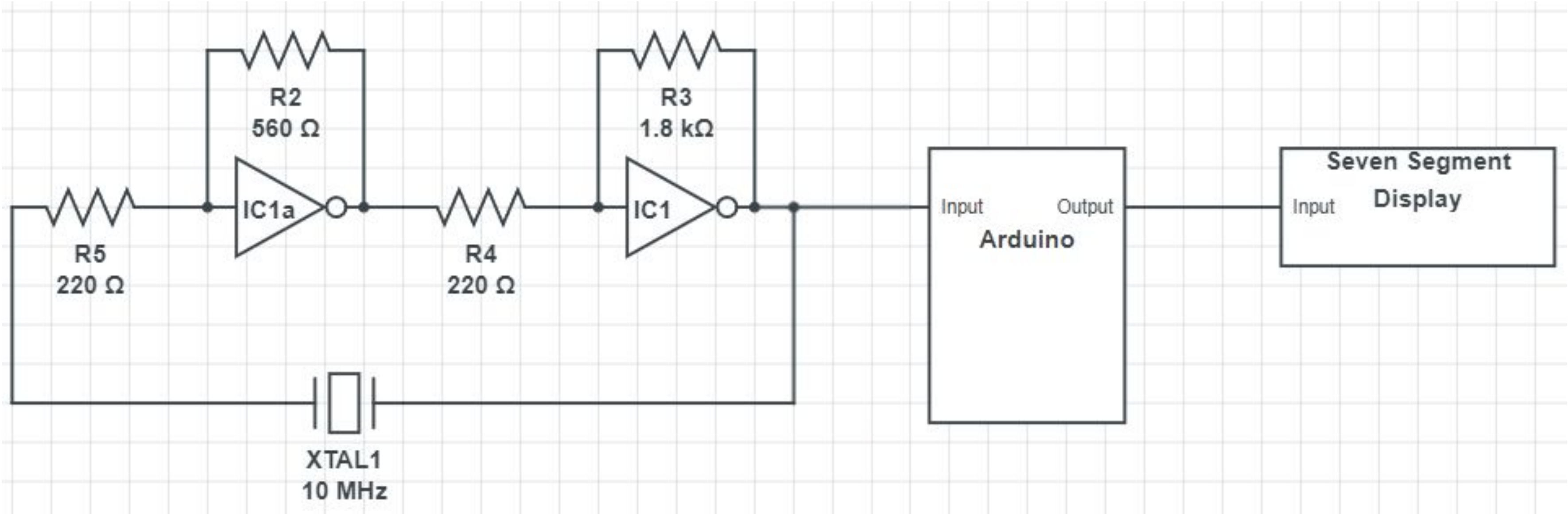
Demo

Quartz Oscillator Circuit



Atomic Clocks

- The current most accurate way to keep time is with an atomic clock
  - Atomic clocks use the cesium atom to keep time
    - In the clock, cesium atoms are hit with microwave radiation at a certain frequency
      - If the frequency is correct, it will change the energy level of some of the cesium atoms
      - These atoms then reach a detector and it counts the ones with the new energy level and corrects the frequency of the microwaves
      - This repeats until 9,192,631,770 cycles of radiation have occurred at which point one second is counted

The Future of Timekeeping

- Scientists and engineers are still actively researching new ways to keep time
    - There are currently active studies into using light in the visible range as the escapement for atomic clocks
        - These are called optical clocks
    - There are also proposed ideas for clocks that use quantum information to tell time though optical clocks currently seem more promising with current research

Questions

Thank You!