How Conductivity Sensors Work

Principles and Practice in Water Quality Monitoring

Zack Henderson

YSI Product Manager

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June 23, 2020

How Sensors Work:

6-Part Series on Water Quality Monitoring

Once a week, we will discuss why it is important to monitor critical water quality parameters.

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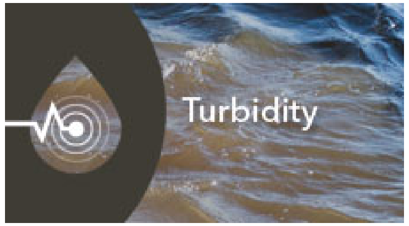
Recording available

Recording available



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June 23rd

Recordings Available

Miss the earlier presentations? Don’t Worry!

- How Anti-Fouling Works
- How Algae Sensors Work
- How Turbidity Sensors Work
- How pH + ORP Sensors Work
- How Dissolved Oxygen Sensors Work

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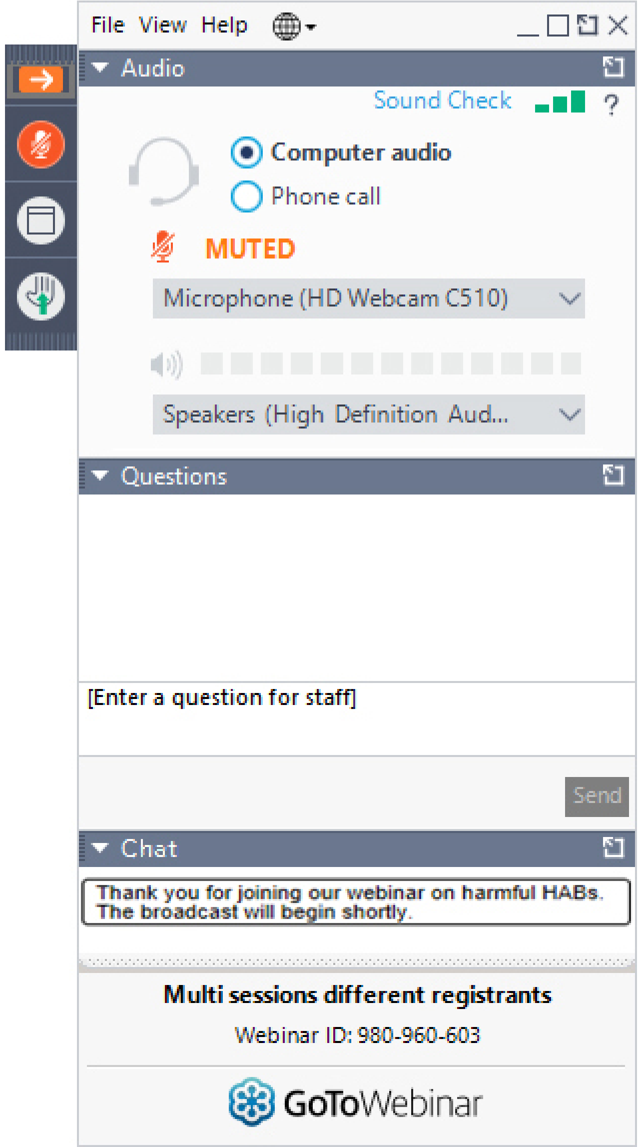
Ask Questions
We'll try to answer as many as we can during the presentation

Chat
You can also use the Chat panel to ask questions or contact us if you're having technical difficulties



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Please Ask Questions!

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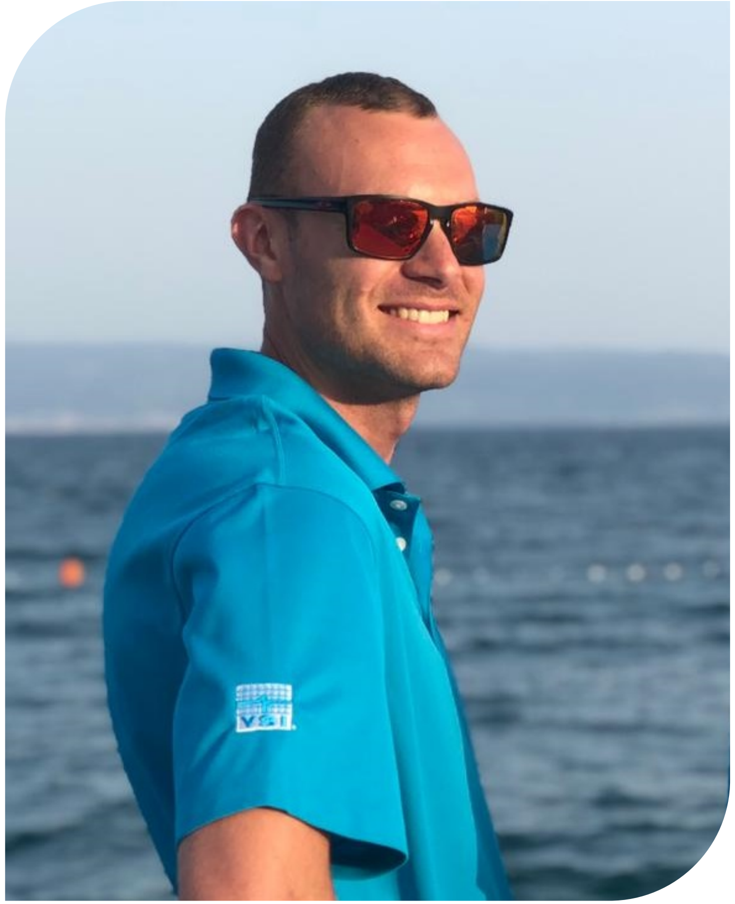

BACKGROUND

BS in International Business
Wright State University

- YSI Product Manager, EMS
- 3 years at Xylem (YSI)
- 10 years experience working with environmental monitoring technology
- Focus on water quality monitoring instruments
  - EXO Sondes

Overview

I. What is Conductivity and Why is it Important?
II. Differences between Conductivity, Specific Conductance, and Salinity
III. Principles: How Conductivity Sensors Work
IV. Practice: Real-World Monitoring

What is Conductivity and Why is it Important?

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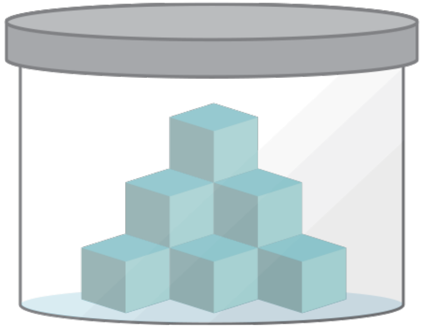
Why do you monitor for conductivity?

Do you know what conductivity is?

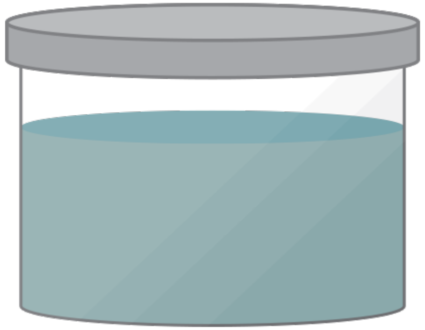
What is Conductance?

- **Conductance**

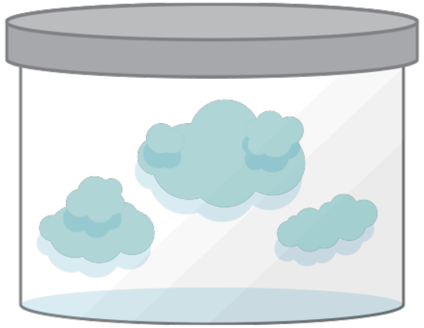
- Substance's Ability to Conduct Something
- Examples:
  - *Substance* = Solid, Liquid, Gas
  - *Something* = Heat, Electricity, Sound



Solid



Liquid

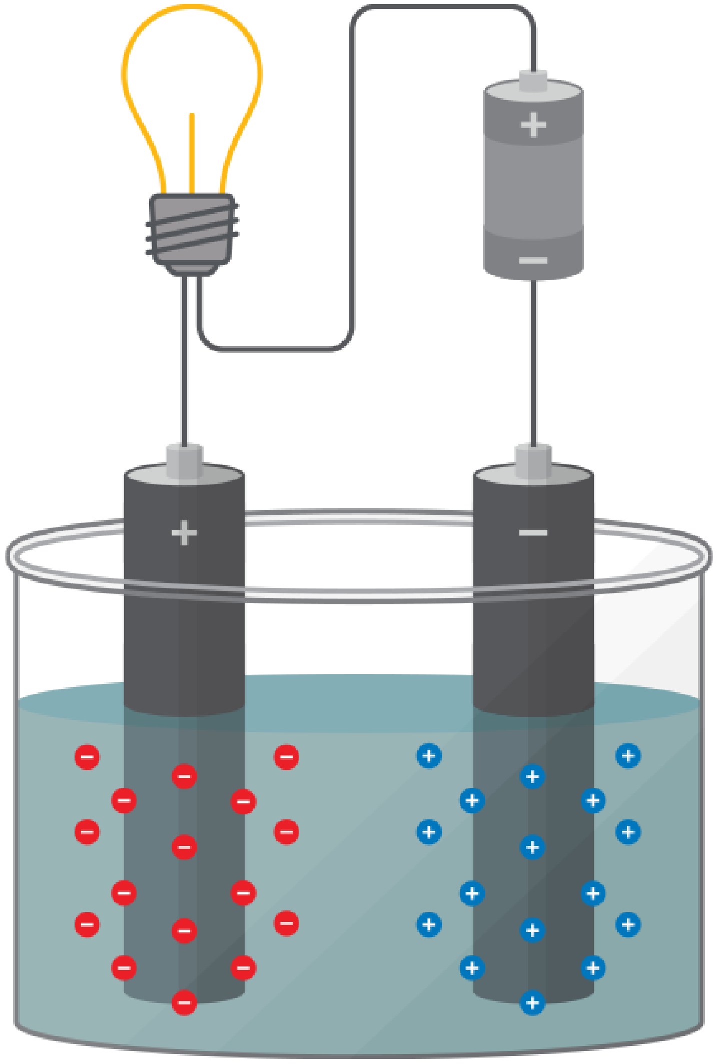


Gas

What is Conductance?

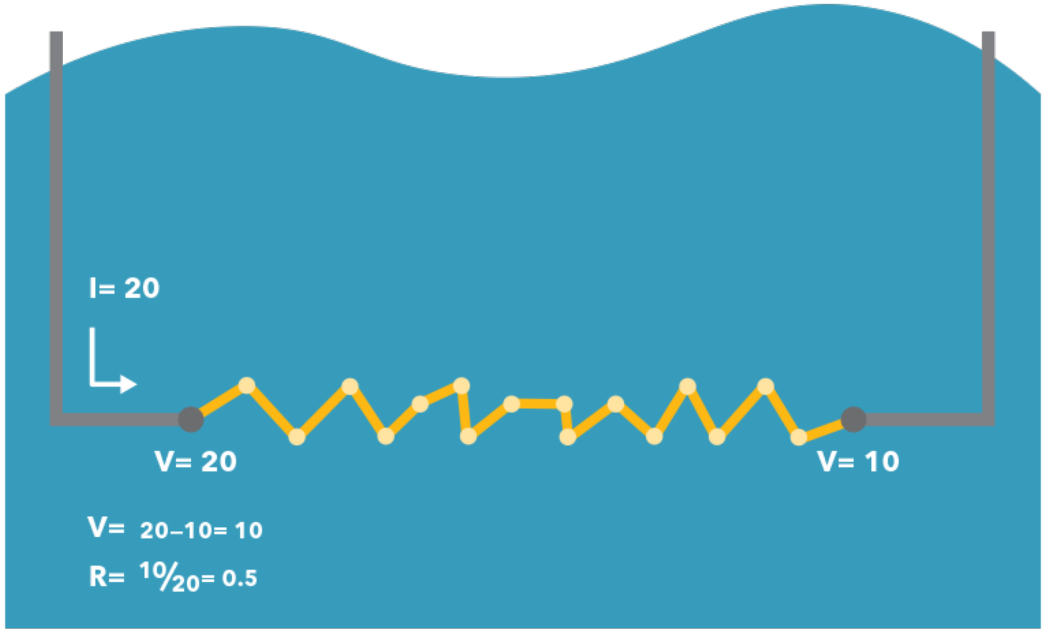
- **Conductance**

- Substance's Ability to Conduct Something
- Example:
  - *Substance* = Water
  - *Something* = Electric Current
    (through ions)



What is Conductance?

- **Conductance** = Inverse of Resistance
  - Ohm's Law: **V = IR**
    - Resistance (**R**) = Change in Potential (**V**) / Current (**I**)
    - **R = V/I**



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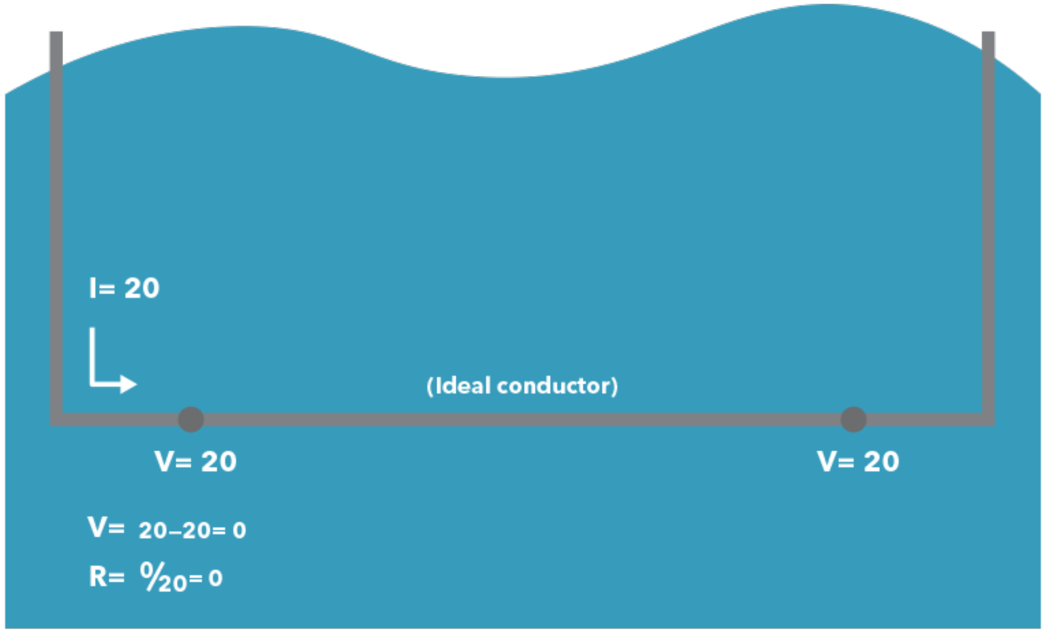

The potential difference (voltage) across an ideal conductor is proportional to the current through it.

What is Conductance?

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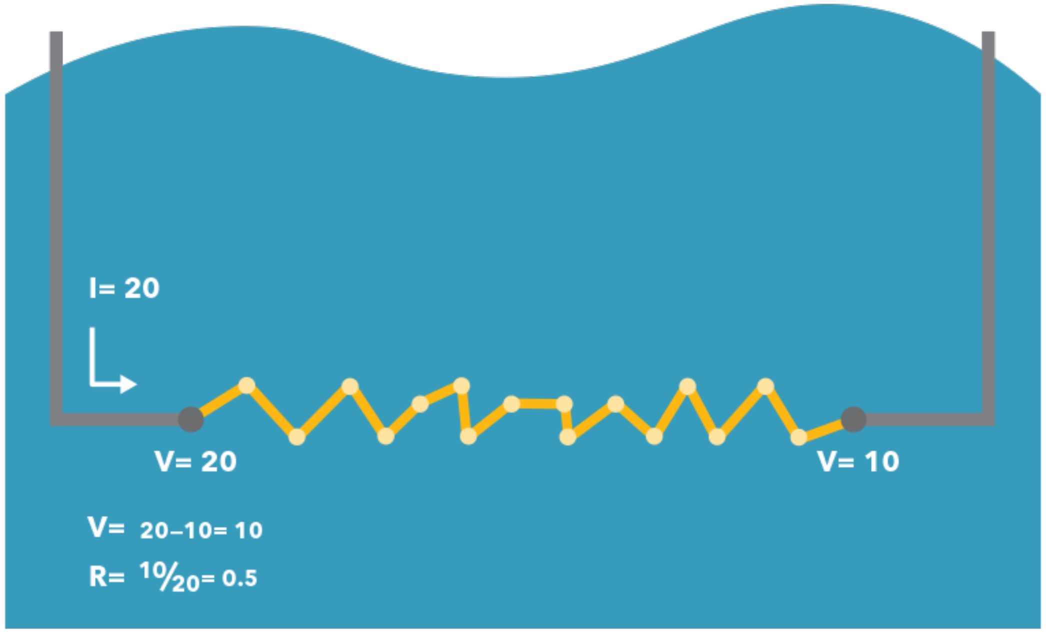

What is Conductance?

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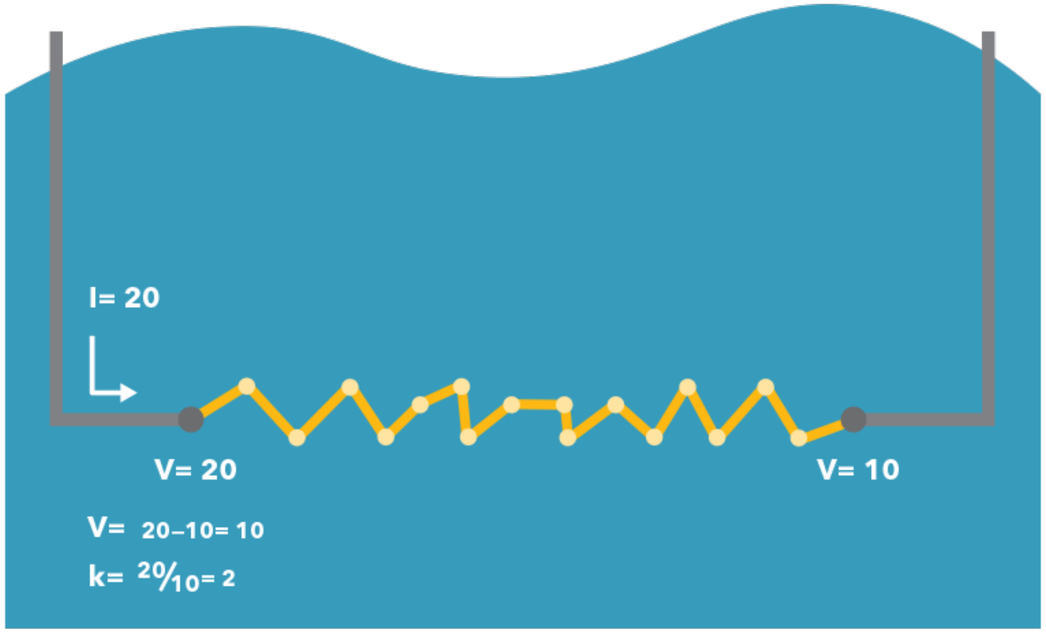
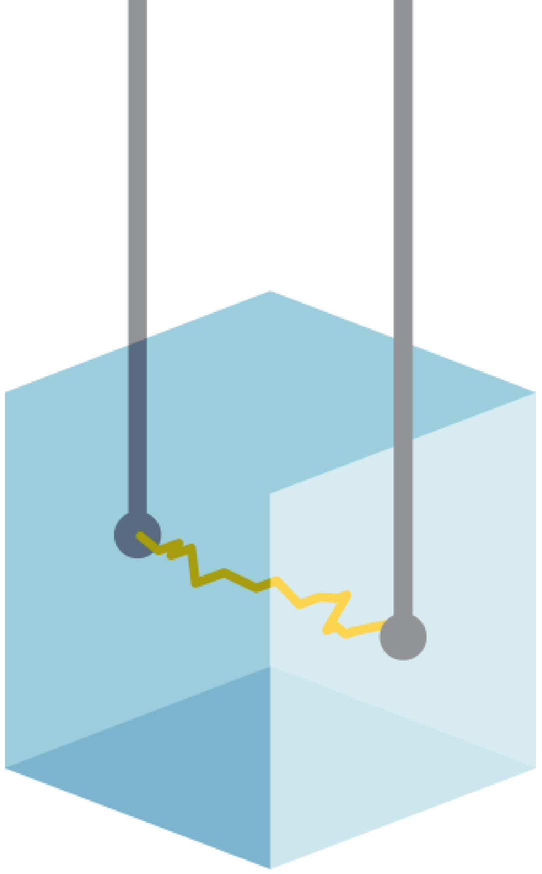
  - Conductance: **k = 1/R**
    - Conductance (**k**) = Current (**I**) / Change in Potential (**V**)
    - **k = I/V**



What is Conductance?

- **Conductance**
  - Measured in Mhos or Siemens
    - Mhos = Siemens
    - Mho is Ohm (unit of resistance) backwards



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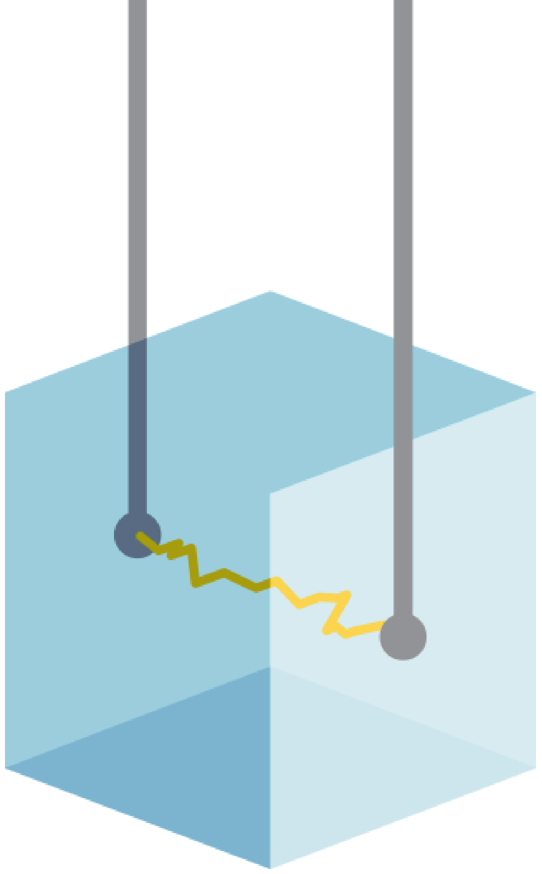
- Ratio of **Current** (**I**) in a Conductor to the difference in Electric Potential, **Voltage** (**V**), between its ends



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What is Conductance?

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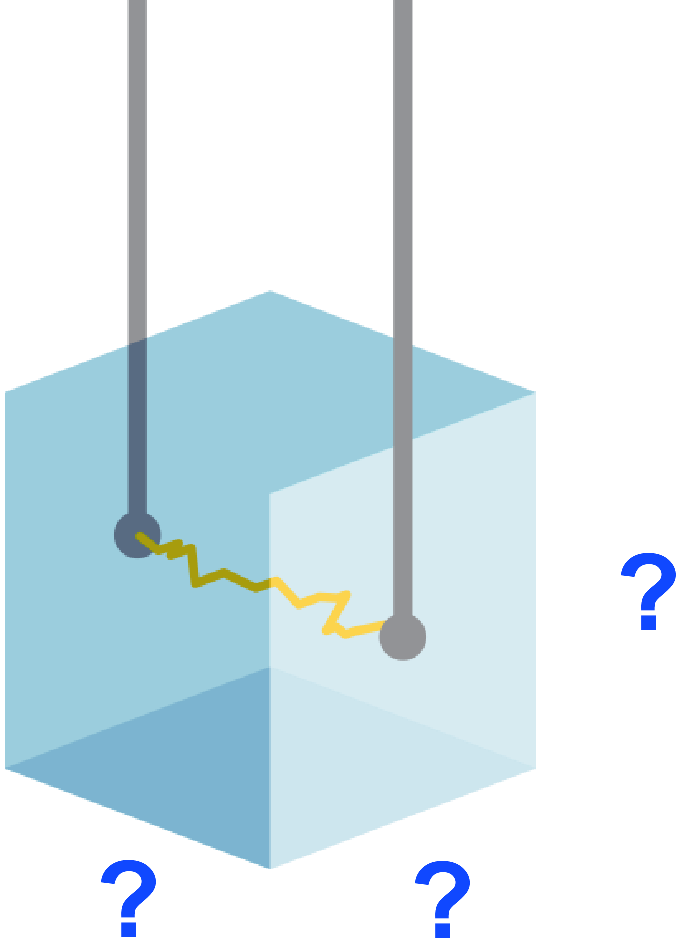
- Ratio of **Current** (**I**) in a Conductor to the difference in Electric Potential, **Voltage** (**V**), between its ends
- Value dependent on cell geometry of conductor



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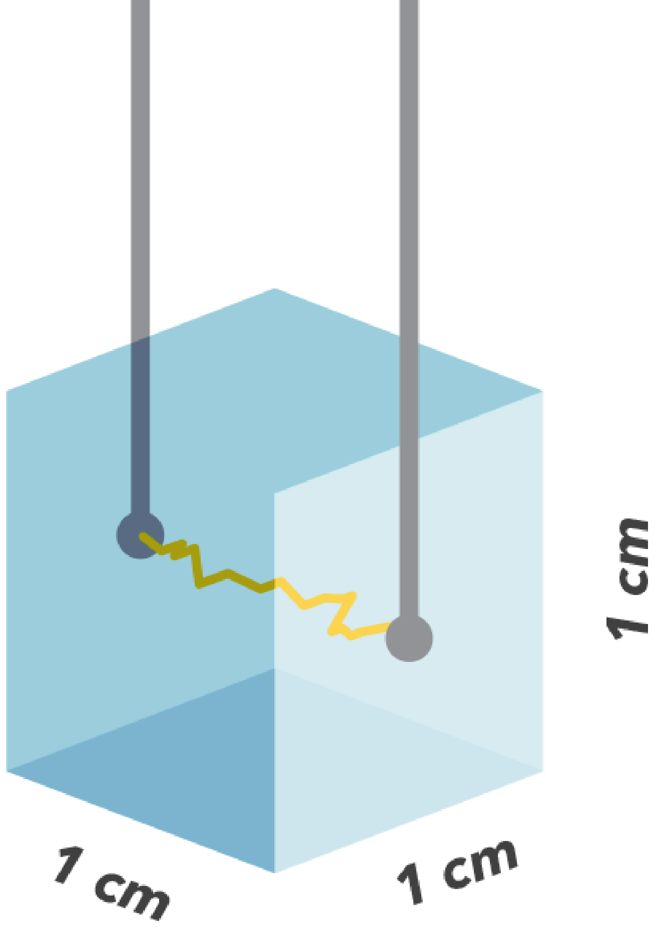
What is Conductivity?

- **Conductivity** = Conductance per unit of conductor length

- Industry Standard = 1 cm
  - Conductance in siemens (S), measured through a 1 cm cube of liquid



What is Conductivity?

- **Conductivity** = Conductance (S) per unit of conductor length (cm)

	S	mS	µS
Siemens | **1 S =**	1 S	1,000 mS	1,000,000 µS
Millisiemens | **1 mS =**	0.001 S	1 mS	1,000 µS
Microsiemens | **1 µS =**	0.000001 S	0.001 mS	1 µS

- Measurement Units = mS/cm or µS/cm
  - Milli- or Mircro-siemens per Centimeter

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What is Conductivity?

"Conductivity is the property of water,
measured through a specific cell geometry,
that allows it to conduct an electric current."

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What is Conductivity?

"Conductivity is the property of water,
measured through a specific cell geometry,
that allows it to conduct an electric current."

What exactly allows water to conduct an electric current?

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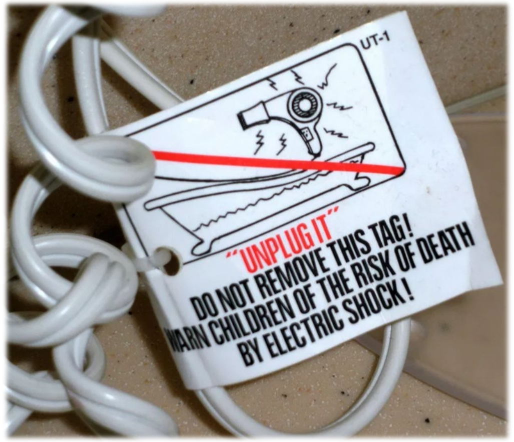
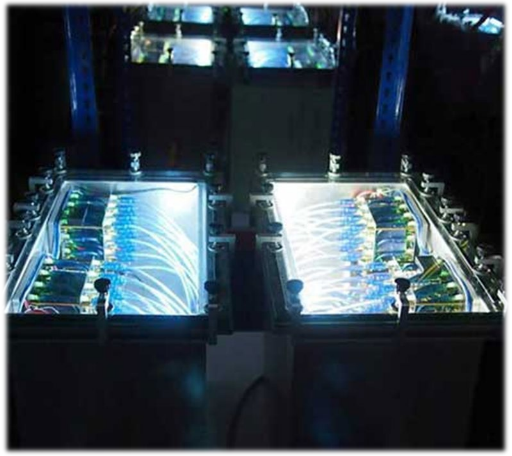
What is Conductivity?

- Ions!
- Conductivity relates to the concentration of ions in the water
  - High ionic strength (ex. seawater) = higher conductivity
  - Low ionic strength (ex. pure water) = lower conductivity



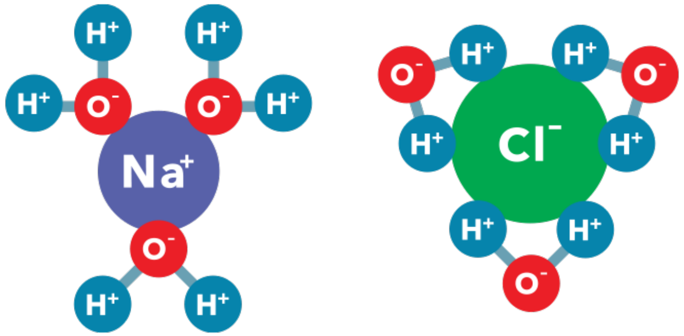


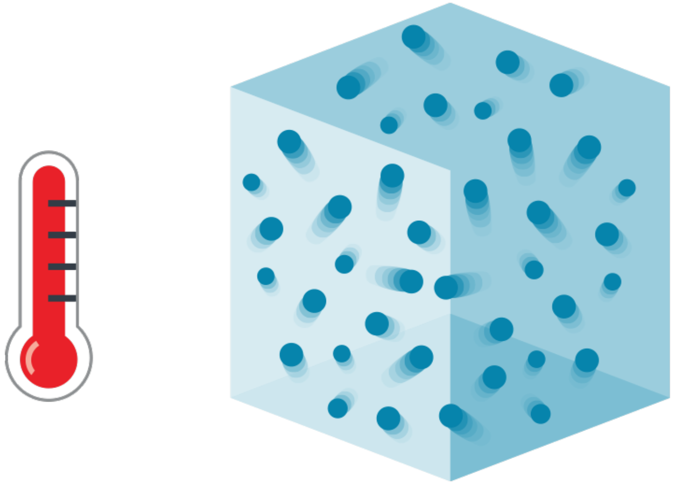
What Influences Conductivity?

- 2 Primary Factors that Impact Conductivity:

1) **Inorganic Dissolved Compounds**

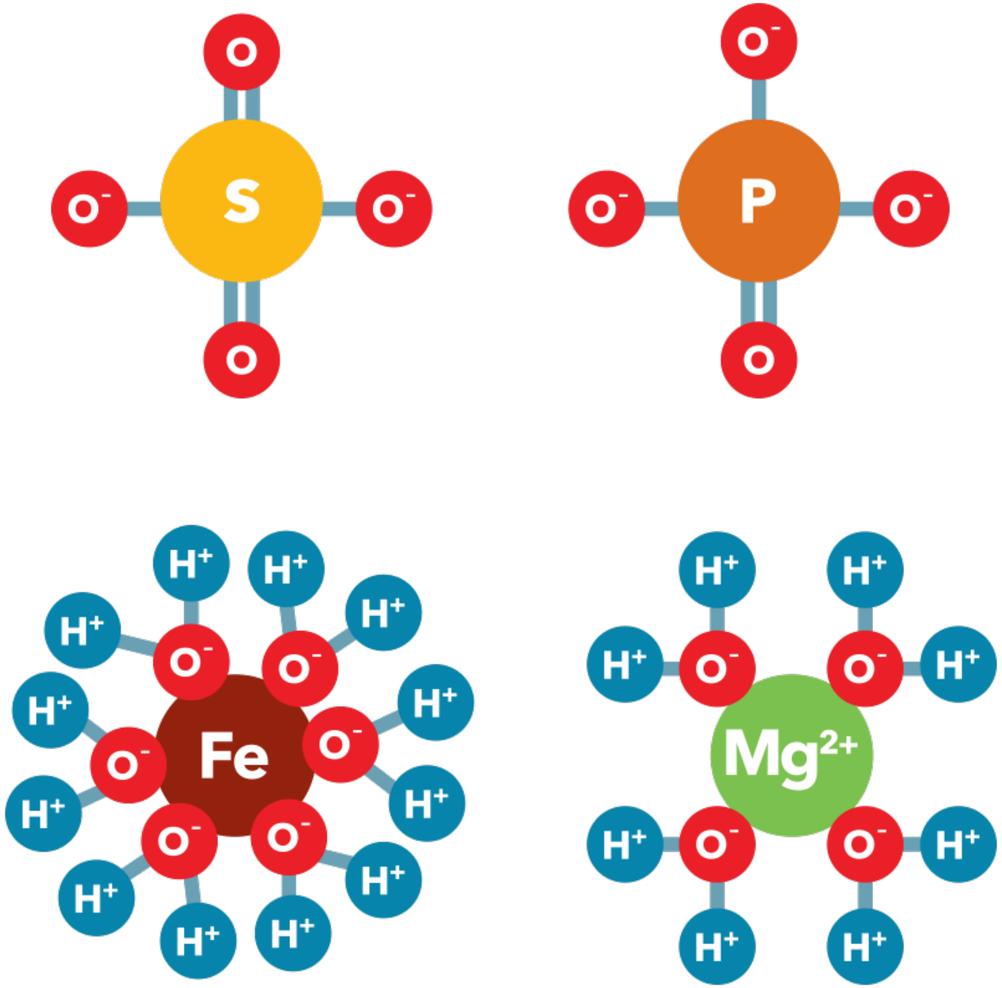
2) **Temperature**





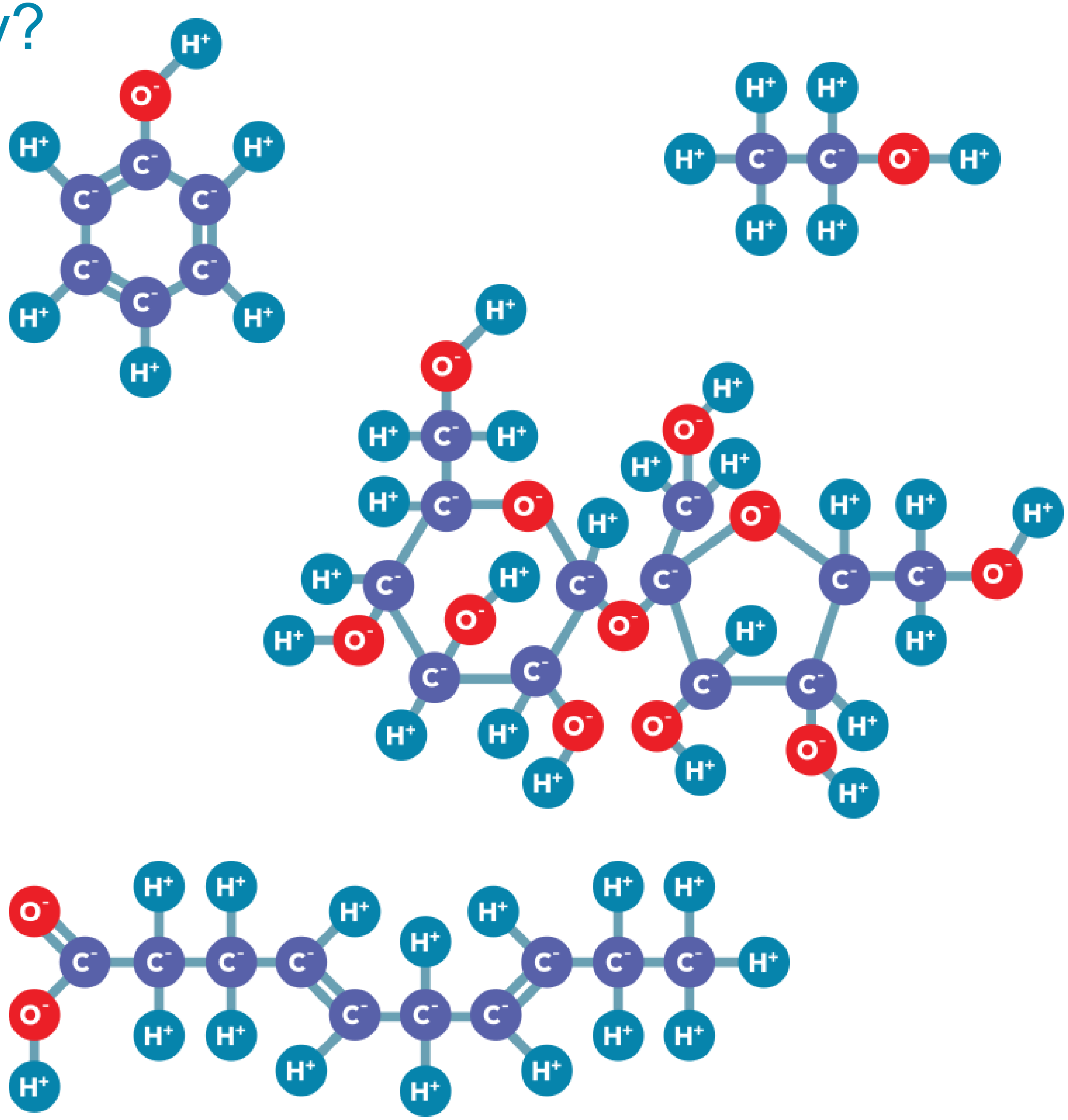
What Influences Conductivity?

- **Inorganic Compounds**
  - Increase Conductivity
  - Anions:
    - Chloride, Nitrate, Phosphate,…
  - Cations:
    - Sodium, Iron, Calcium,…



What Influences Conductivity?

- Organic Compounds
  - Not Conductive
    - Oil
    - Phenol
    - Alcohol
    - Sugar



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What Influences Conductivity?

- **Temperature**
- Conductivity is highly dependent on temperature varying with the nature of the ionic species present
- Affects:
  - Actual Conductivity
    - Evaporation increases ionic concentration
  - Reported Conductivity
    - Measured value higher/lower depending on sample temperature

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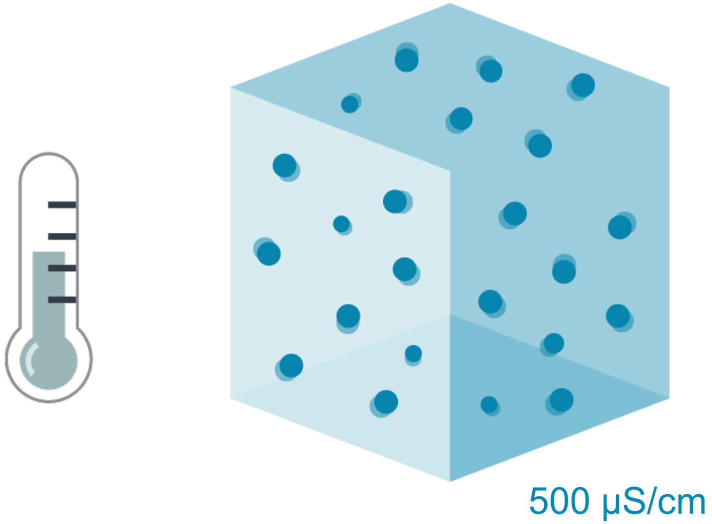
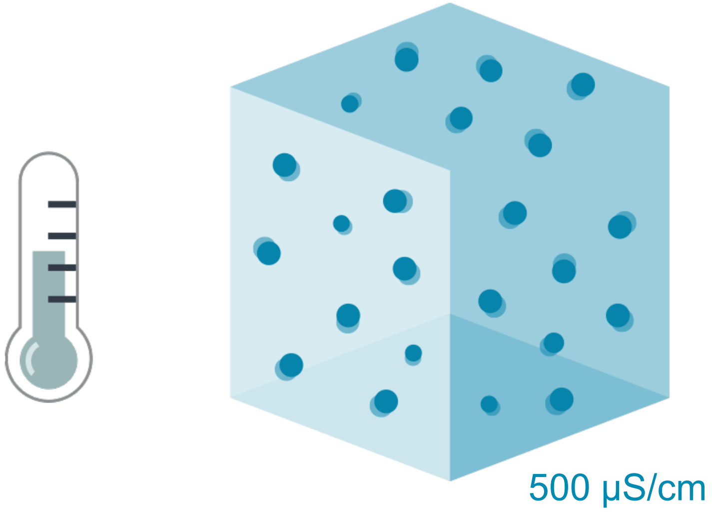
What Influences Conductivity?

- **Temperature**

- Same amount of ions at different temperatures will read as different conductivity values





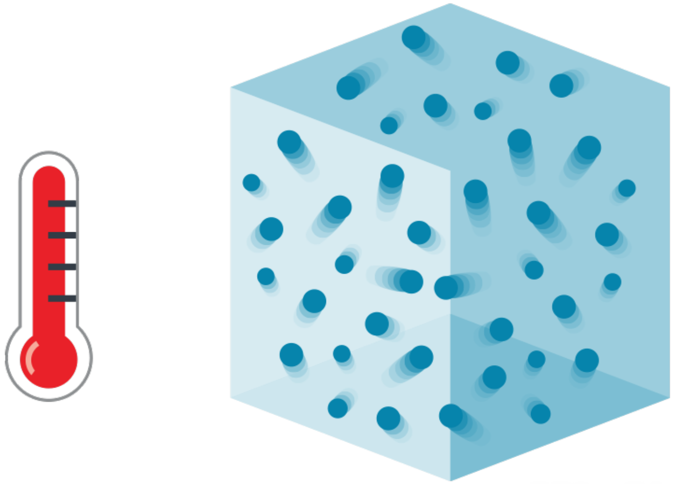
What Influences Conductivity?

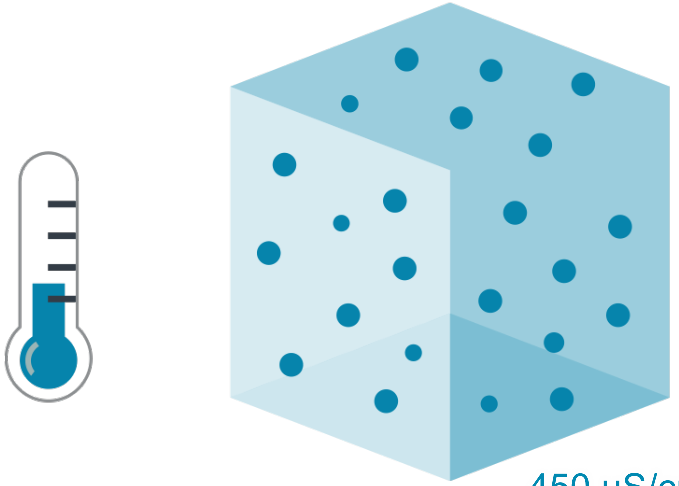
- **Temperature**

- Same amount of ions at different temperatures will read as different conductivity values

  - Cold Water = Lower Conductivity Reading
  - Warm Water = Higher Conductivity Reading

- Therefore, it is **best to report conductivity at a particular temperature**





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What is Conductivity?

- Examples of typical conductivity:

	Conductivity at 25 °C
ultrapure water	0.055 µS/cm
De-ionized water	1 µS/cm
Rain water	50 µS/cm
Drinking water	500 µS/cm
Industrial waste-water	5 mS/cm
Seawater	50 mS/cm
1 mol/L NaCl	85 mS/cm
1 mol/L HCl	332 mS/cm

1 mS/cm = 1,000 µS/cm

Why Conductivity is Important?

- Indicator of Water Quality
  - One of the Most Important and Widely Measured Parameters!
  - Conductivity can be used to:
    - Detect contaminants
    - Determine the purity of water

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Why Conductivity is Important?

- Indicator of Water Quality
- Stream Example:
  - Two different contaminants
    - Sewage introduced would increase the conductivity because of the presence of chloride, phosphate, and nitrate
    - An oil spill would lower the conductivity

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Why Conductivity is Important?

- Industrial applications to measure:
  - Ultrapure water
  - Concentrated salt solutions
  - Acids/Alkalis

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- Industrial applications to measure:
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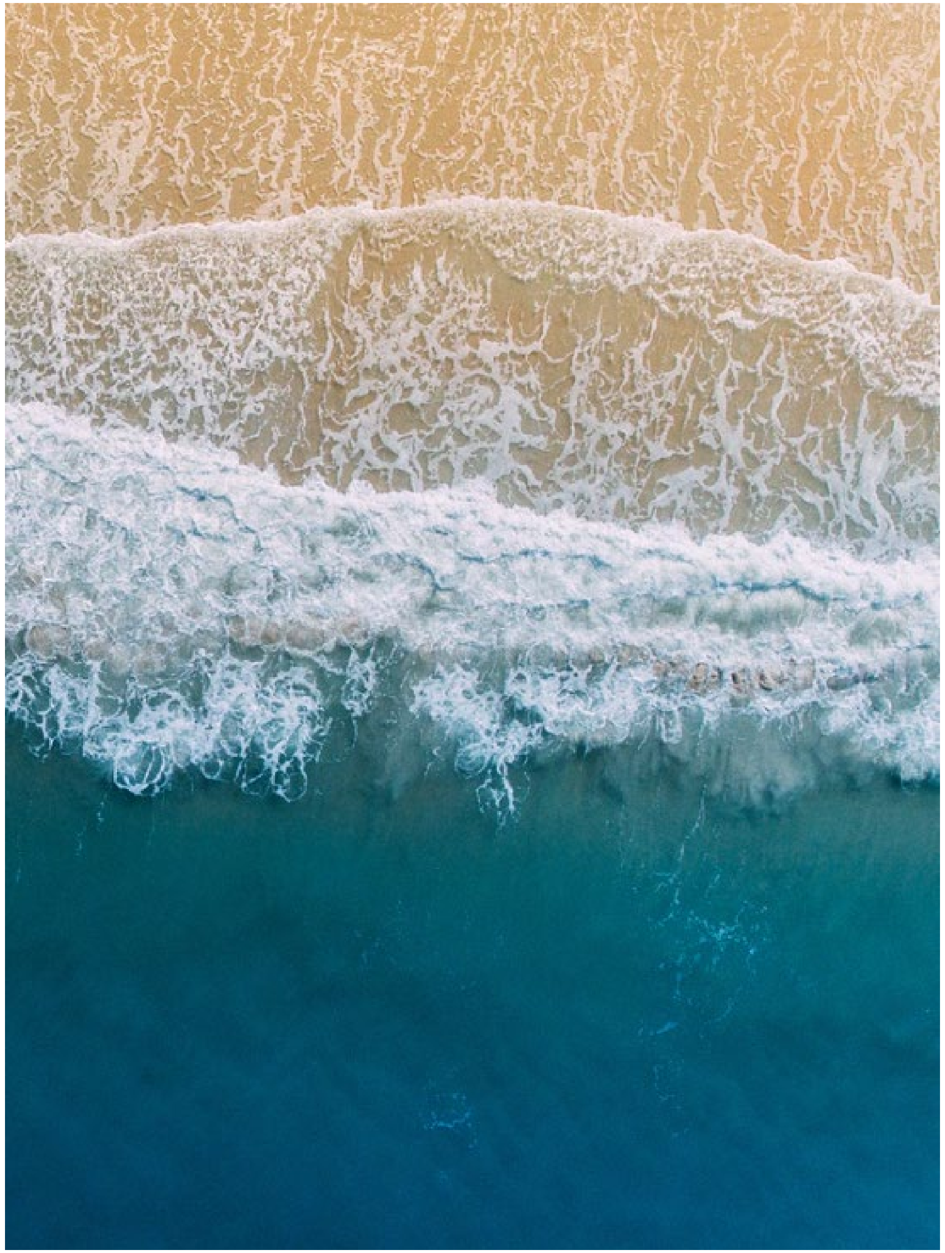
- Coastal environments to measure:
  - Salinity of brackish and seawater



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- Industrial applications to measure:
  - Ultrapure water
  - Concentrated salt solutions
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- Coastal environments to measure:
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- Fresh water rivers/streams/lakes to:
  - Detect agricultural runoff
    - Pesticides and fertilizers increase the conductivity of water

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Why Conductivity is Important?

- Industrial applications to measure:
  - Ultrapure water
  - Concentrated salt solutions
  - Acids/Alkalis
- Coastal environments to measure:
  - Salinity of brackish and seawater
- Fresh water rivers/streams/lakes to:
  - Detect agricultural runoff
    - Pesticides and fertilizers increase the conductivity of water
  - Detect stormwater runoff
    - Road Salts from winter snow melt can threaten aquatic life sensitive to salt levels

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Why Conductivity is Important?

- Factors into other parameters
  - Dissolved Oxygen
    - Solubility of oxygen decreases as conductivity increases
    - This means we get fish kills due to suffocation as a result of too much salt runoff

Why Conductivity is Important?

- Surrogates for Additional Parameters
  - Specific Conductivity
  - Salinity
  - Total Dissolved Solids (TDS)
  - Resistivity
  - Water Density

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Differences between Conductivity, Specific Conductance, & Salinity

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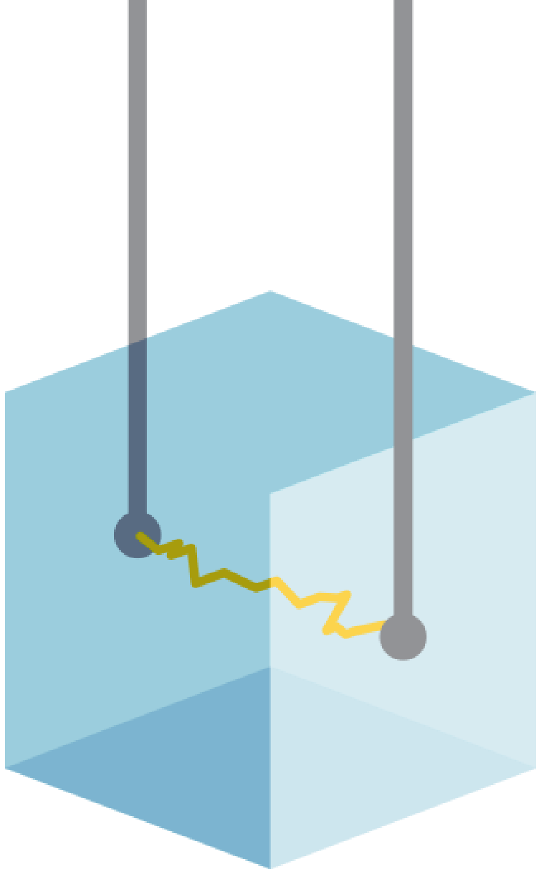
Which conductivity-related parameter are you most interested in measuring?

What is Conductance?

"**Conductance** is
the property of water,
that allows it to conduct an electric current."



What is Conductivity?

"**Conductivity** is
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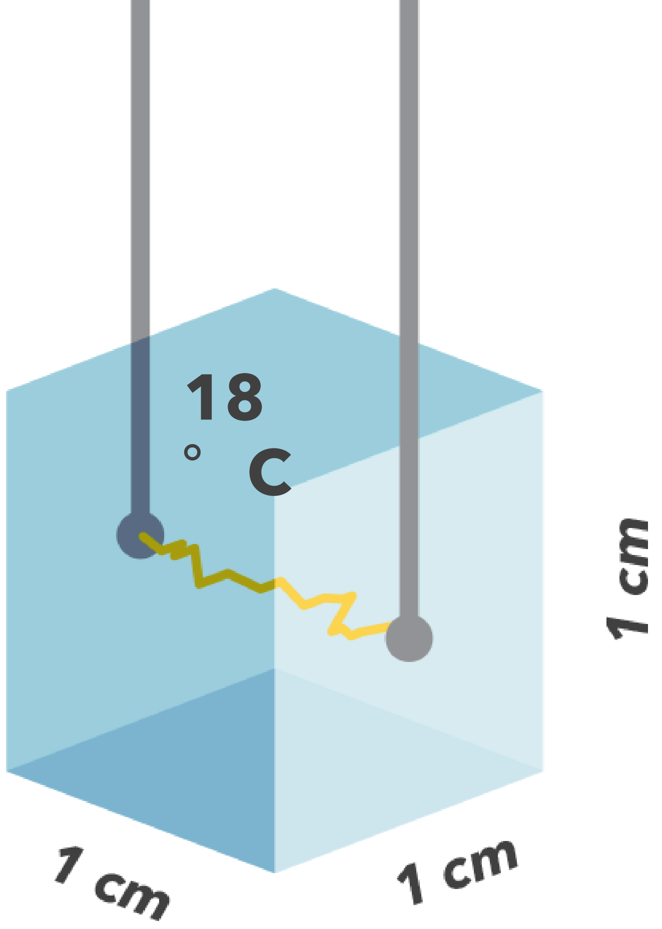

As this relates to sensors,
the measured conductance value
is normalized to 1 cm.

(Normalization occurs by way of the Cell Constant)

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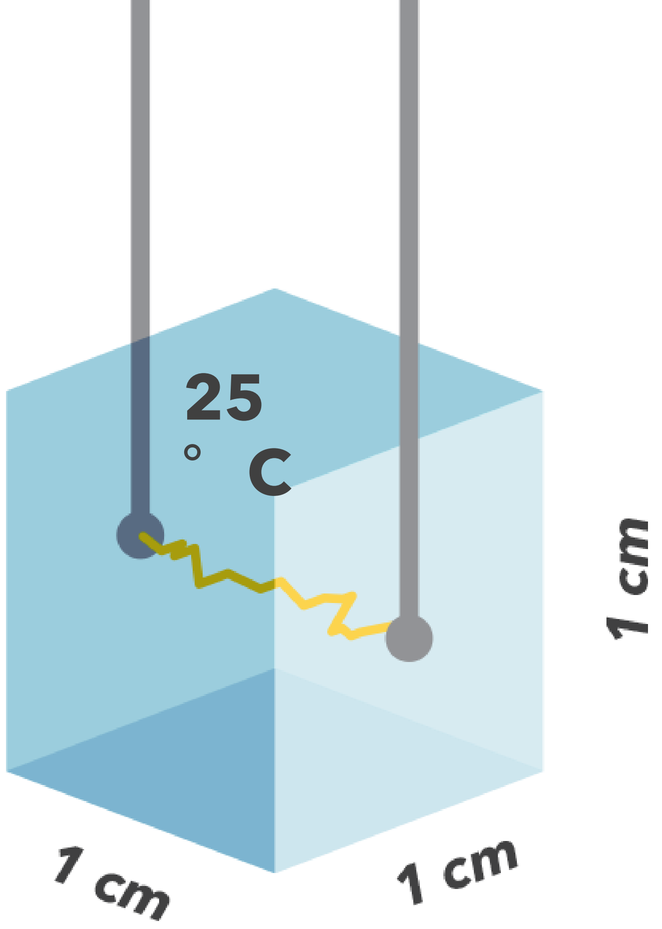
What is Specific Conductance?

"**Specific Conductance** is
the property of water,
measured through a specific cell geometry,
at or *compensated to* a specific temperature,
that allows it to conduct an electric current."



As this relates to sensors,
the measured conductivity value
is normalized to 25 ° C.

(Normalization occurs by way of the Temp Coefficient)

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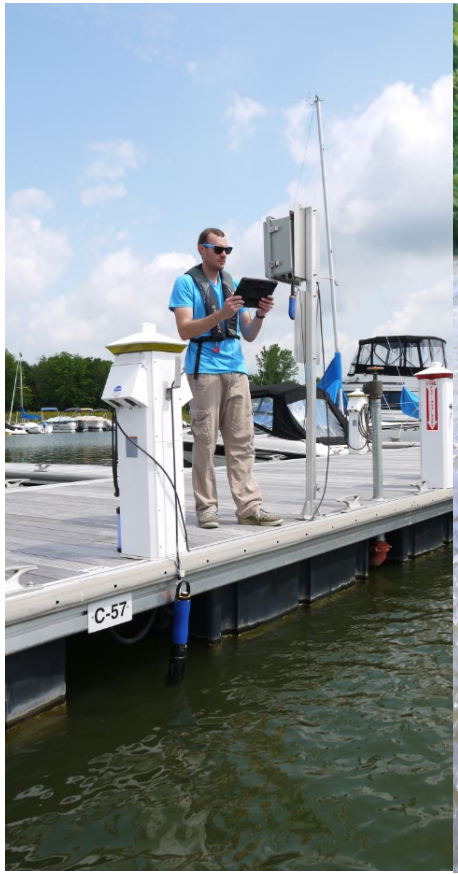
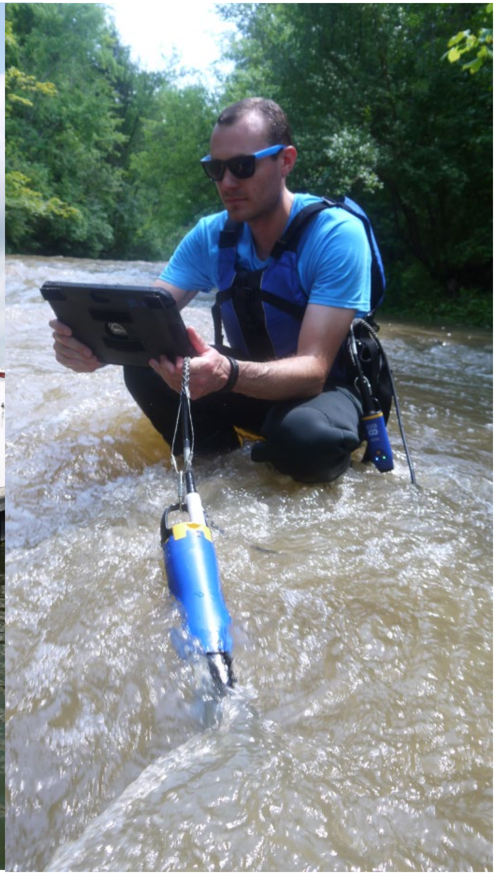
What is Specific Conductance?

- Specific Conductivity eliminates the influence of temperature
  - Just focusing on the ions
- Determine if changes occur in ionic content of the sample at a glance
- Useful for comparing conductivity between different locations and/or different times





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Differences between Conductivity and Specific Conductance

- **Specific Conductance** = Conductivity measured at or compensated to 25 ° C

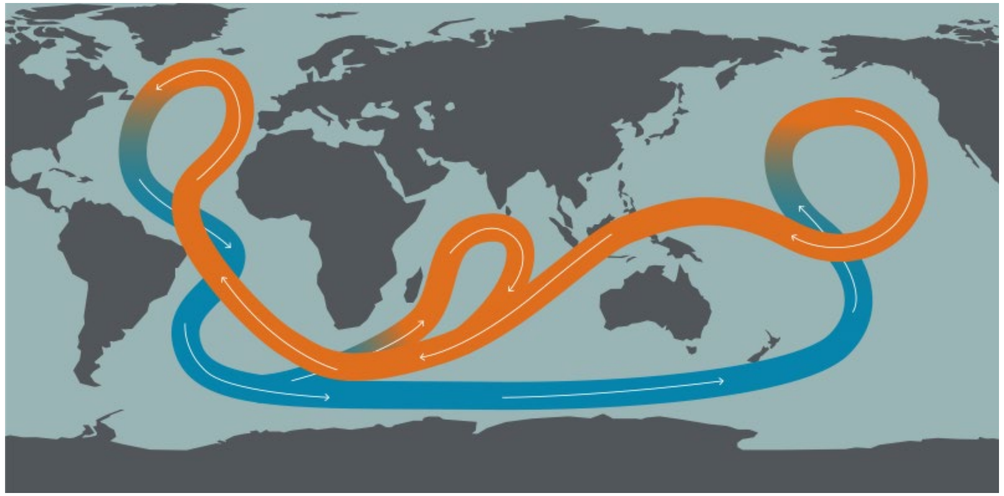
- Calculated using the measured Conductivity value with the measured Temperature value (T) and the Temperature Coefficient (TC)

$$\text{Specific Conductance } (25^\circ C) = \frac{\text{Conductivity}}{1 + TC * (T - 25)}$$

- Conductivity = true conductivity
- Specific Conductance = compensated conductivity

What is Salinity?

- **Salinity** = Concentration of Dissolved Salt in Water
- Proportional to Conductivity as it is related to the Ionic Content of Water
  - More dissolved salts = higher ionic strength
- Key Factor in Global Ocean Circulation (Thermohaline Circulation)
  - Caused by rising and sinking water masses due to variations in density
  - Salinity/Temp/Pressure affect water density



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Differences between Conductivity & Salinity

- How Salinity is Measured
  - Concentration of grams of salt per kilogram of water (g/kg)
  - More commonly expressed as Parts Per Thousand (ppt)

  - Historically measured via chemical analysis
    - Titration and Evaporation
      - Evaporating all of the water away from the samples
      - Time intensive and prone to errors
      - Not practical for many applications

Differences between Conductivity & Salinity

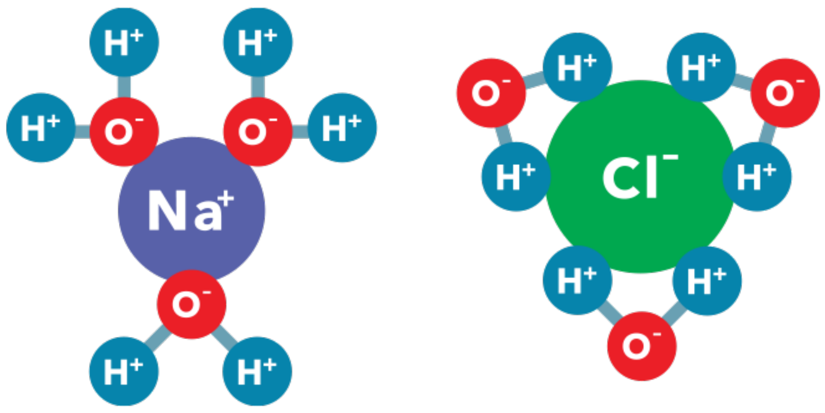
- How Salinity is Measured
  - Now more commonly with a conductivity meter
    - Derived from conductivity and temperature measurements
  - Practical Salinity Scale 1978 (PSS-78) is unitless, but values are sometimes reported in psu (practical salinity units)
    - psu = ppt

Other Conductivity-Related Parameters

- **Resistivity** = Inverse of Conductivity
  - Property of water, measured over a specific length, that quantifies how much it resists electric current
  - Unit:
    - ohms/cm

Other Conductivity-Related Parameters

- **TDS** (Total Dissolved Solids)
  - Measure of dissolved combined content of all inorganic and organic substances present in water
    - Conductivity can be used as a rough estimate of the amount of these substances are present
    - User must determine TDS Constant for the water at the site of interest



How Conductivity Sensors Work: Principles of Operation

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What range of conductivity values do you measure?

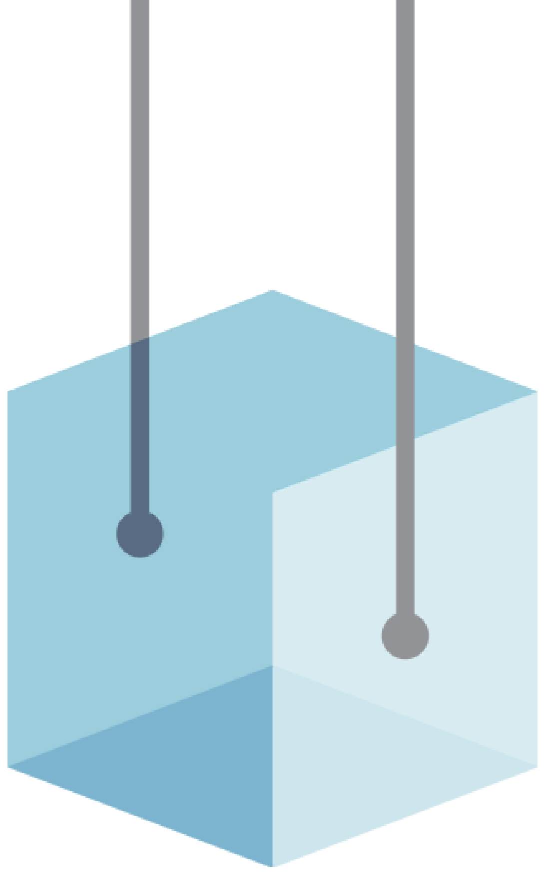
How Conductivity Sensors Work

I. Principles of Conductivity Measurement
II. Types of Conductivity Cells
III. Length & Area of Conductor
IV. Cell Constant
V. Temperature Coefficient
VI. How YSI Sensors Work

How Conductivity Sensors Work

- Principle by which instruments measure conductivity:

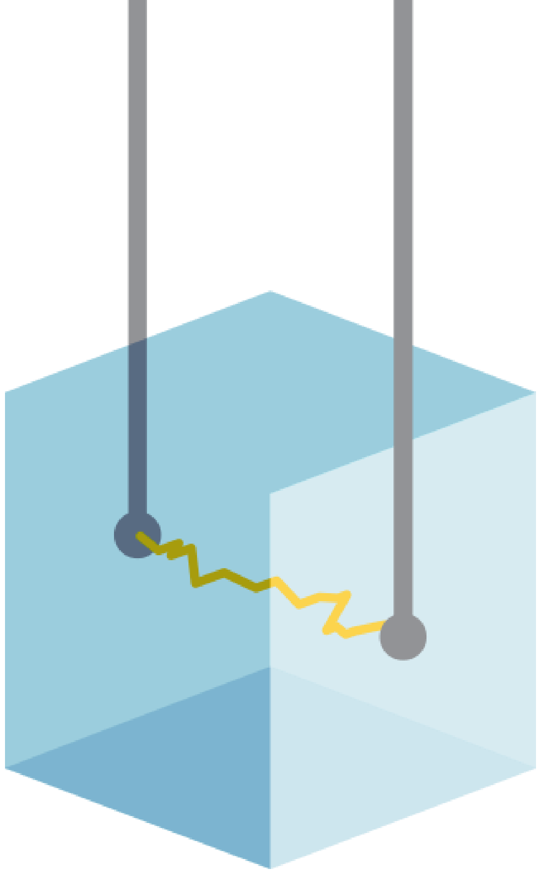
1. Electrodes are placed in the sample



How Conductivity Sensors Work

- Principle by which instruments measure conductivity:

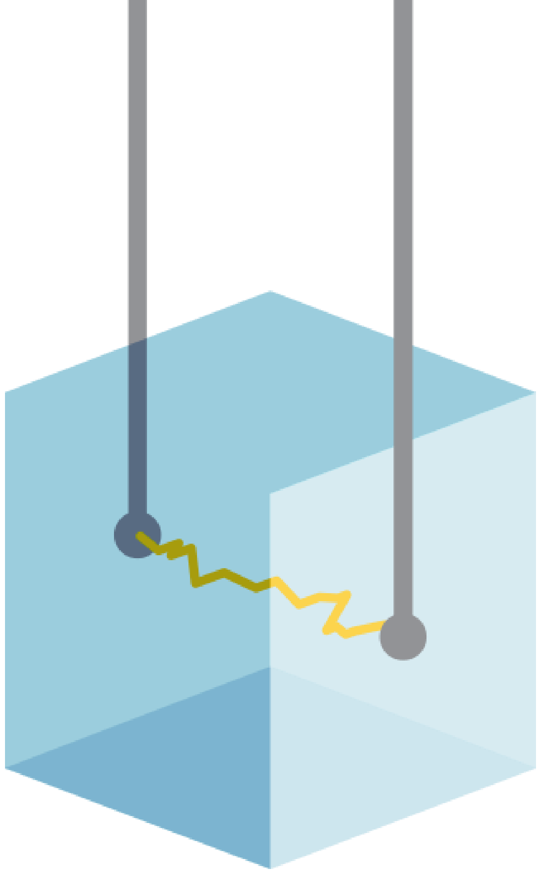
1. Electrodes are placed in the sample
2. Current is driven through the electrodes



How Conductivity Sensors Work

- Principle by which instruments measure conductivity:

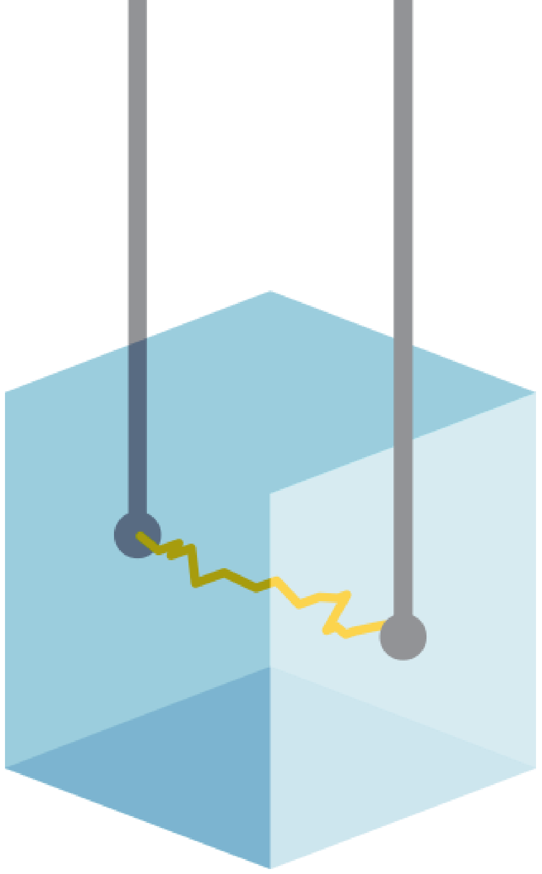
1. Electrodes are placed in the sample
2. Current is driven through the electrodes
3. Resultant change in potential (voltage) is measured



k = I/V

How Conductivity Sensors Work

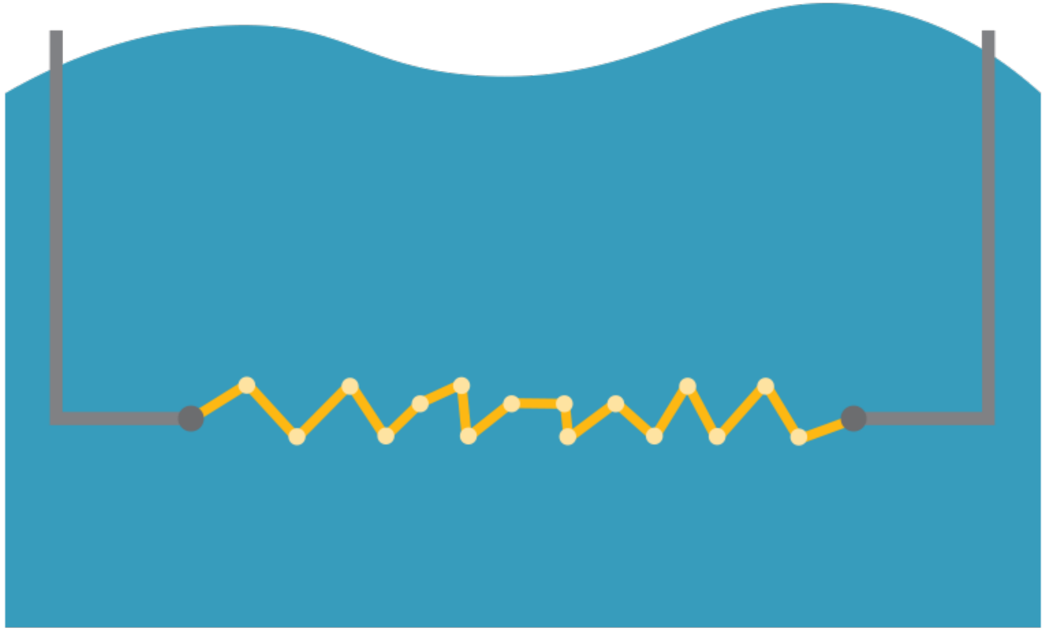
- Conductivity cell = sensing area
- Conductivity cells consist of electrode pairs to which a current is applied
- Voltage is measured and conductivity is calculated



k = I/V

Conductivity Cell Types

- 2-Electrode Cell
  - Best for low-conductivity solutions
  - Susceptible to polarization



Conductivity Cell Types and Polarization

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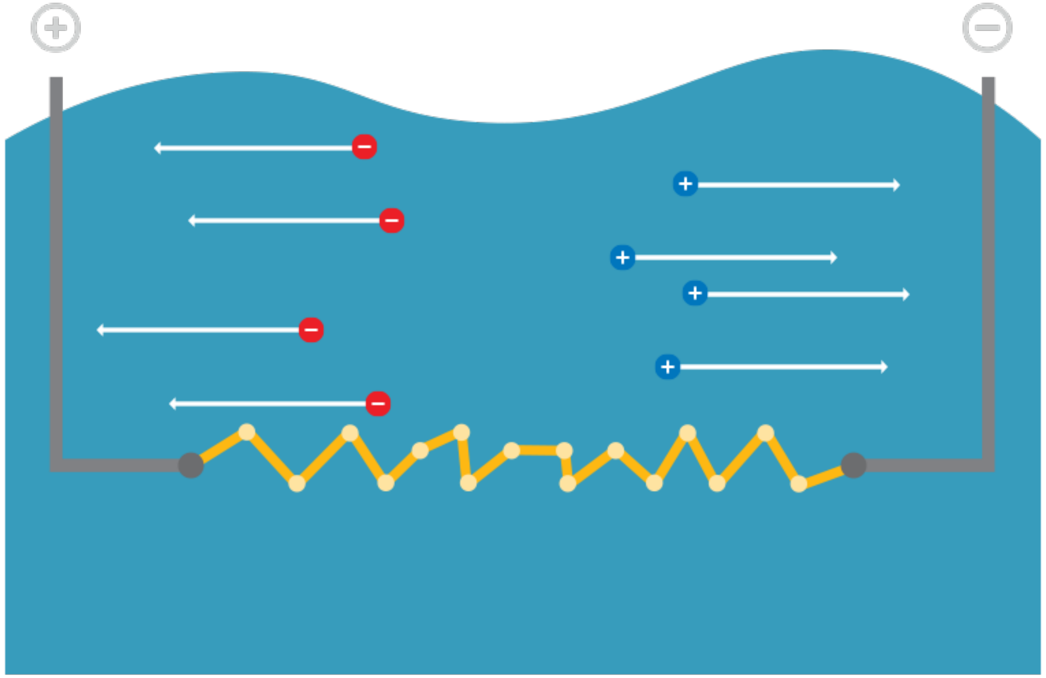
- Polarization
  - Leads to artificially low values



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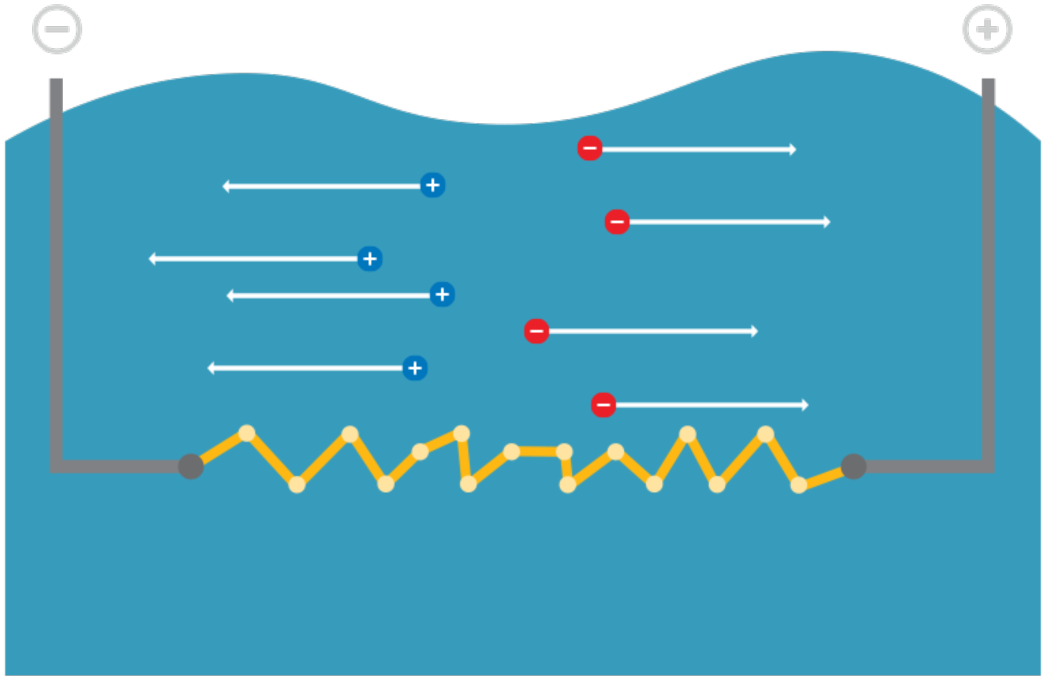
- Polarization
  - Leads to artificially low values
  - Can be reduced by:
    - Alternating voltage



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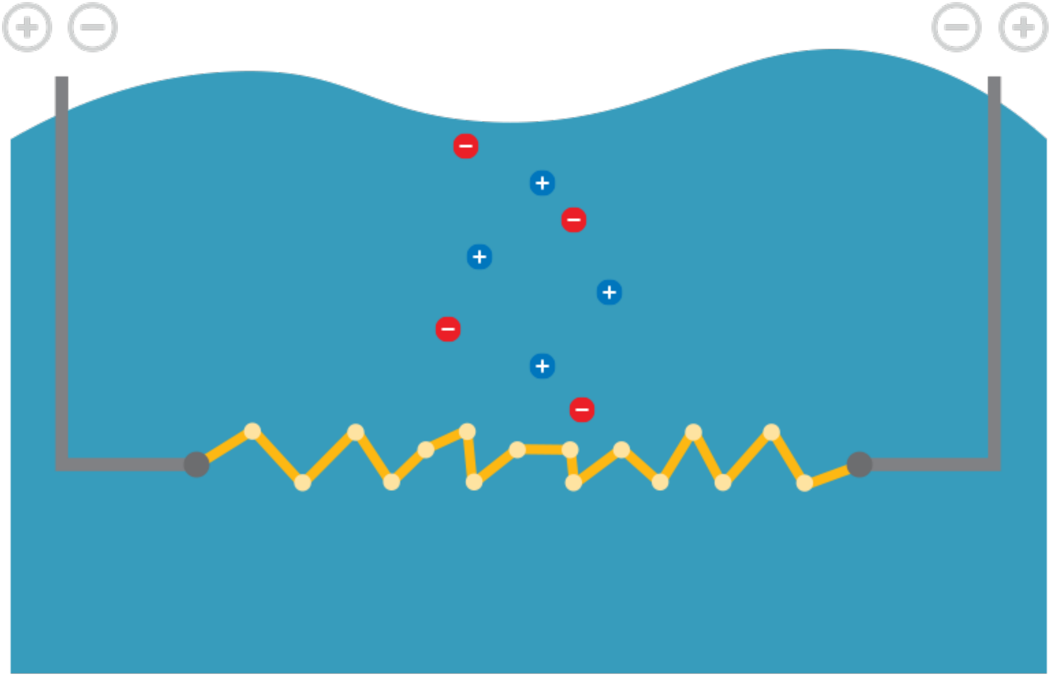
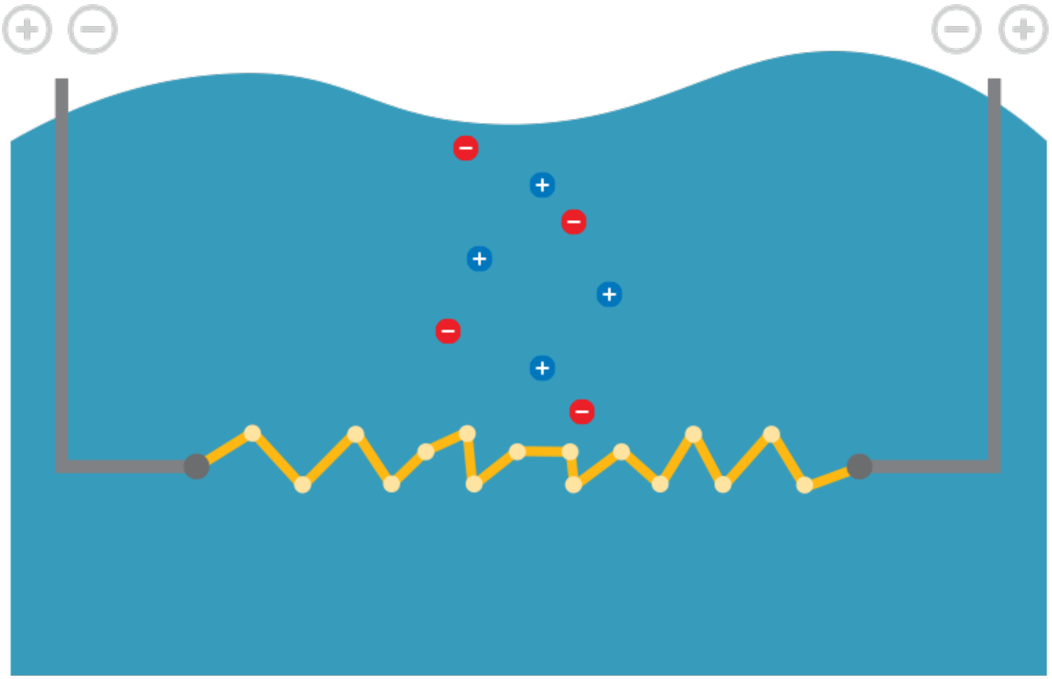


Conductivity Cell Types and Polarization

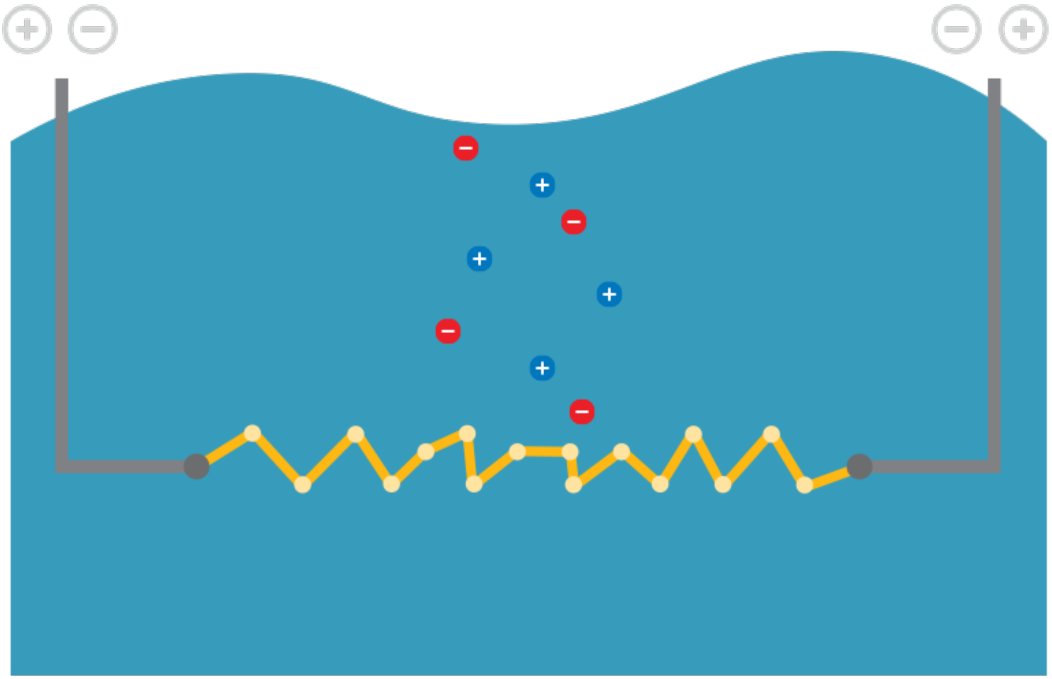
- 2-Electrode Cell
  - Best for low-conductivity solutions
  - Susceptible to polarization

- Polarization
  - Leads to artificially low values
  - Can be reduced by:
    - Alternating voltage
    - Renewing the electrode surface (platinizing solution)



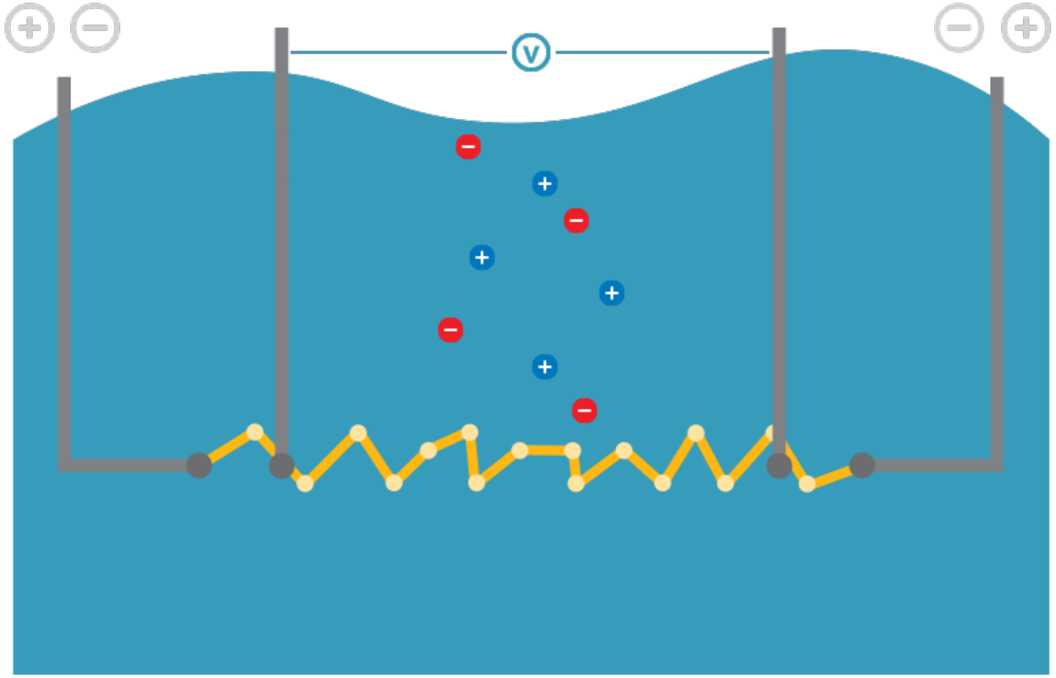
Conductivity Cell Types and Polarization

- 2-Electrode Cell
  - Best for low-conductivity solutions
  - Susceptible to polarization
- Polarization
  - Leads to artificially low values
  - Can be reduced by:
    - Alternating voltage
    - Renewing the electrode surface (platinizing solution)
  - Cannot be avoided in high ionic concentrations



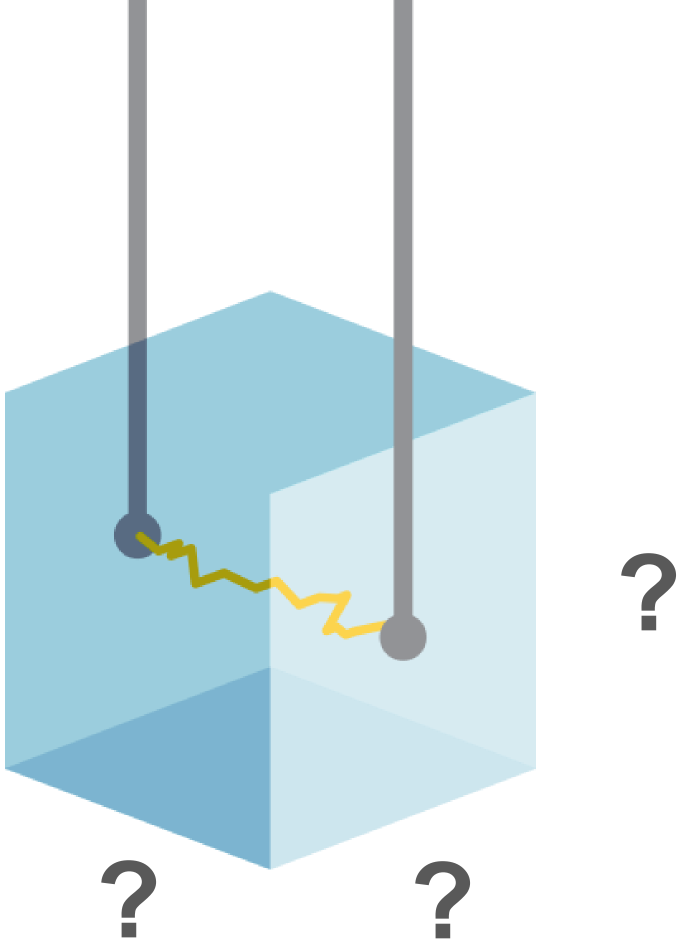
Conductivity Cell Types

- 4-Electrode Cell
  - Two voltage electrodes + two current electrodes
  - Best for wider conductivity ranges
  - Compensated for scale or build-up on electrodes
  - Minimizes the effects of polarization



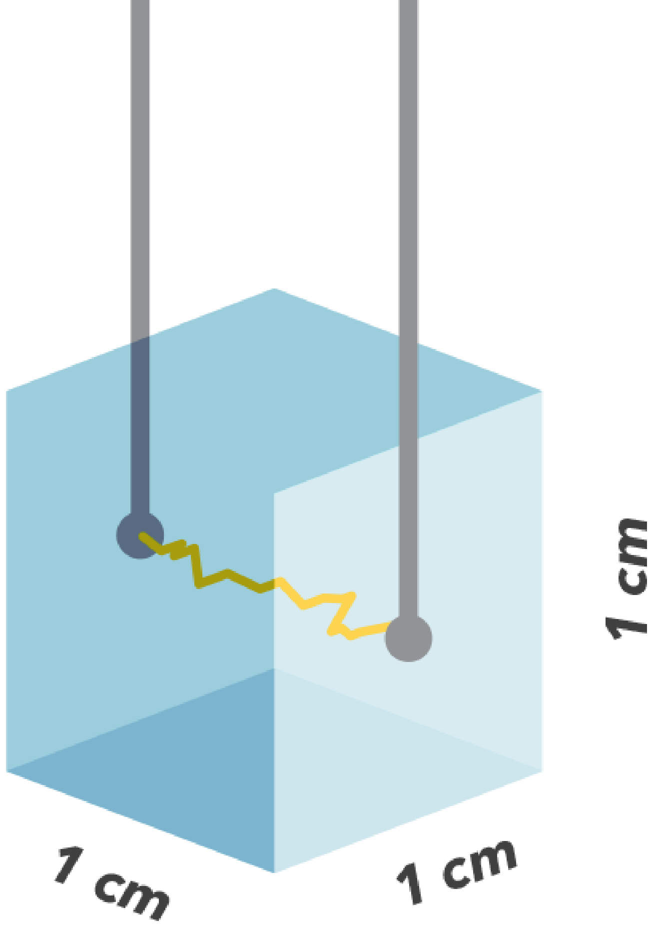
Length & Area of Conductor

- Conductivity is the conductance per **unit of conductor length**
  - Conductor = measured water or liquid in a cell



Length & Area of Conductor

- Conductivity is the conductance per **unit of conductor length**
  - Conductor = measured water or liquid in a cell
- Industry Standard = conductance in siemens is measured across **1 cm cube of liquid** at a specified temperature
  - 1 cm cube = theoretical (ideal) conductivity cell
  - Cell = sensing area



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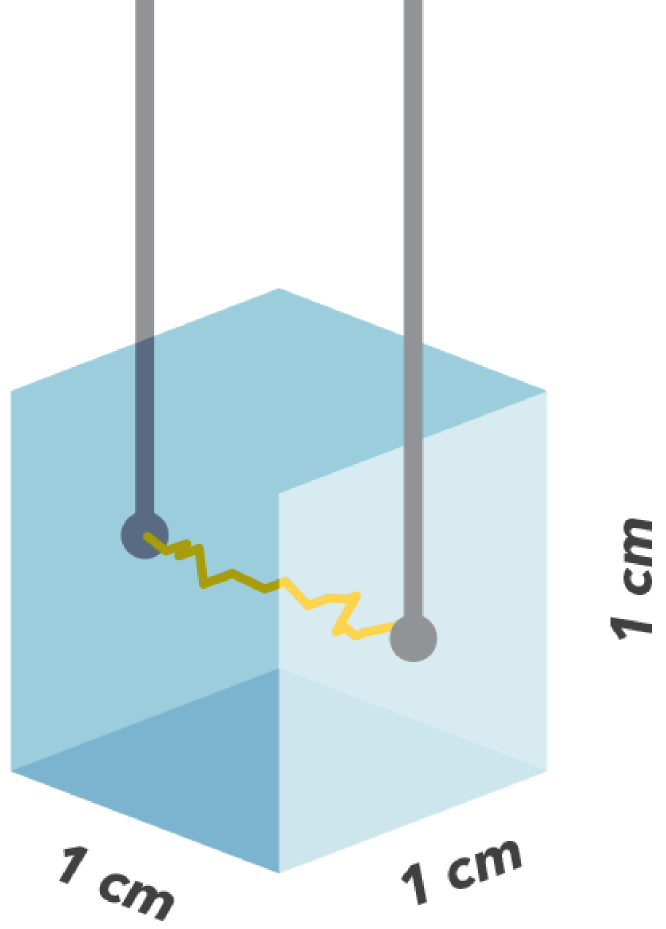
Length & Area of Conductor

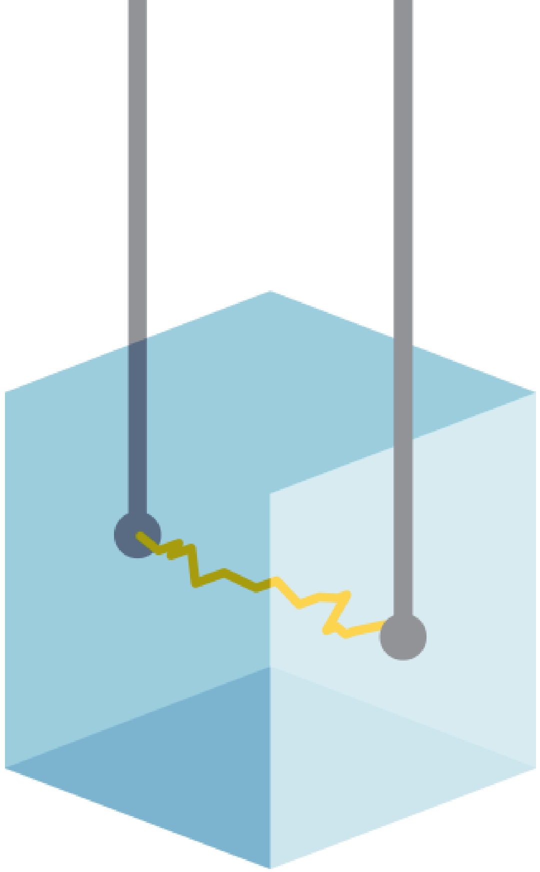
- Cell geometry affects the measured values

- BUT not every sensor is designed to measure precisely 1 cm cube of liquid



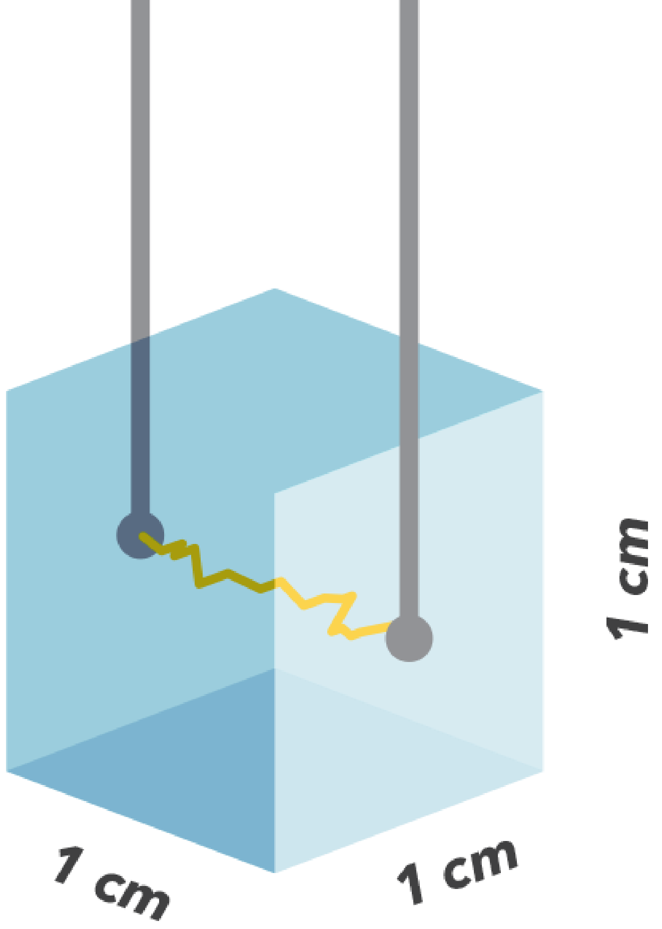
Length & Area of Conductor

- Cell geometry affects the measured values
- BUT not every sensor is designed to measure precisely 1 cm cube of liquid
- So… how do we account for this?



Conductivity Cell Constant

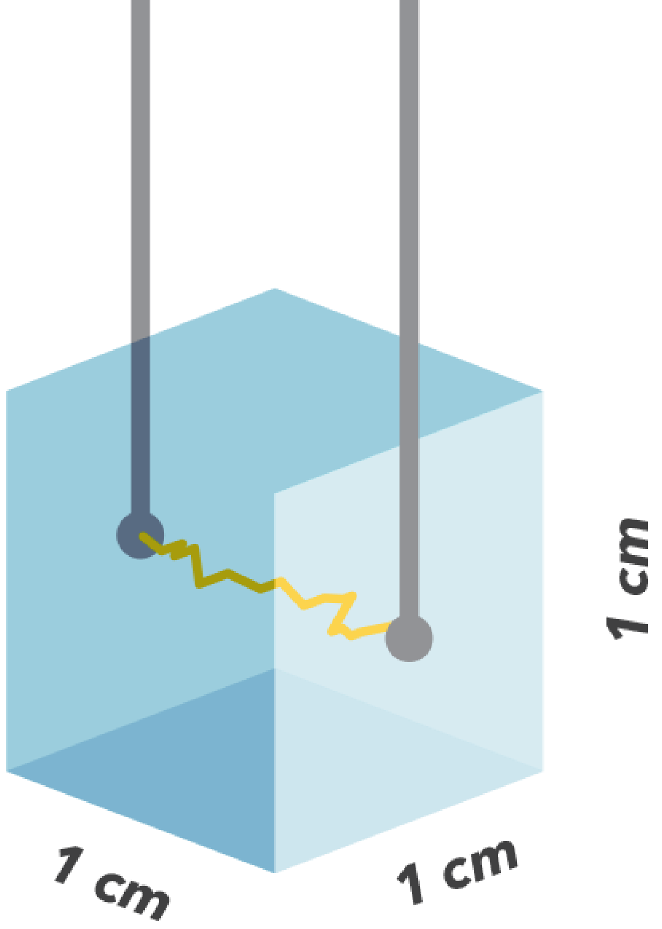
- **Cell Constant** = (**K**)
  - Cell Geometry defines the Cell Constant
  - Formula: **K = d/A**
- Ratio of the distance (**d**) between the electrodes to the cross sectional area (**A**) of the electrodes
  - **d** = distance between electrodes
    - ex. 1 cm
  - **A** = area of electrode
    - L x W = 1 cm²



Conductivity Cell Constant

- Cell Constant: **K = d/A**
  - **d** = distance between electrodes
  - **A** = area of electrode

- Example:
  - K = 1 cm/1 cm^2



Conductivity Cell Constant

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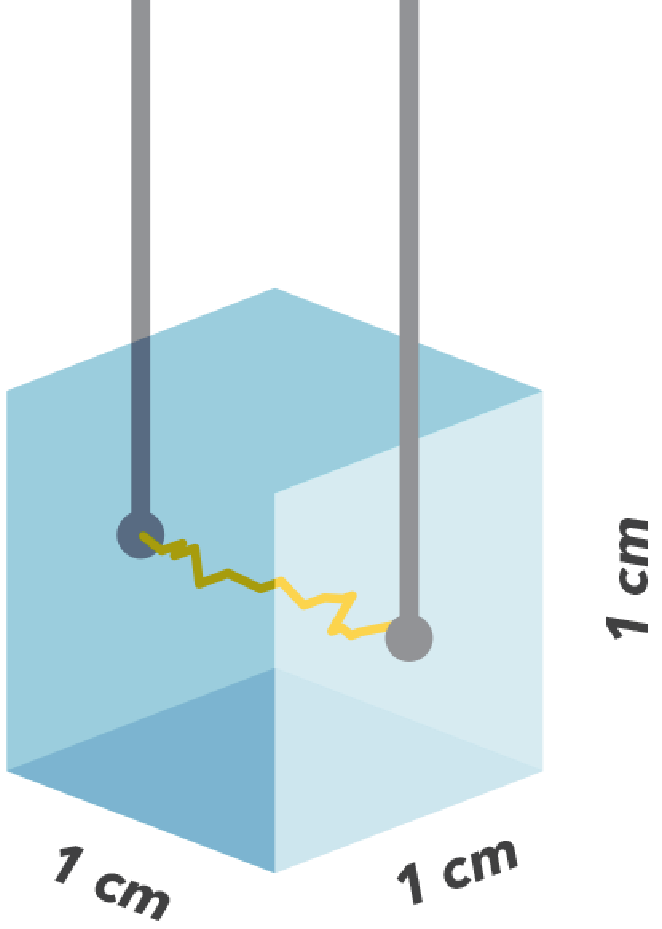
  - Cell Constant = 1/cm



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- Example:
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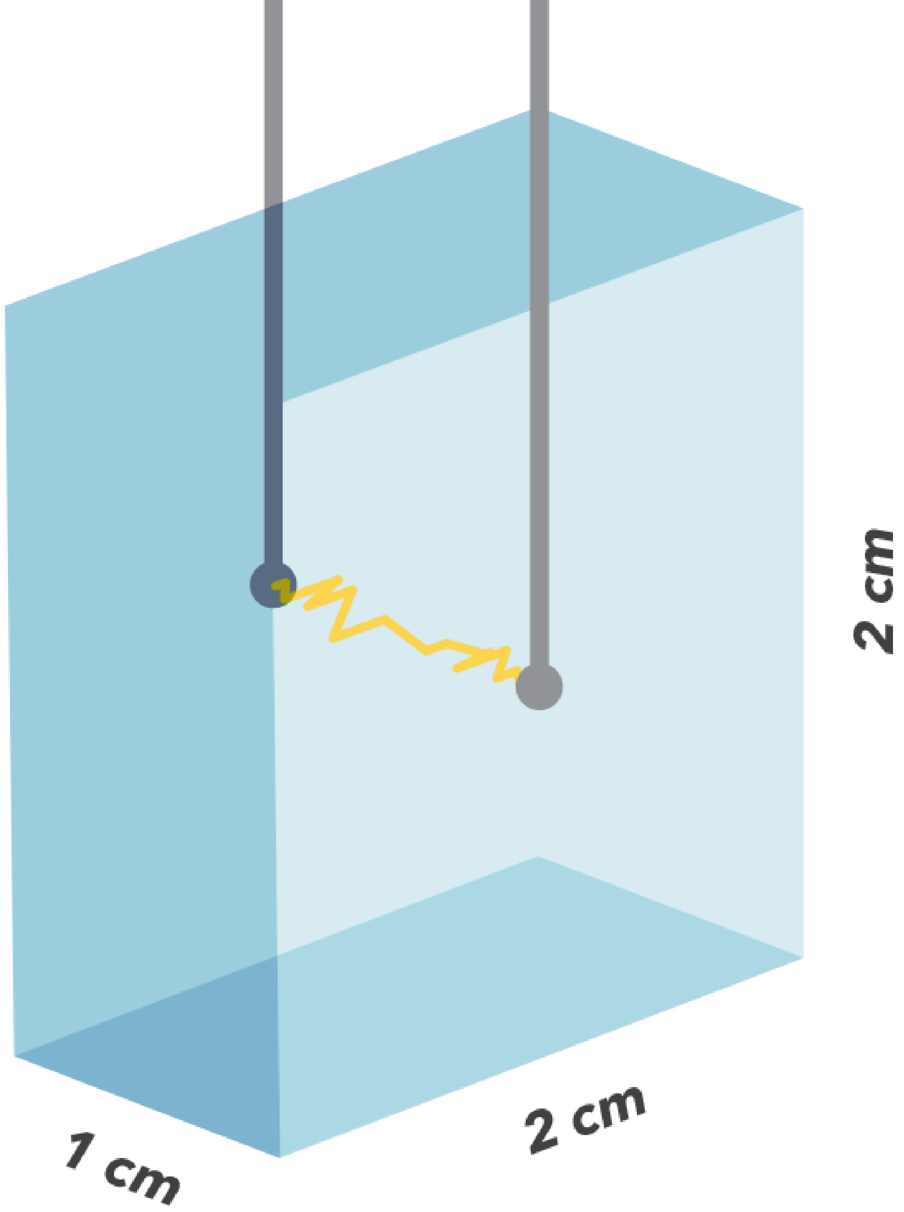
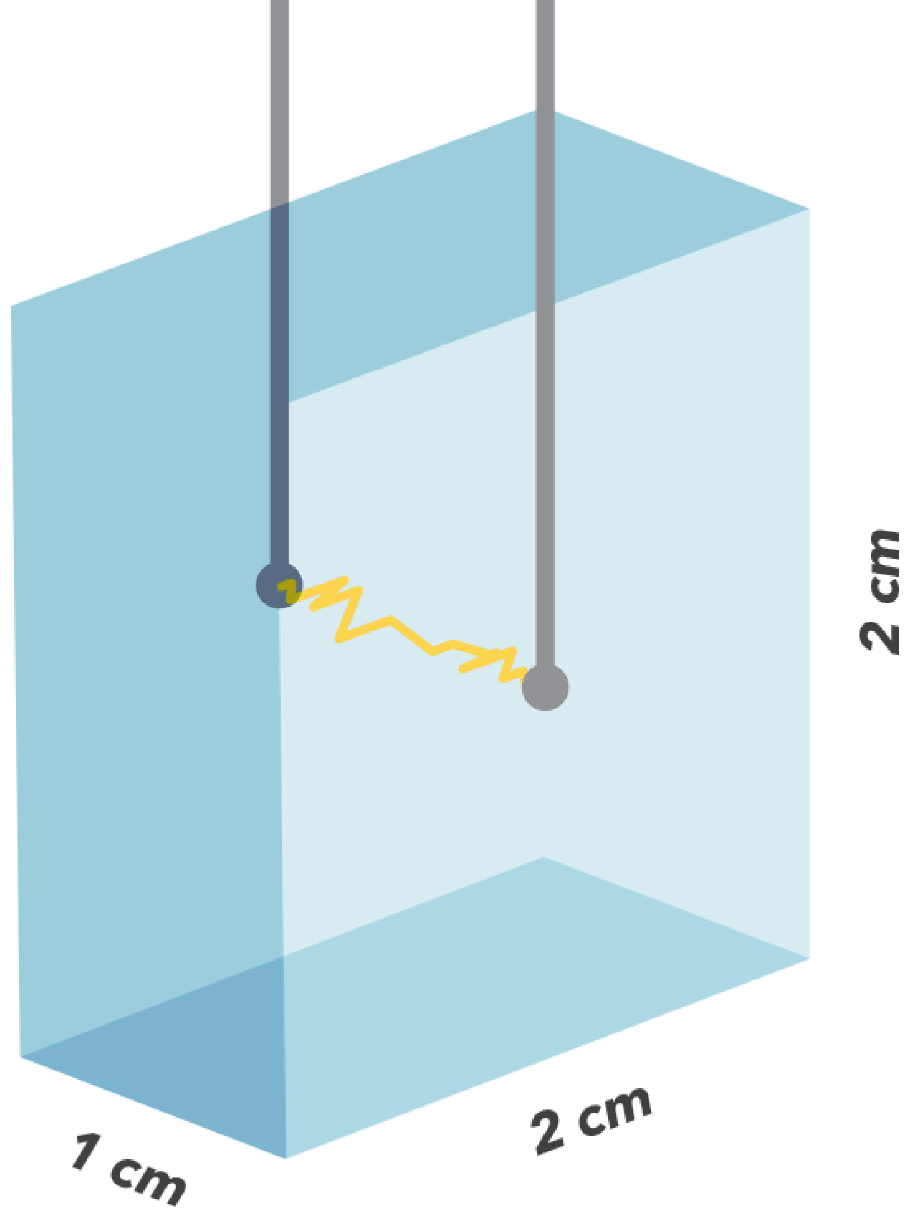


Conductivity Cell Constant

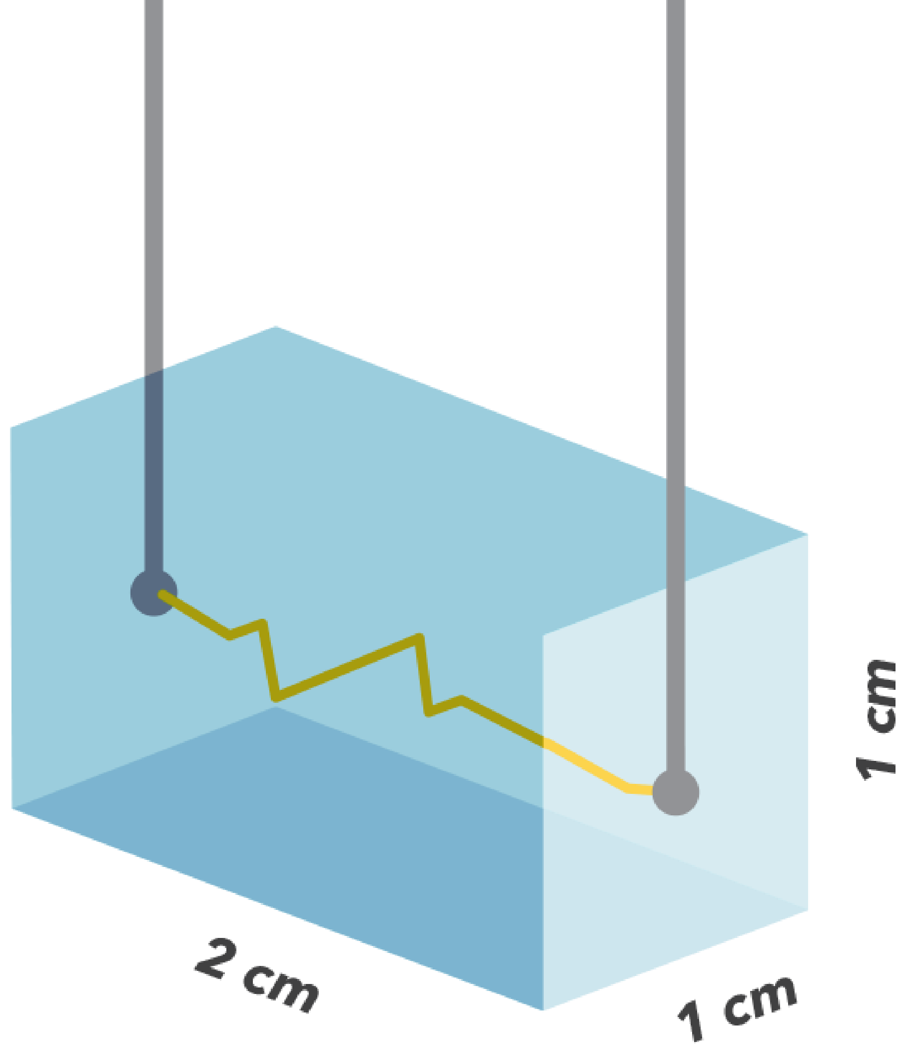
- Cell Constant: **K = d/A**
  - **d** = distance between electrodes
  - **A** = area of electrode

- Example:
  - K = 1 cm/4 cm^2
  - Cell Constant = 0.25/cm



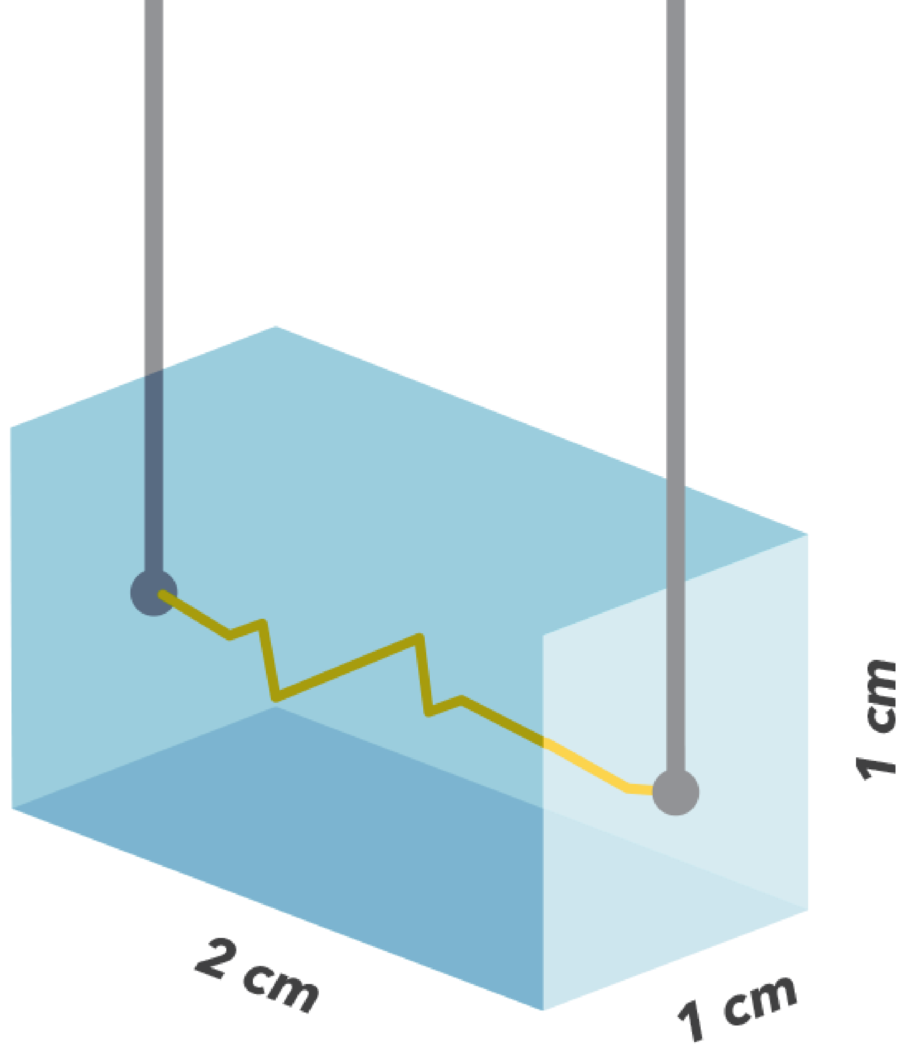
Conductivity Cell Constant

- Cell Constant: **K = d/A**
  - **d** = distance between electrodes
  - **A** = area of electrode
- Example:
  - K = 2 cm/1 cm²



Conductivity Cell Constant

- Cell Constant: **K = d/A**
  - **d** = distance between electrodes
  - **A** = area of electrode
- Example:
  - K = 2 cm/1 cm²
  - Cell Constant = 2/cm



Conductivity Cell Constant

- **Conductivity** (**ℵ**) equals **Conductance** (**k**) multiplied by the **Cell Constant** (**K**)
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Conductivity Cell Constant

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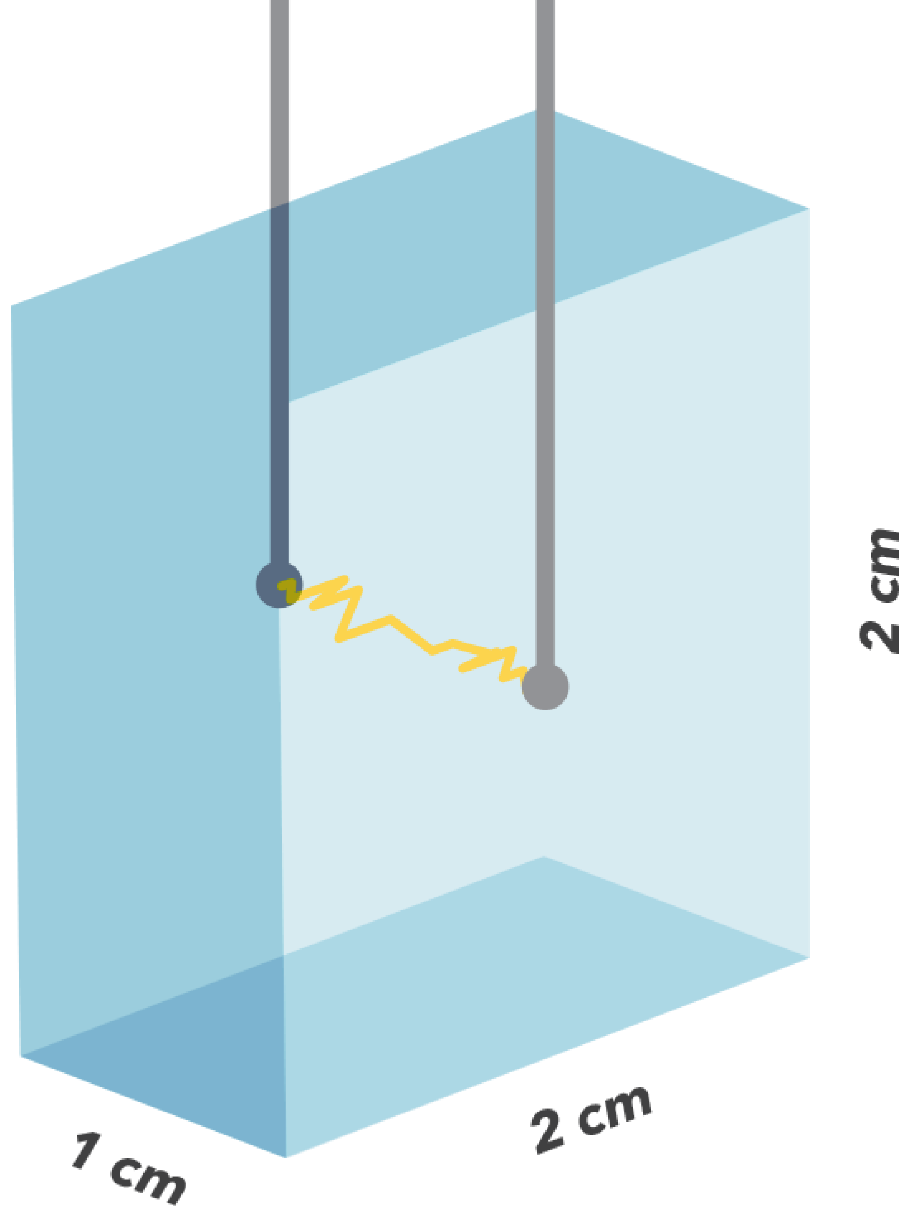
- Example:
  - Observed Conductance = 100 µS (**k**)
  - Sensor Cell Constant = 0.25/cm (**K**)
  - **א = 100 µS x 0.25/cm**



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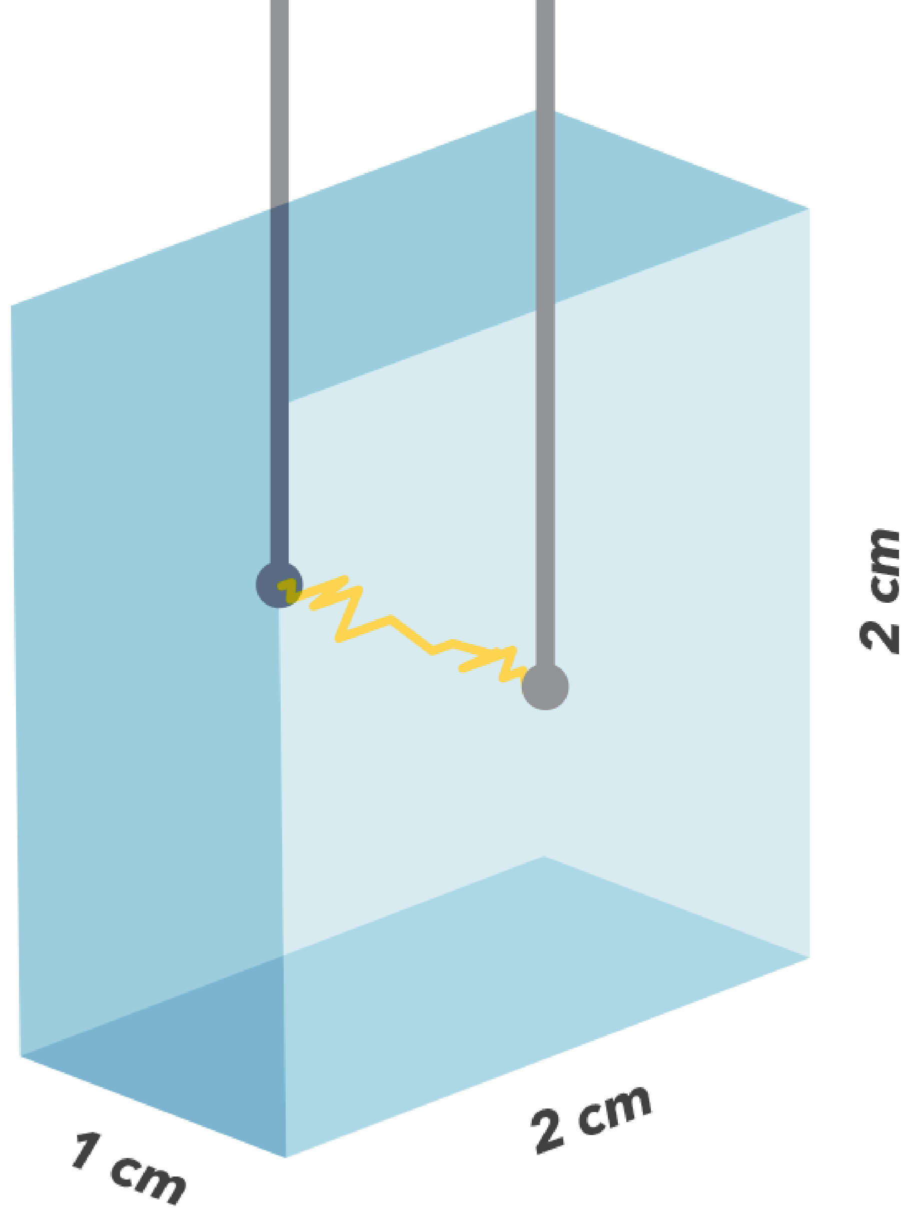
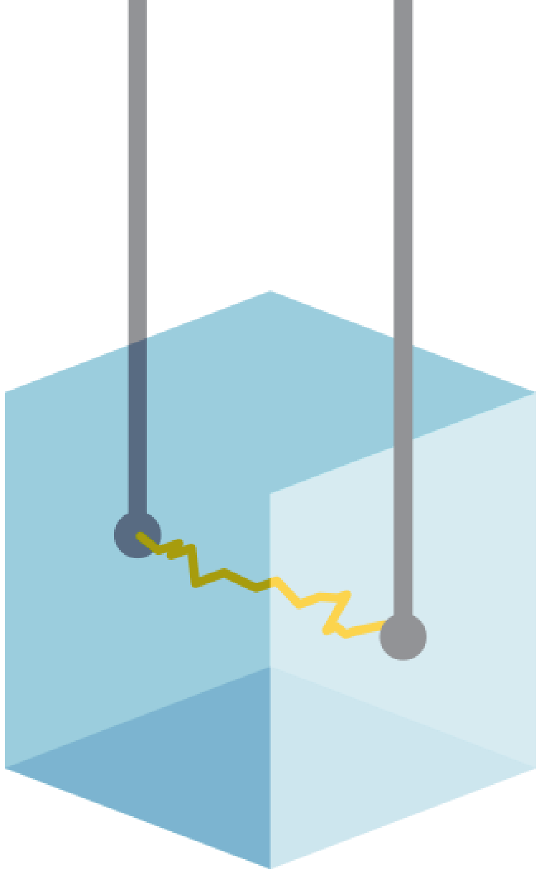
  - Sensor Cell Constant = 0.25/cm (**K**)
  - **ℵ = 100 µS x 0.25/cm**
  - Conductivity = 25 µS/cm



Conductivity Cell Constant

- Cell Constant is relatively stable, but will drift with use over time
  - Cell geometry changes occurs during use



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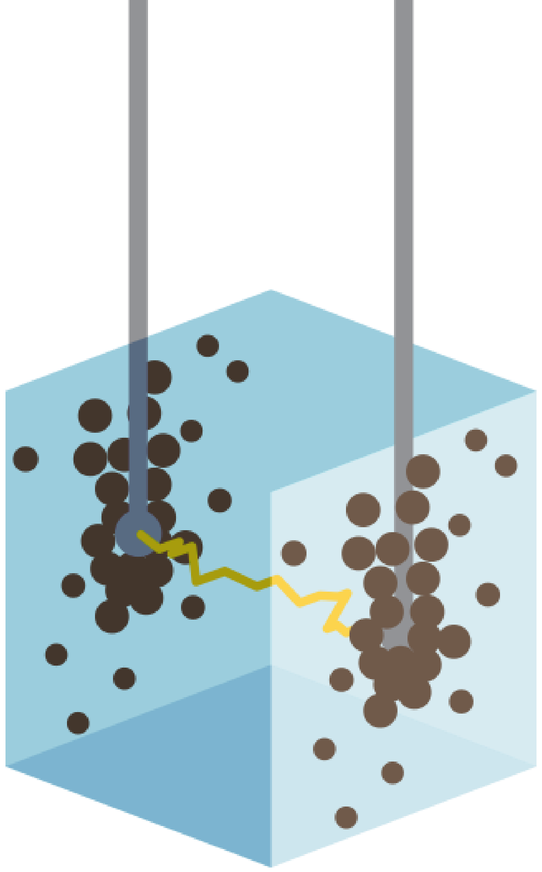

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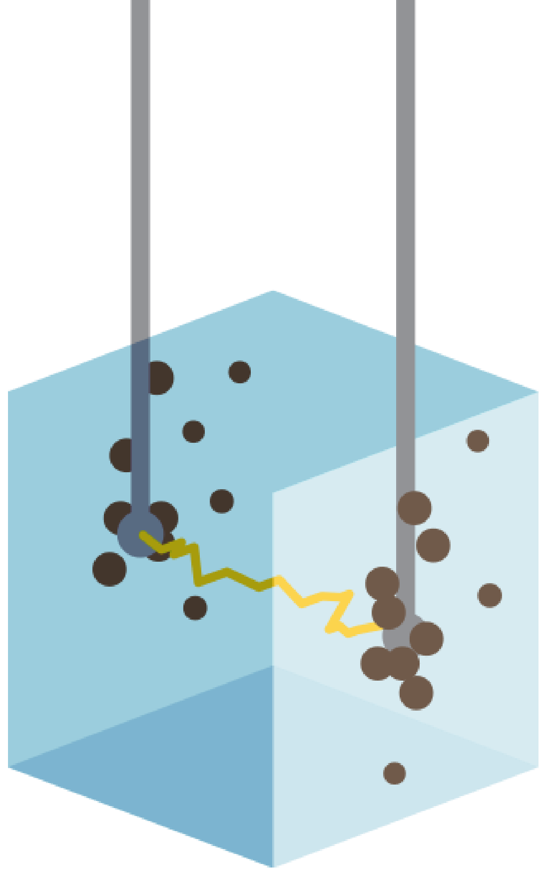

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Conductivity Cell Constant

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  - This is why we calibrate

Cell Constant ≠ Conductivity Cell

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  - Cell geometry changes occurs during use
  - Even after cleaning, the cell is slightly different
  - Cell Constant must be updated to account for this
  - This is why we calibrate

- Every time you calibrate, you update the cell constant to account for changes to the cell
  - Track changes to the cell with calibration reports

Cell Constant = Conductivity Cell

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Temperature Coefficient

- Conductivity is strongly dependent on temperature
  - Can vary up to 3% for each change of 1 ° C
- Temperature Coefficient = Percent change in conductivity for each degree change in temperature (%/°C)
- Temp Co varies depending on the sample

  (varies with sample; not with hardware like Cell Constant)
  - Can be determined from:
    - Published data
    - Measurements of representative samples

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Temperature Coefficient

- Temp Co = %change in conductivity per 1 °C change
- Example:
  - Conductivity Standard Solution
  - At 25 °C, the solution reads 1,413 µS/cm

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    - 1440/1413 = 1.0191
  - Conductivity value increases by 1.91% per 1 °C change in temperature

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- Temp Coefficient = 0.0191
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  - Allows for the calculation of Specific Conductance for easy comparison

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$$\text{Specific Conductance (25°C)} = \frac{\text{Conductivity}}{1 + TC * (T - 25)}$$

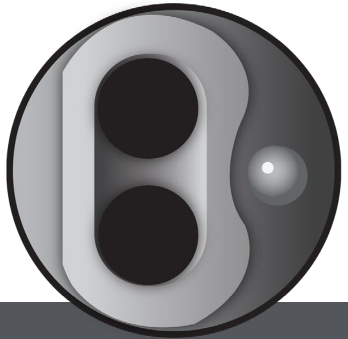
→ 1440/1.0191(26-25)

↓ 1440/1.0191

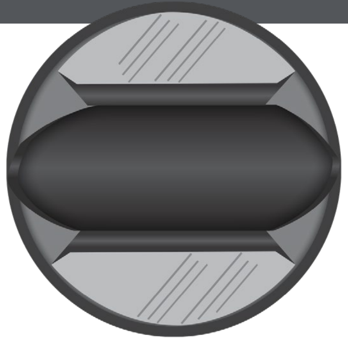
↓ ~1413

How Conductivity Sensors Work

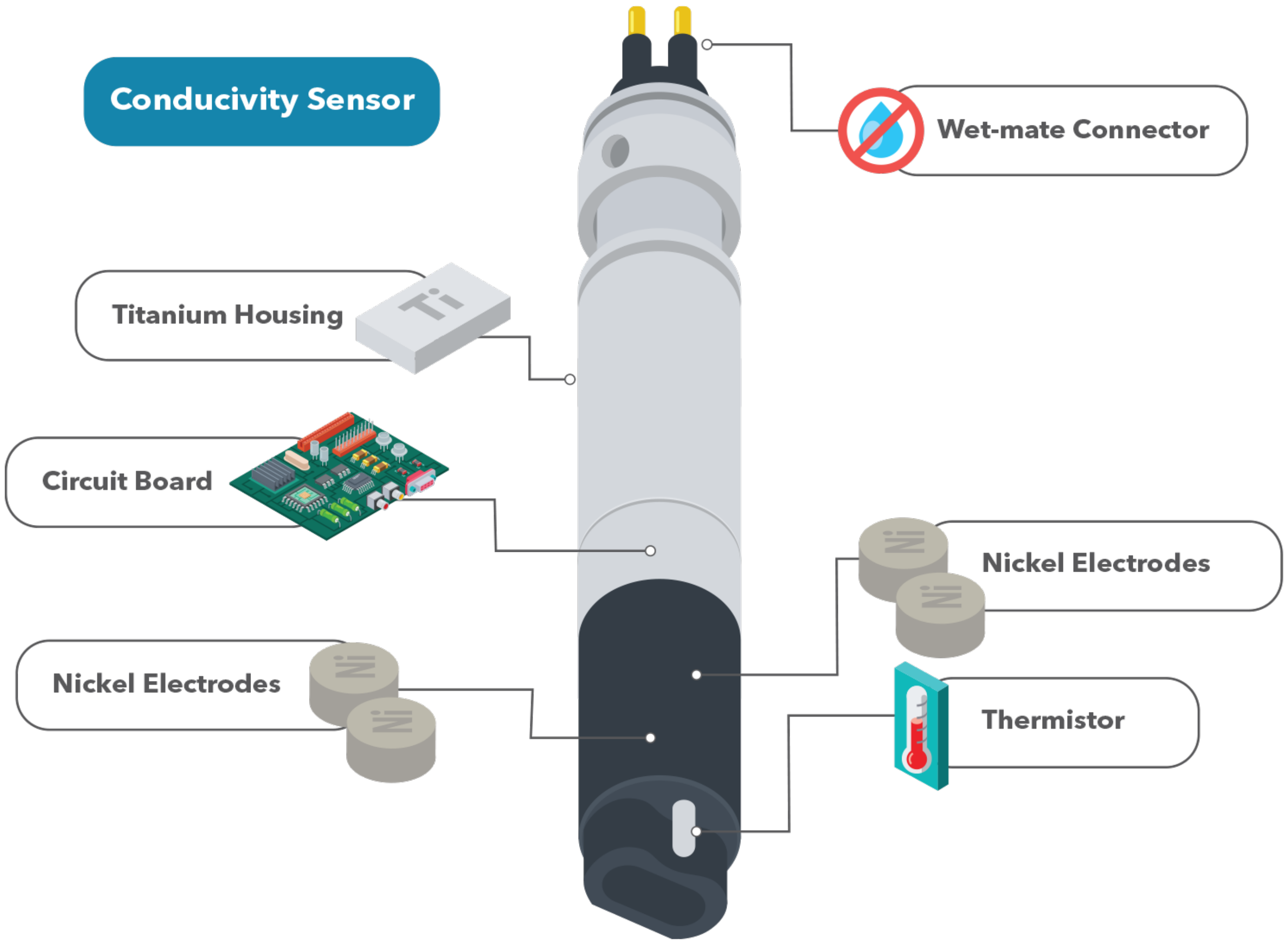
Continuous Monitoring

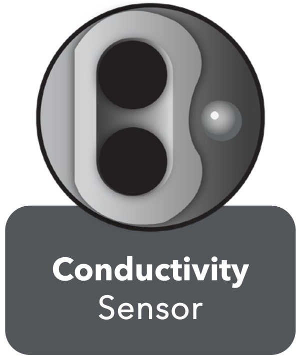


Conductivity
Sensor



How Conductivity Sensors Work



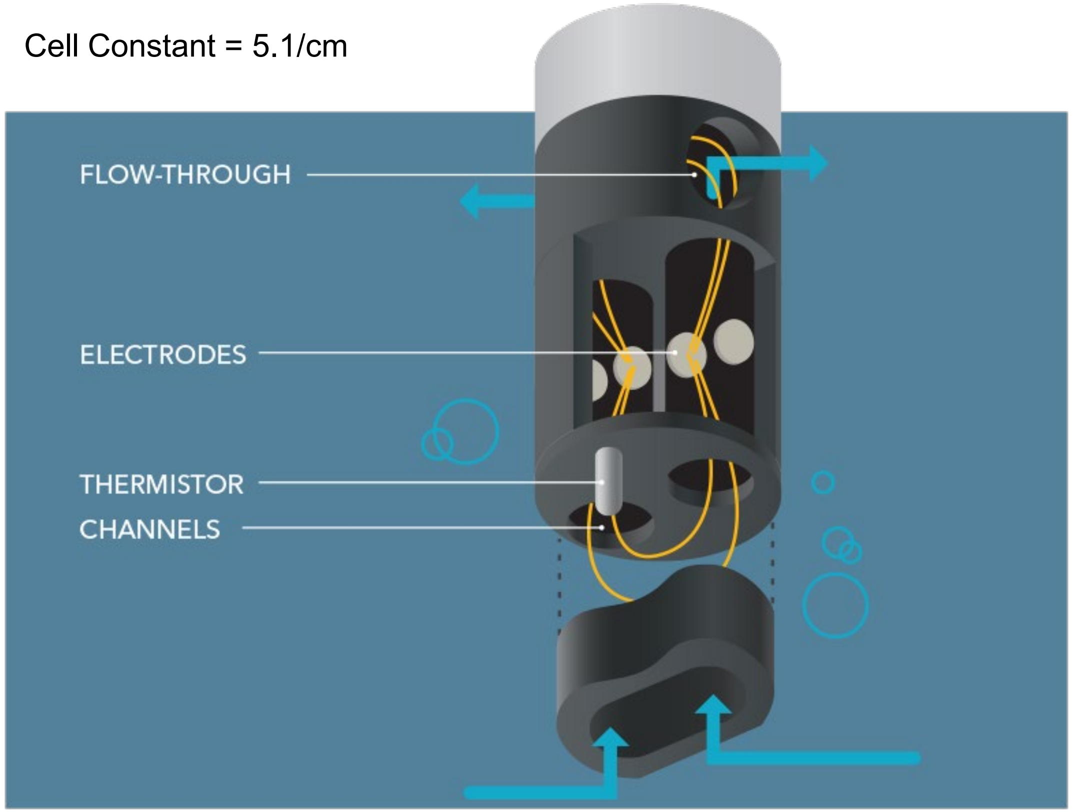


How Do Conductivity Sensors Work?

- EXO Conductivity (non-wiped)
  - Uses 4 nickel electrodes housed inside the sensor tip

1. Sonde applies current to electrodes
2. Current flows through the electrodes and the sample
3. Voltage change is measured
4. **ΔV** (or simply "**V**") has direct relationship with conductivity of the sample

Cell Constant = 5.1/cm



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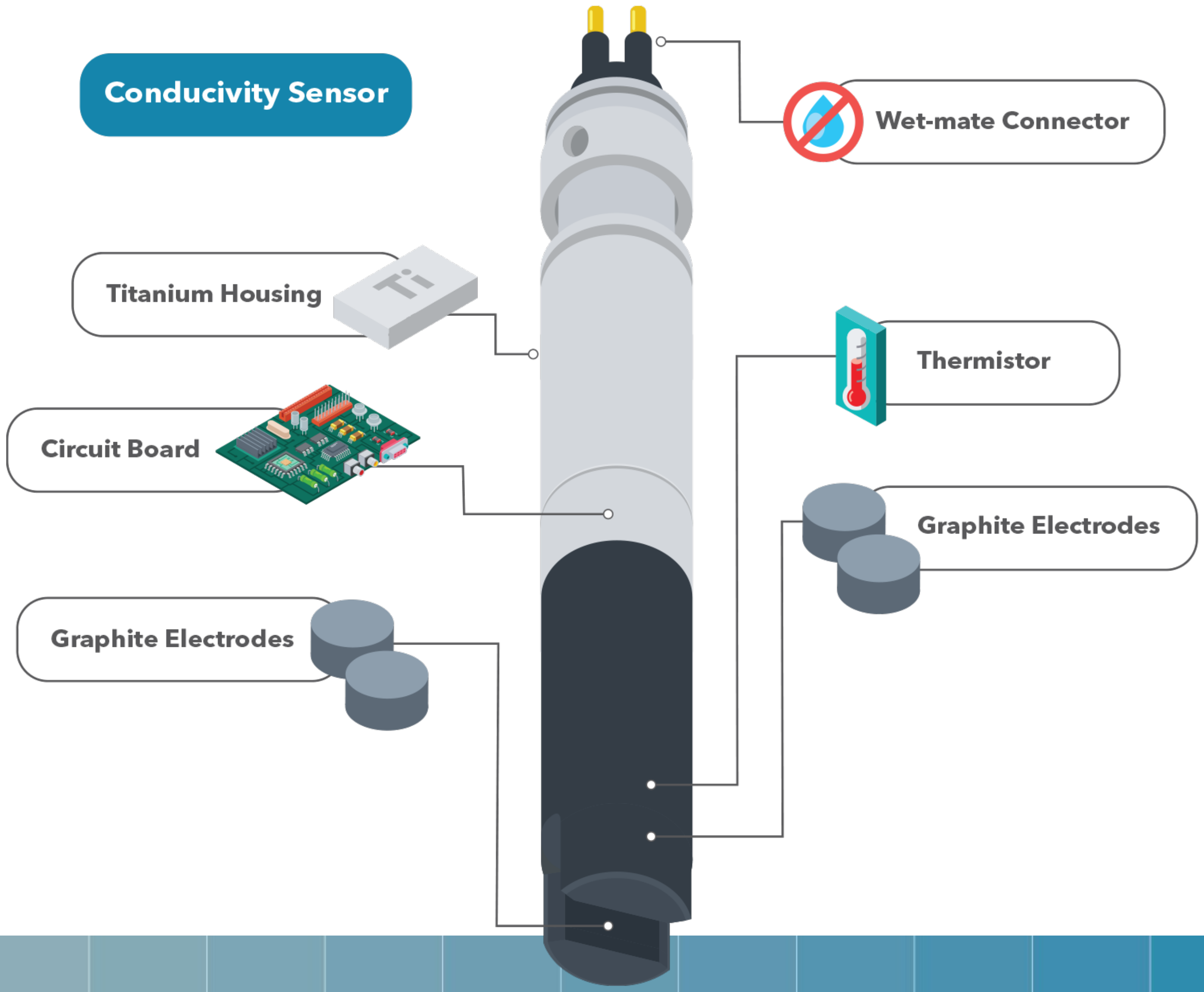
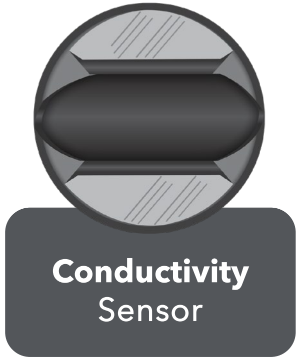
How Conductivity Sensors Work



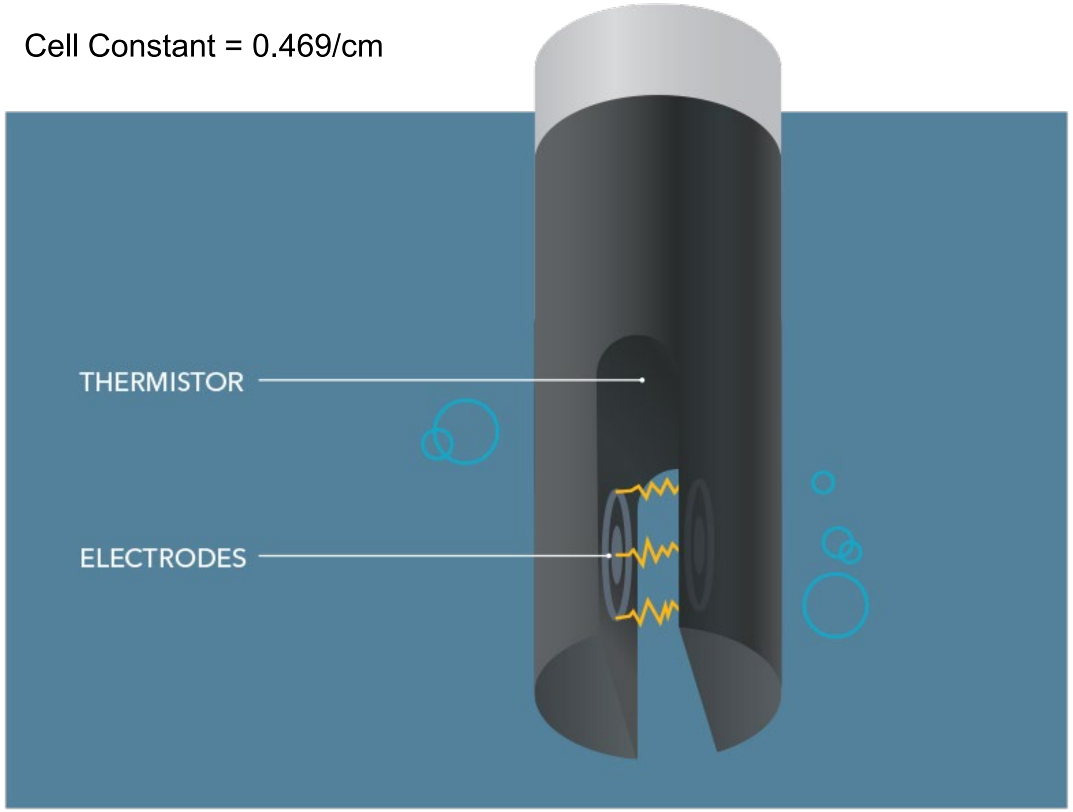


How Do Conductivity Sensors Work?

- EXO Wiped Conductivity
  - Uses 4 graphite electrodes in the open sensor tip

- Same principals apply
- Different cell constant – accounts for different range and accuracy
- Open design is wipeable

Cell Constant = 0.469/cm



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Real World Application: Values, Limitations, and Best Practices

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What concerns you most about monitoring for conductivity?

Conductivity Monitoring

I. Maryland DNR Application
II. Challenges with Continuous Monitoring
III. Choosing the Right Conductivity Sensor
IV. Choosing the Right Calibration Standard
V. Best Practices: Calibration
VI. Best Practices: Sensor Maintenance

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Maryland DNR: Road Salt Study

- Impact of Road Salt of the Environment
- Stormwater carries accumulated salt into stormdrains and surface waters
- Maryland DNR deployed conductivity loggers upstream & downstream from Interstate 68

Maryland State Highway Administration

"Do Road Salts Cause Environmental Impacts?" [Maryland DNR]
https://mde.state.md.us/programs/Marylander/Documents/2013_Stranko_Road_Salt_(final)_TMF_edits.pdf

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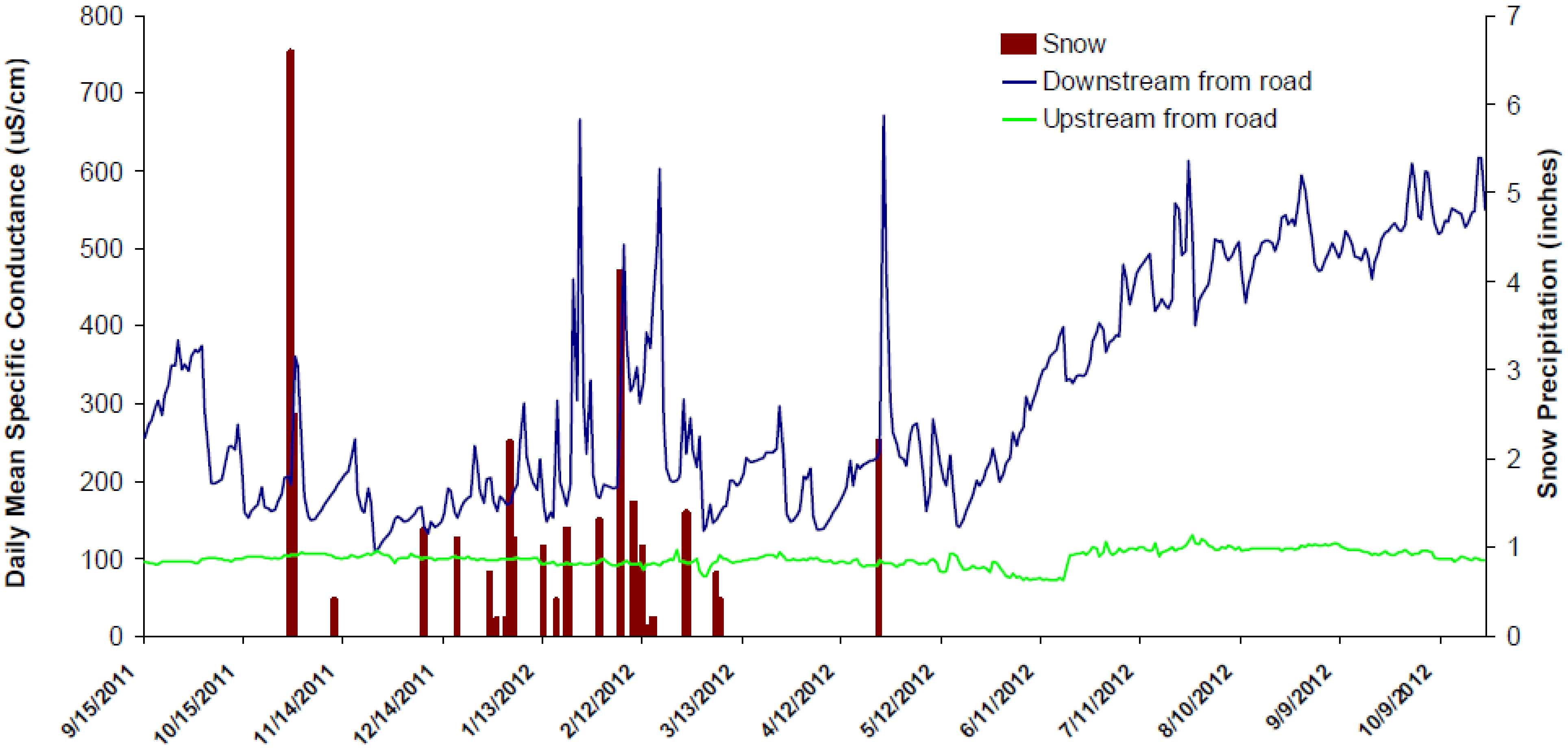
Maryland DNR: Road Salt Study



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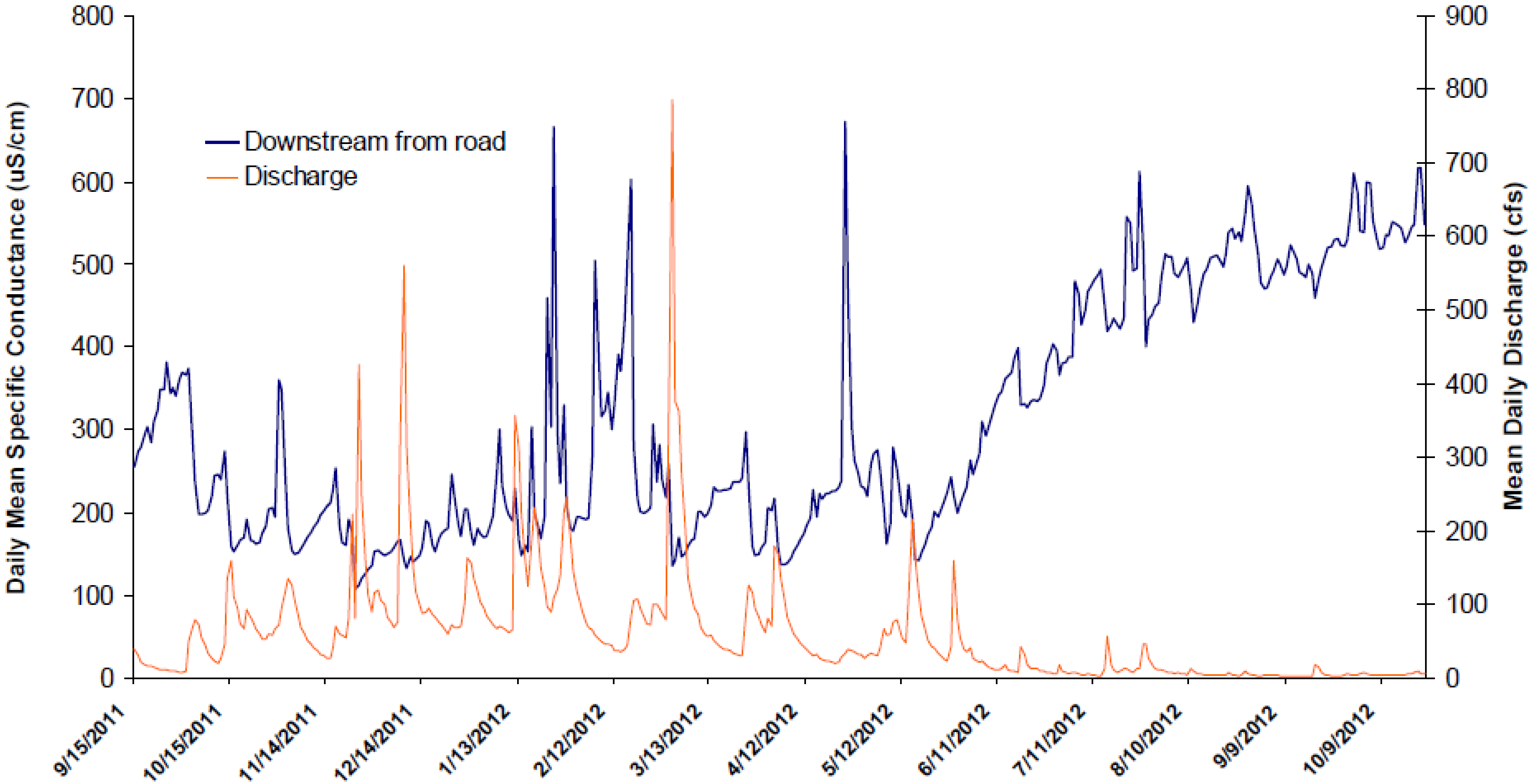
Maryland DNR



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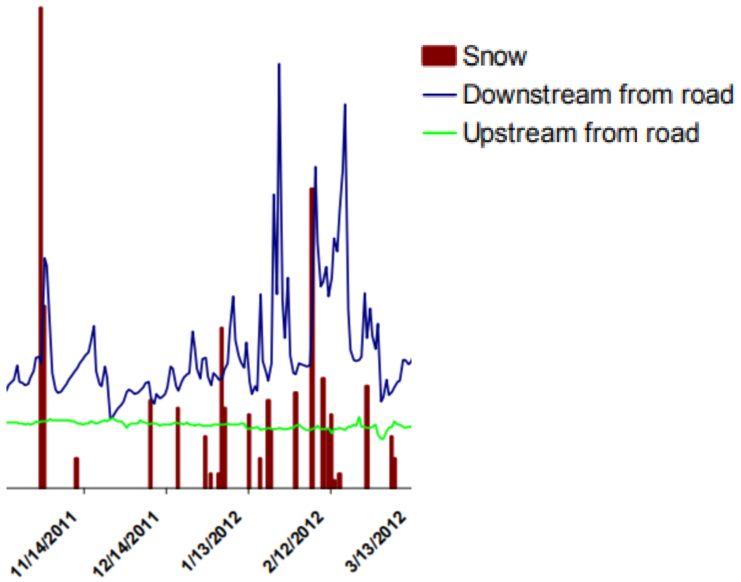
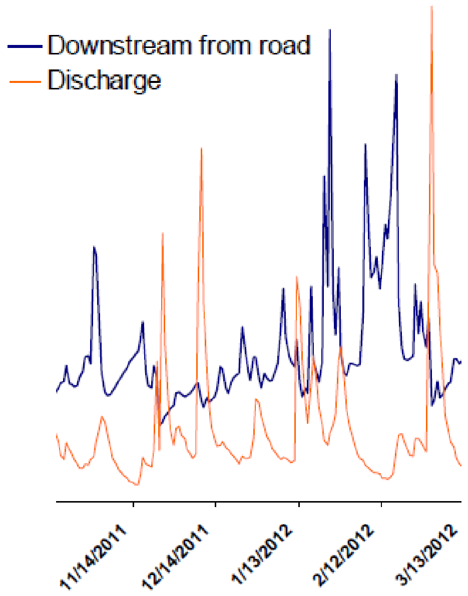
Maryland DNR: Road Salt Study

- Impact of Road Salt of the Environment
- Maryland DNR Study:
  - Baseline SpCond = >100 µS/cm (Upstream)
  - Highest SpCond spikes after snow fall events (Downstream); then drops after high flow events
  - Also observed increases in SpCond during summer low flow season





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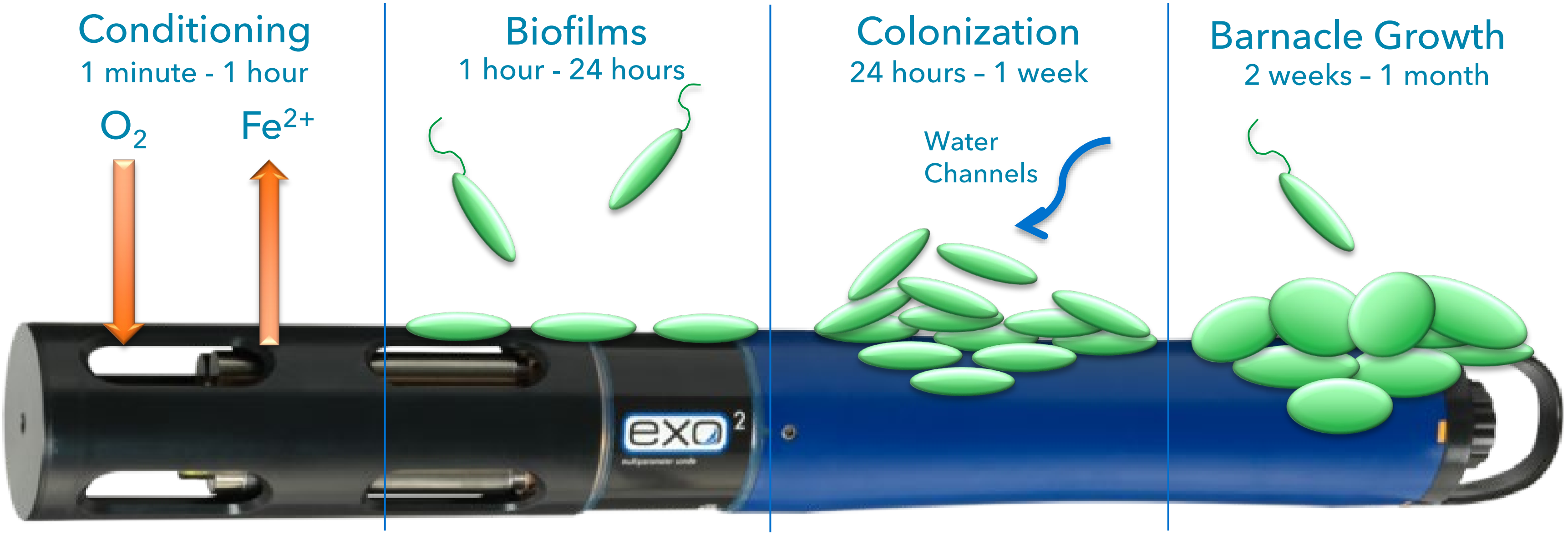
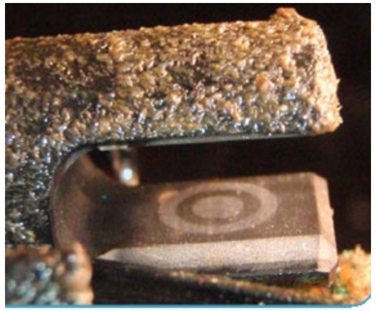
Challenges with Continuous Monitoring

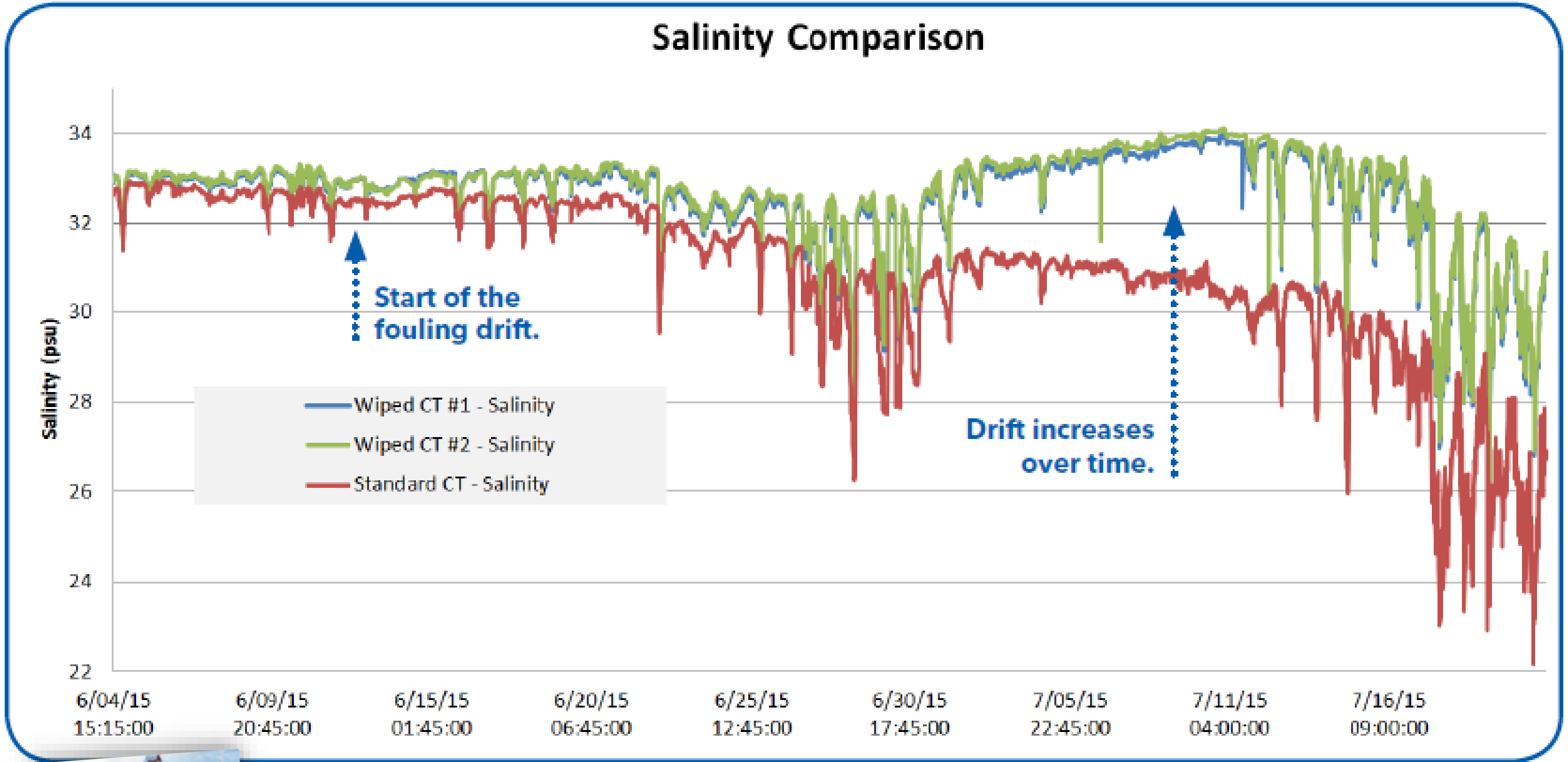
Challenges with Continuous Monitoring

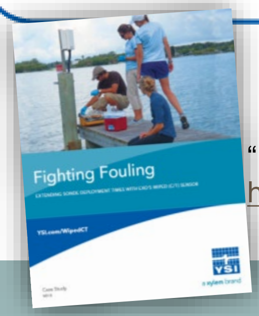
- Fouling!
  - Build-up over time
  - Affects sensor performance
  - Non-wiped sensor limitations





Challenges with Continuous Monitoring





"Fighting Fouling" [YSI Case Study]
https://www.ysi.com/File%20Library/Documents/News%20Briefs/NB18_EXO_Wiped_CT_Case_Study.pdf

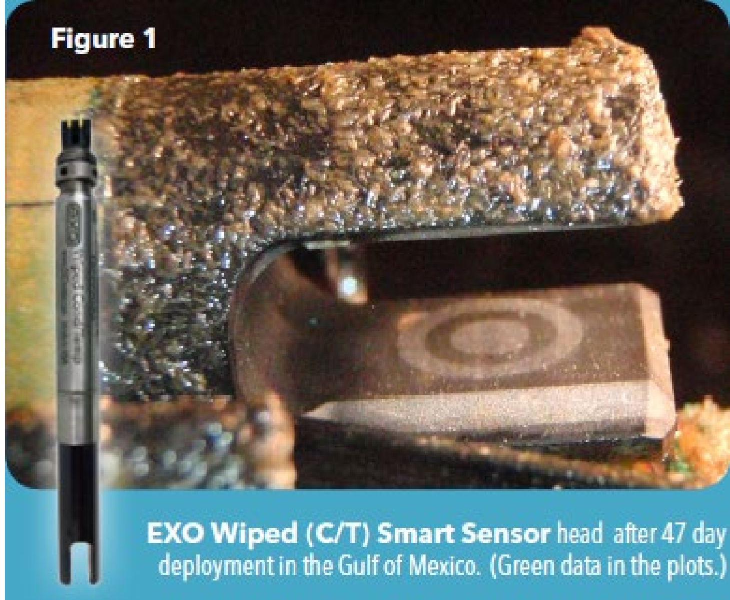


Figure 1

EXO Wiped (C/T) Smart Sensor head after 47 day deployment in the Gulf of Mexico. (Green data in the plots.)

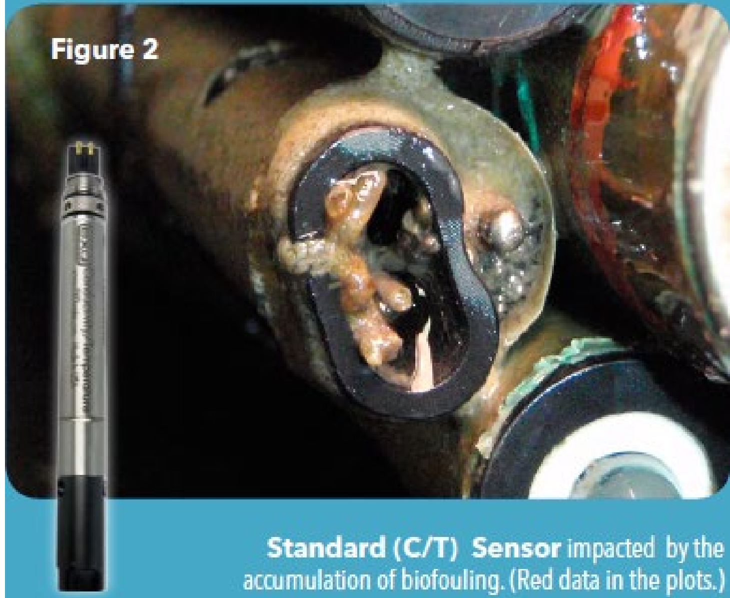


Figure 2

Standard (C/T) Sensor impacted by the accumulation of biofouling. (Red data in the plots.)

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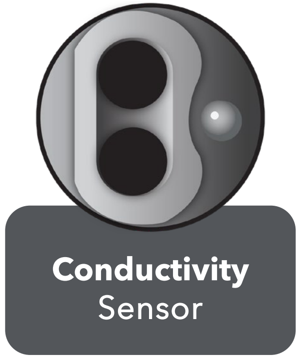
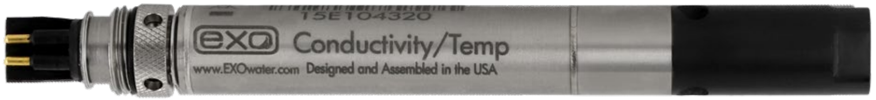
Choosing the Right Conductivity Sensor

YSI.com/MultiLab

Choosing the Right Conductivity Sensor



- EXO Conductivity Sensor (Non-Wiped)
  - Optimal for Sampling & Profiling
    - Faster temperature response



  - Measurement Range
    - 0 – 200,000 µS/cm
  - Limitations with Long-Term Monitoring
    - Cannot be effectively wiped

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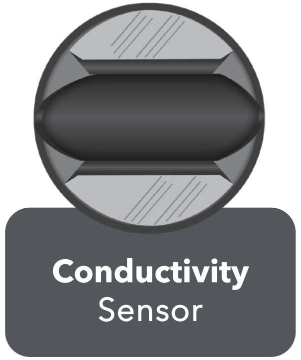
Choosing the Right Conductivity Sensor



- EXO Wiped Conductivity Sensor
  - Optimal for Continuous Monitoring & Long-Term Deployments
    - Wiper effectively cleans electrodes and minimizes fouling

  - Measurement Range
    - 0 – 100,000 µS/cm
  - Not Designed for Rapid Profiling
    - Cell geometry and embedded thermistor

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Choosing the Right Calibration Standard

- Which Standard do I Choose?
  - Closest to your expected sample value
  - YSI does NOT recommend calibrating below 1,000 µS/cm
    - Why?
    - Recommend a minimum level of ionic strength to achieve a reliable calibration:
      - Free from contamination
      - Good for the full range of the sensor

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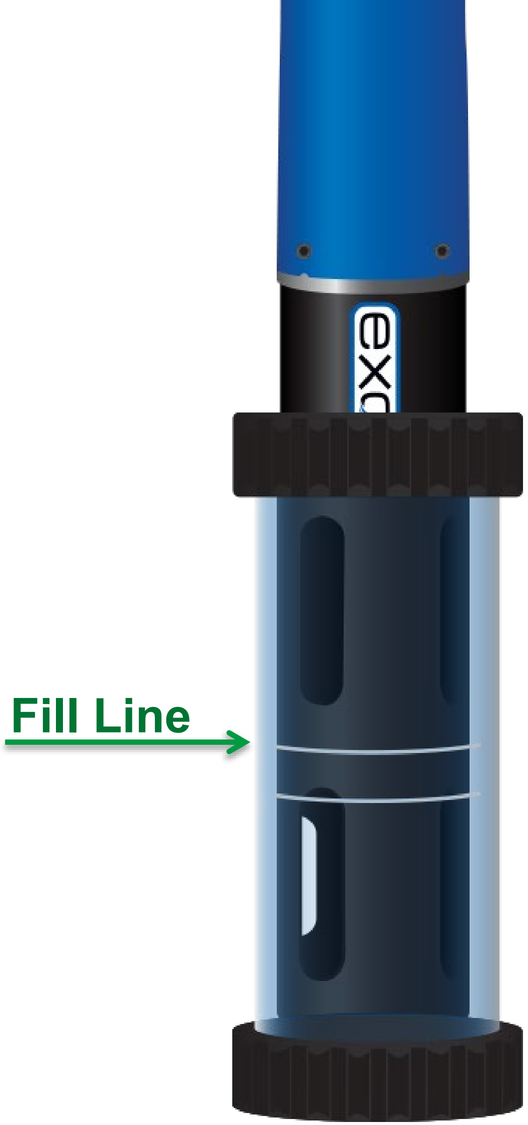
Best Practices: Calibration

- Conductivity Standard is one of the easiest standards to contaminate
- Calibrate Conductivity First
  - Not required, but may help prevent contamination from other standards
- Keep it Clean
  - Sensors, Probe Guard, Cal Cup
  - Remove wiper brush if necessary
  - Pre-rinse; triple rinse (best practice)

Best Practices: Calibration

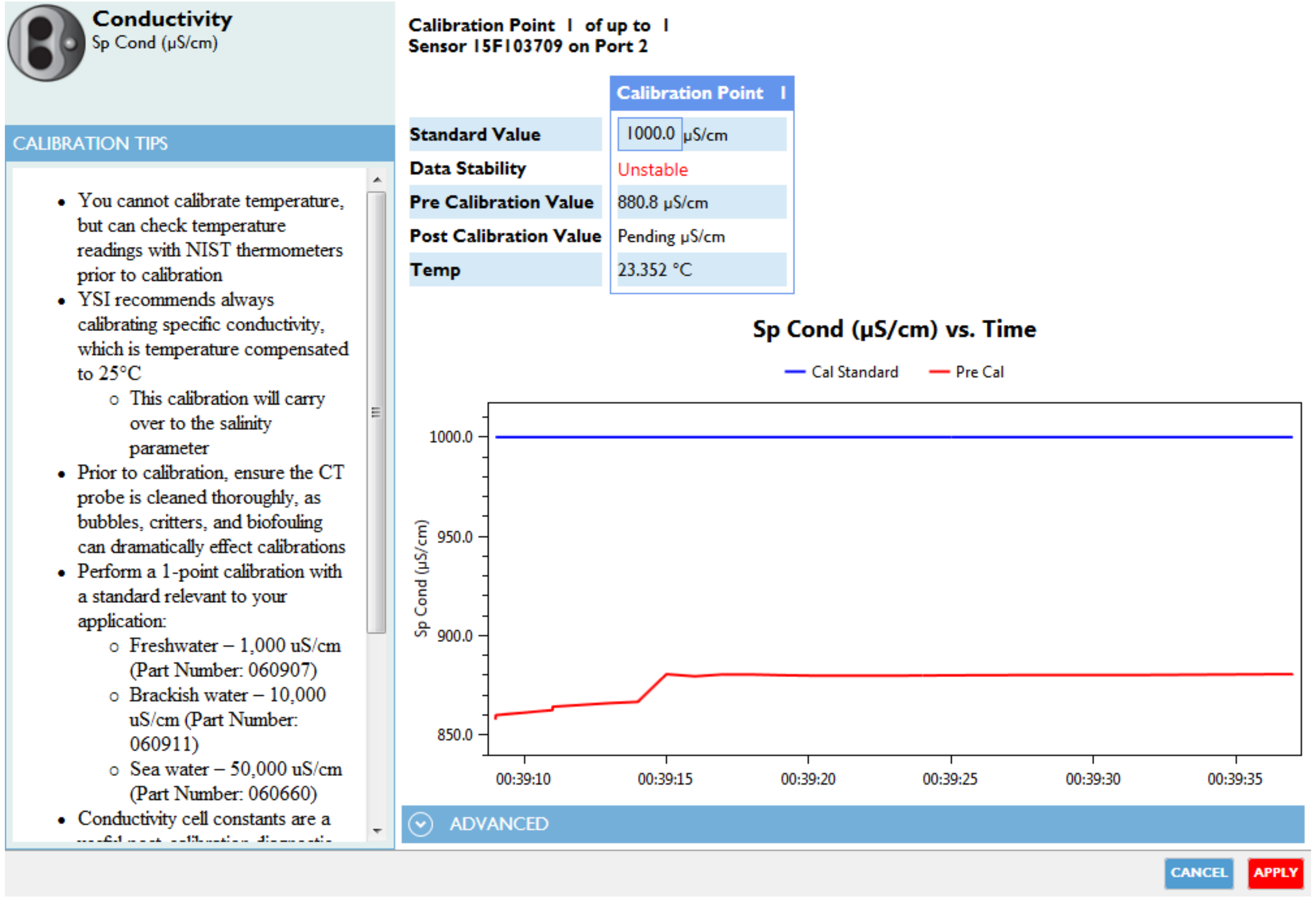
- Periodically Check Temperature
- Check Reading in Dry Air
  - Should be zero
- Calibrate with Probe Guard Installed
  - Should be in the same state as when its used
- Make Sure Conductivity Cell is Fully Submerged
  - Solution should reach the second fill line
- Agitate to Release Trapped Air Bubbles



Best Practices: Calibration

- 1-Point Calibration
- Things to Pay Attention To:
  - Standard Value
  - Stability
  - Pre-Cal Value
  - Temperature

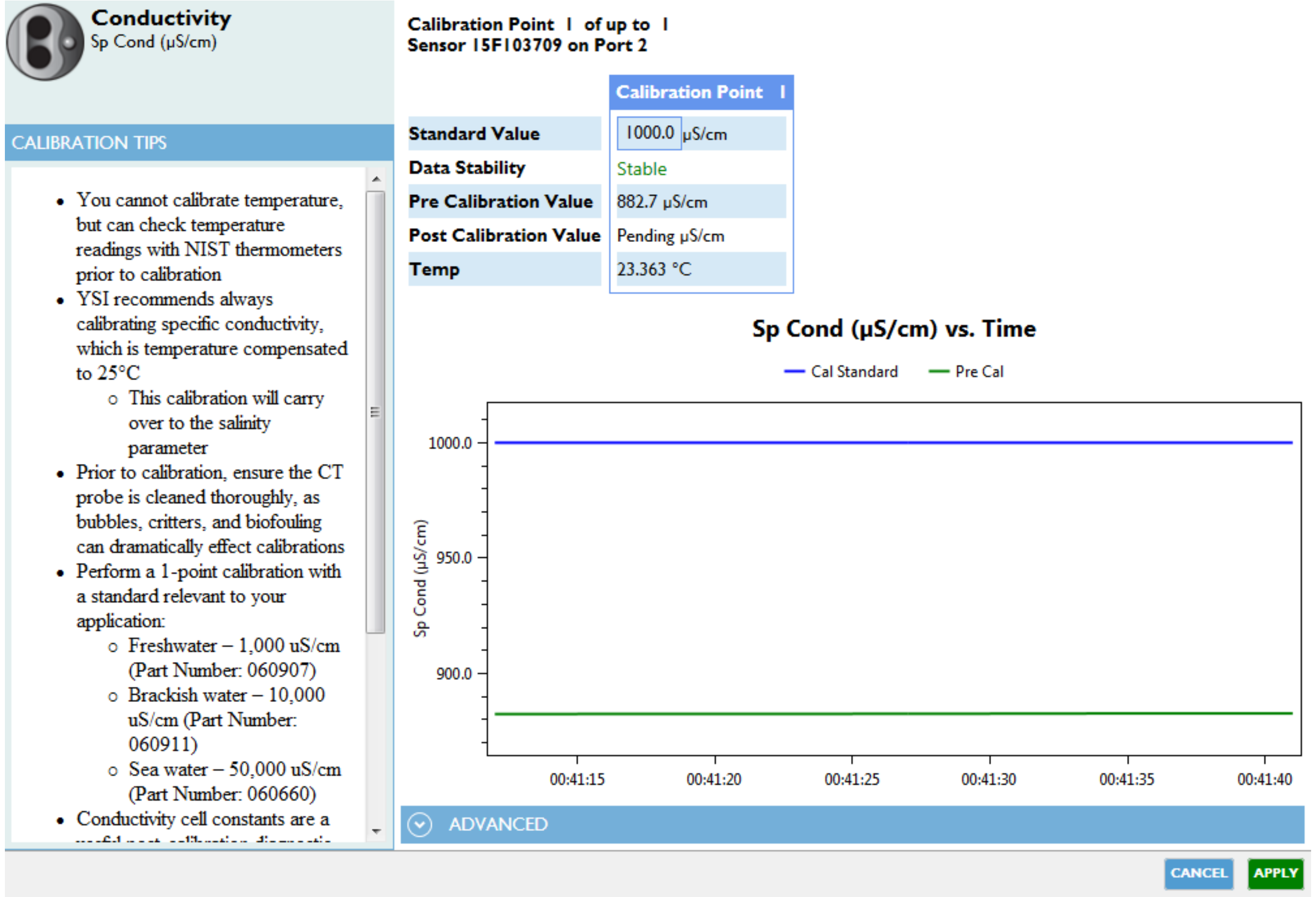
- Wait for Stabilization!



a xylem brand

Best Practices: Calibration

- 1-Point Calibration
- Things to Pay Attention To:
  - Standard Value
  - Stability
  - Pre-Cal Value
  - Temperature
- Wait for Stabilization!
- Then Apply the Calibration

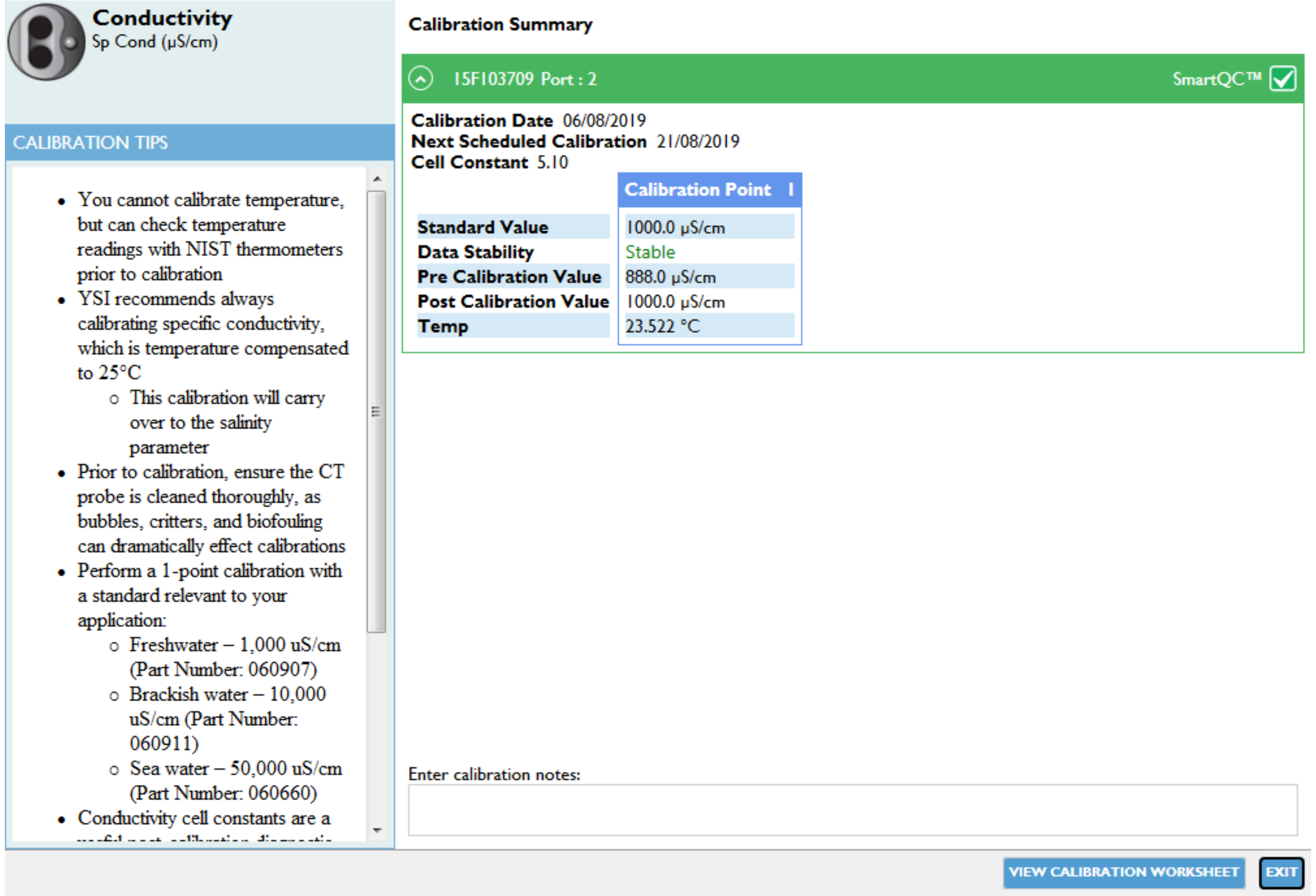


YSI
a xylem brand

Best Practices: Calibration

- 1-Point Calibration
- Things to Pay Attention To:
  - Standard Value
  - Stability
  - Pre-Cal Value
  - Temperature

- Wait for Stabilization!
- Then Apply the Calibration



YSI
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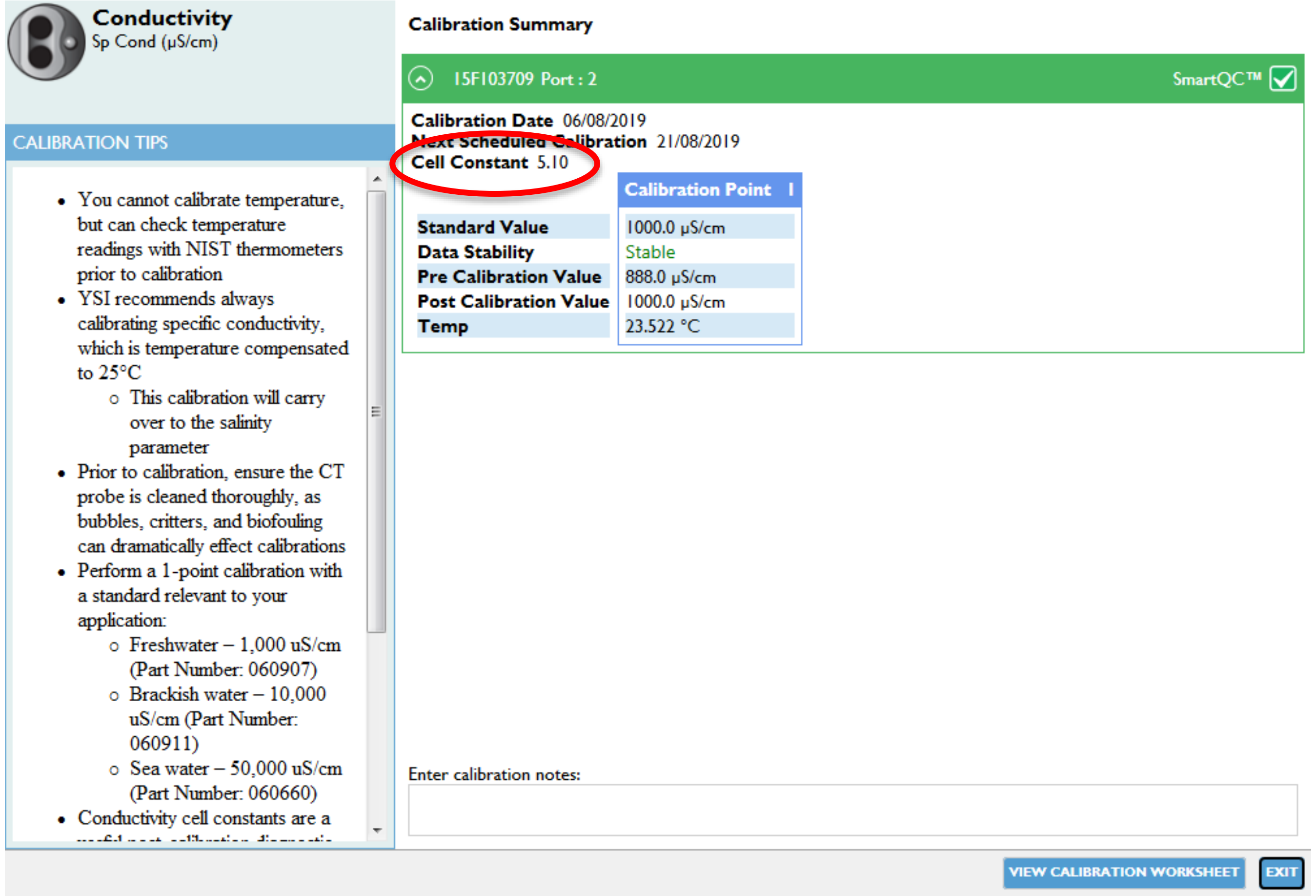
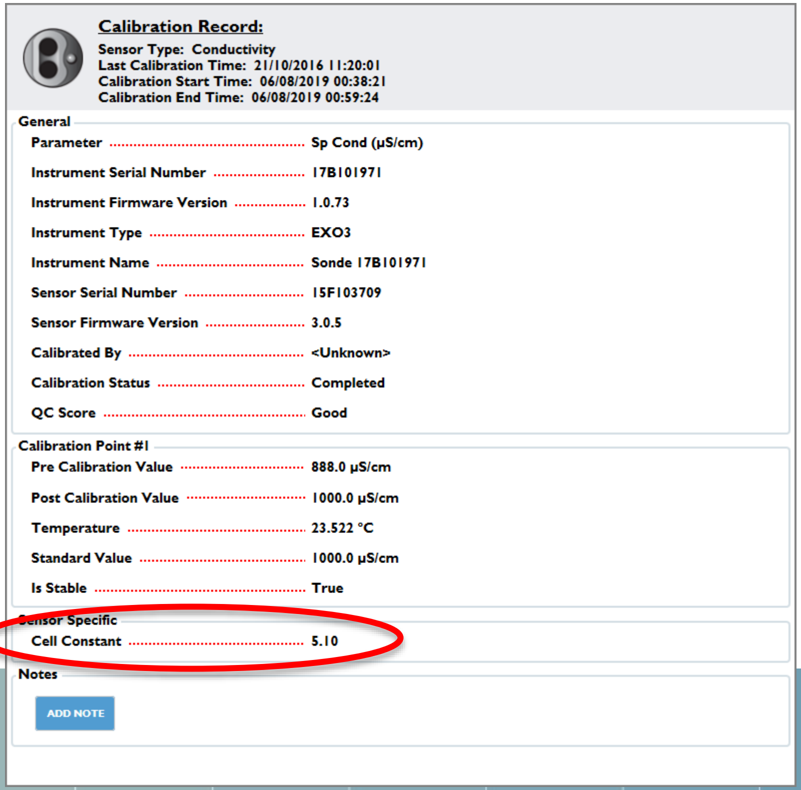
Best Practices: Calibration

- Keep an eye on the Cell Constant with every calibration
- Shows how much the sensor is drifting





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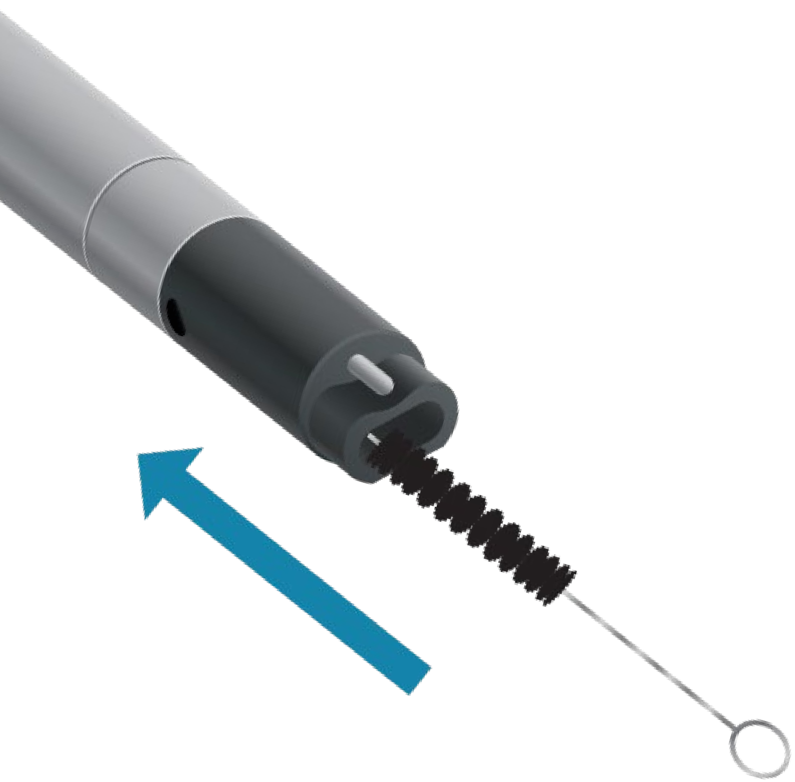
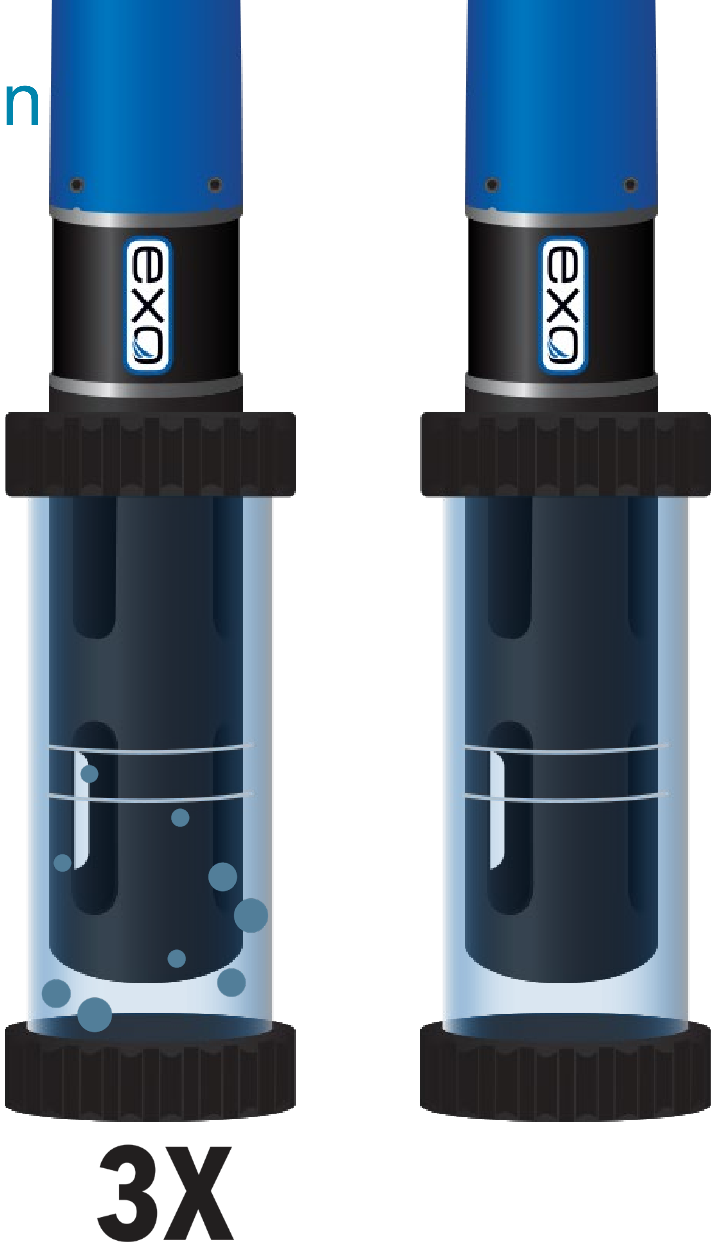
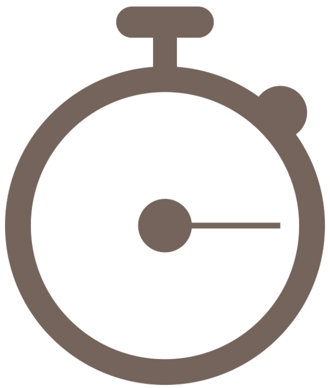
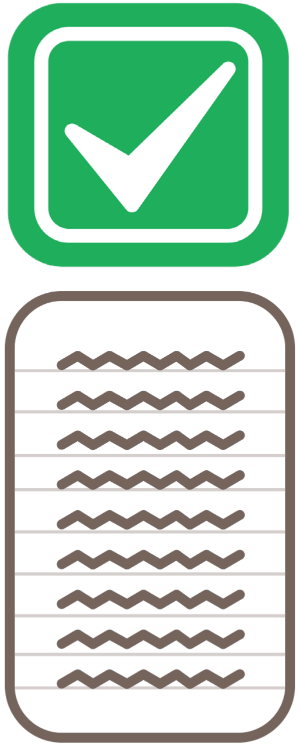
Best Practices: Calibration









Best Practices: Sensor Maintenance

- Clean After Each Use!
  - Warm soapy water and conductivity cleaning brush
    - Hand soap or mild dish soap
    - For heavy fouling, soak in white vinegar
    - Use correct conductivity brush
    - Rinse thoroughly
- Storage
  - Can be stored wet or dry (short term)
  - Dry preferred for long-term storage

Do you want someone from YSI to contact you to discuss conductivity sensors?

Questions?

Contact us:

YSI
info@ysi.com

Xylem APAC & MEA
info.apac@xyleminc.com

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