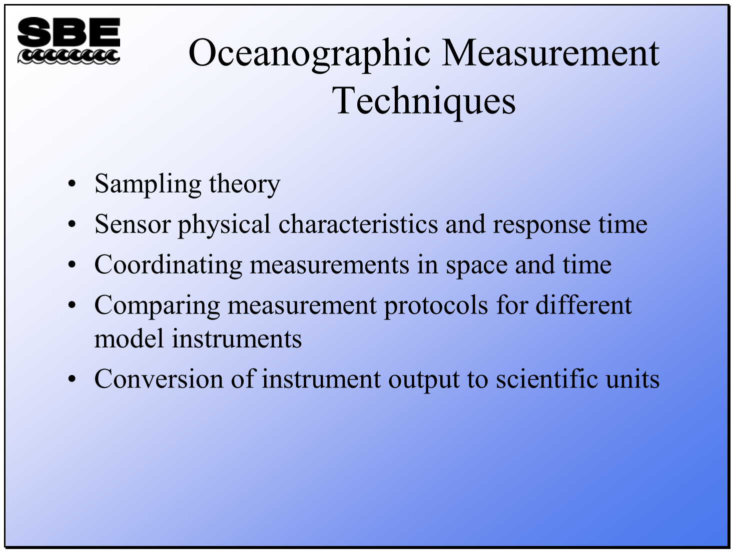
**Module 6**

# Making Measurements in the Ocean

## Overview

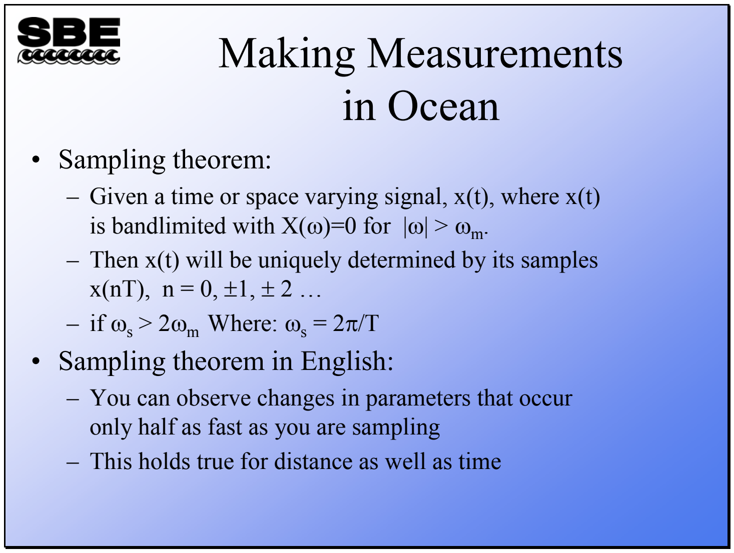



In this section we will take a close look at how measurements are made, in the environment in general and in the ocean specifically. We will discuss what to expect from measurements in terms of resolution and how to judge if we can make the measurements needed for our scientific purpose with the equipment at hand. Many common oceanographic parameters, such as salinity or density, require measuring multiple physical parameters, such as temperature and conductivity, to calculate the single new parameter. We will consider how measurement techniques impact the accuracy of these parameters. Finally, we will consider what is required to convert sensor output to scientific units.

At the end of this module, you should be able to:

- Determine what resolution your data will have, based on instrument sampling rate and descent rate in the ocean.
- Describe what a sensor is and how it operates.
- Explain the importance of correlating temperature, conductivity, dissolved oxygen, and pressure measurements in time and space.
- Describe how scientific units are gleaned from sensor output, and how these values and errors relate to the primary standards.

## The Sampling Theorem



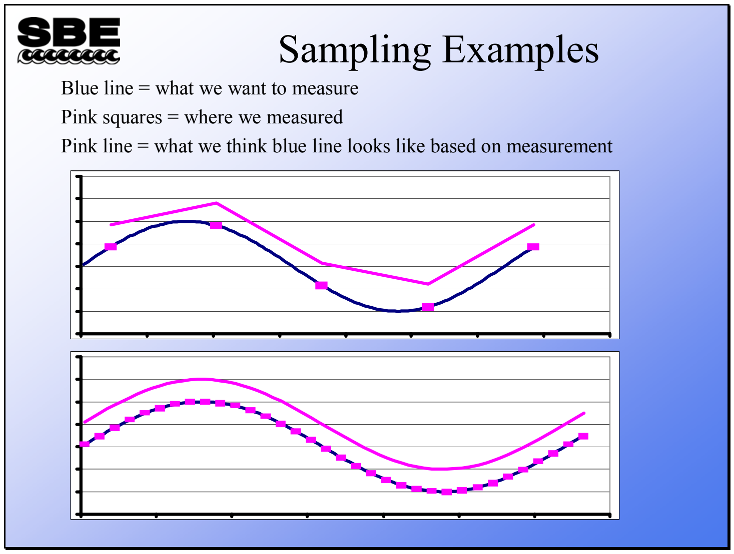

It is rather difficult to understand what this has to do with making measurements in the ocean by looking at the math.

The sampling theorem tells us how much information we can extract from a signal, given the rate at which we sample. In this case, the signal is any of the parameters we measure in the ocean. The sample rate is the rate at which the instrument makes a measurement or takes a scan.

The sampling theorem states *the highest frequency of information we can extract from a signal is half the frequency that we sample*. This means that if you sample at 24 times a second, you can observe changes no faster than 12 times a second.

This holds true for distance as well as time. If we sample every 50 cm as our instrument descends into the ocean, we can only accurately sense parameters that change every 100 cm.

## Sampling Theorem: Sampling Examples




### Top Illustration - Under Sampled:

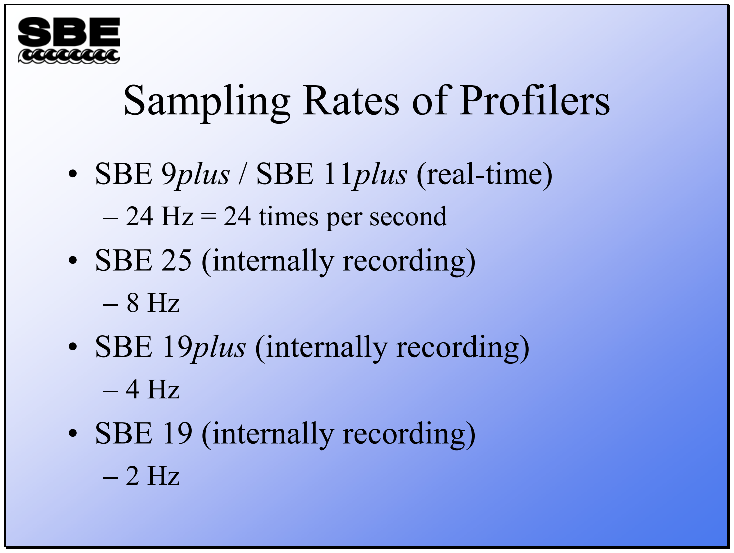
Suppose we wish to measure a sine wave that changes 16 times a second. However, our sampling equipment is only capable of taking a measurement 5 times a second. The upper line is our estimate of what the sine wave looks like.

Since there are no labels on the axis we can state it in terms of distance. Suppose we are working in a strange part of the ocean where the temperature changes in the form of a sine wave 16 cycles every meter, or every 6.25 cm. If our sampling equipment only samples every 20 cm, the upper line is how we will perceive the temperature profile.

### Bottom Illustration - Properly Sampled:

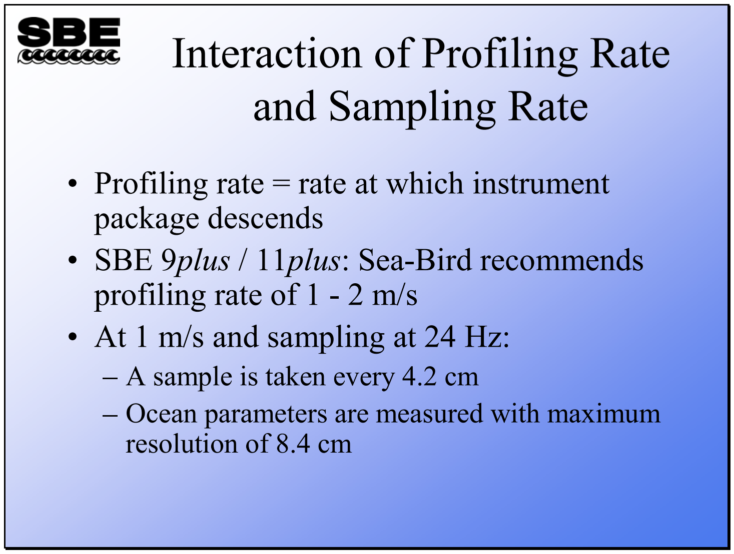
This signal is properly sampled; the upper line is a complete representation of the lower line.

## CTD Sampling Rates




Sea-Bird offers CTDs with sampling rates shown above. The SBE 9*plus*, with the fastest sampling rate, produces the most detailed data. The other instruments are less capable but offer lower price, less complex deployment equipment, and a more compact instrument package. Not all applications require or benefit from the sampling rates achievable with the SBE 9*plus*.

## Sampling Rate and Profiling Rate




In earlier slides we mentioned that the sampling theorem applies to distance as well as time. In the case of ocean profiling we are afflicted with a combination of the two. Let's first consider a perfect case.

The CTD samples at a fixed rate and the instrument package is lowered through the ocean at a fixed rate. Consider the SBE 9*plus*, sampling at 24 Hz and falling through the ocean at 1 m/s. We would be taking a sample every 4.2 cm.

$$100 \text{ cm sec}^{-1} / 24 \text{ sec}^{-1} = 4.2 \text{ cm}$$

*According to the sampling theorem, in this case we can resolve events that take place on a length scale of 8.4 cm.*

Now consider reality. The CTD samples at 24 Hz and the instrument package falls through the ocean at a nominal 1 m/s. However, the ship heaves, alternately slowing and lifting the instrument package or dropping and accelerating the instrument package. This situation is not well enough constrained to assign an exact length scale to our measurement. We will investigate this problem further in the advanced data processing portion of the course.

## Sampling Rate and Profiling Rate (continued)

### Interaction of Profiling Rate and Sampling Rate

- SBE 25: At 1 m/s and sampling at 8 Hz
  - A sample is taken every 12.5 cm, yielding 25 cm resolution
- SBE 19*plus*: At 1 m/s and sampling at 4 Hz
  - A sample is taken every 25 cm, yielding 50 cm resolution
- SBE 19: At 1 m/s and sampling at 2 Hz
  - A sample is taken every 50 cm, yielding 1 m resolution

As discussed earlier, the lower sample rates of the SBE 19 and 25 instruments translates into a coarser resolution than that calculated in the SBE 9*plus* example. The following page illustrates the impact that sample rate has on resolution.

## CTD Resolution Comparison


The left-most plot is data collected at 24 Hz with a nominal 1 meter/second lowering speed. The middle plot is the same data set decimated to 8 Hz to represent the resolution of the SBE 25. The right-most plot is the 24 Hz data set decimated to 2 Hz, which is representative of the resolution that would be seen with an SBE 19. The obvious conclusion is that a faster sampling rate yields higher resolution of temperature structure in the ocean temperature profile.

## Sensors Revealed

### How Does a Sensor Work?

- Device that allows a physical characteristic of environment to be converted into an electrical signal
- Composed of:
  - Active element having a property that changes in response to physical characteristic, and
  - Circuit that converts this change into a signal that may be measured by normal methods
- Normal methods mean frequency measurement or analog-to-digital conversion

Sensors convert a physical property of the environment into an electrical signal. Variations in the physical property are followed by variations in the signal. Consider a telephone, which converts the pressure wave that is sound into an electrical signal that can be transmitted through a wire. In similar fashion, oceanographic sensors convert pressure, temperature, conductivity, or some other physical parameter into varying electrical signals which are proportional to the value of the physical parameter. Typically a sensor is composed of two parts:

- Active element

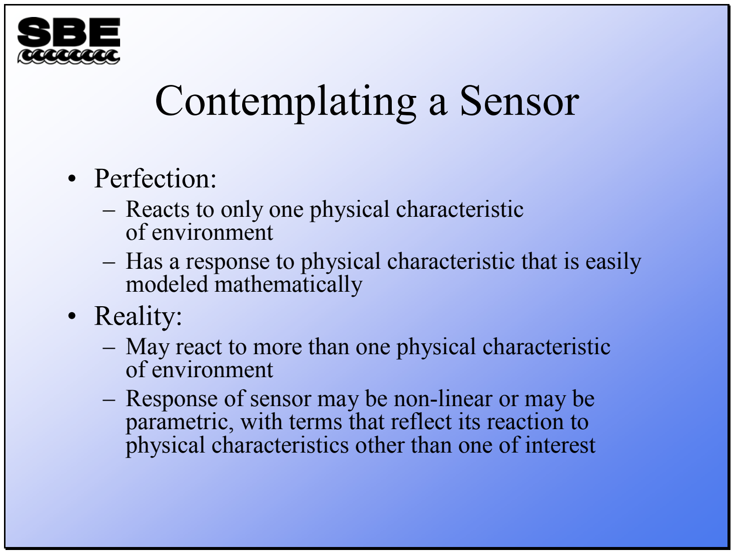
  The active element converts the physical parameter of interest into an electrical signal. To operate, the active element generates an electrical current or modifies an electrical current in response to changes in the value of the physical parameter.

- Conditioning circuitry

  The conditioning circuitry provides any electronics required for the active element to work. The circuit might use changes in a property of the active element, as in the case of a thermistor. For example, oceanographic thermometers often use a thermistor to measure temperature. A thermistor changes its resistance to current flow as its temperature changes.

  The circuit might also convert the active element's output into an electrical signal type and range that is more easily converted to digital format. For example, the dissolved oxygen active element has a cathode that reacts with $O_2$ to produce a weak electrical current; the conditioning circuit converts that current into a 0 to 5V sensor output.

## Sensors Revealed (continued)




The best sensor has an active element that:

- Reacts only to 1 environmental parameter.

  This is a rather rare occurrence. *Almost any semiconductor or wet electrode will react to changes in temperature and pressure*. Response to multiple environmental parameters is referred to as *non-specific response*.

- Responds to changes in temperature and pressure in a fashion that is easily modeled.
- Responds instantly to changes in the physical parameter.

The problem of non-specific sensor response can be overcome with:

- The housing or mounting arrangement of the active element.

  For example, placing the thermistor of the SBE 3 in a fine needle protects it from pressure effects, but still allows it to react rapidly to changes in ocean temperature.

- The conditioning circuitry, which might have elements that compensate for temperature effects within the conditioning circuitry itself.
- The mathematical equation that converts sensor output to scientific units.

  For example, the SBE 4 conductivity sensor is affected by temperature as well as pressure; this is characteristic of the glass used for the cell. The best way to remove these effects is mathematically, turning the calibration equation into a parametric equation that has terms that depend on temperature and pressure.

- A second shielded sensor that compensates for non-specific response.

  For example, pH sensors have an electrode that is measured against a reference electrode contained within the sensor body.

## Sensors' Response Times

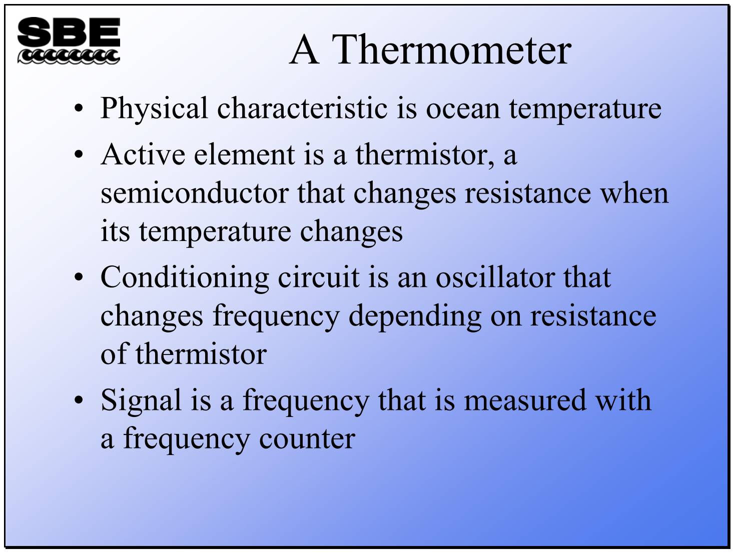
### Sensor Response Times

- Sensors do not respond infinitely quickly to changes in their environment
- Sensor response to a step change in their environment is termed their *time constant*
- Time constant is typically stated as time to come to 63% of final value, given a *step* change in environment

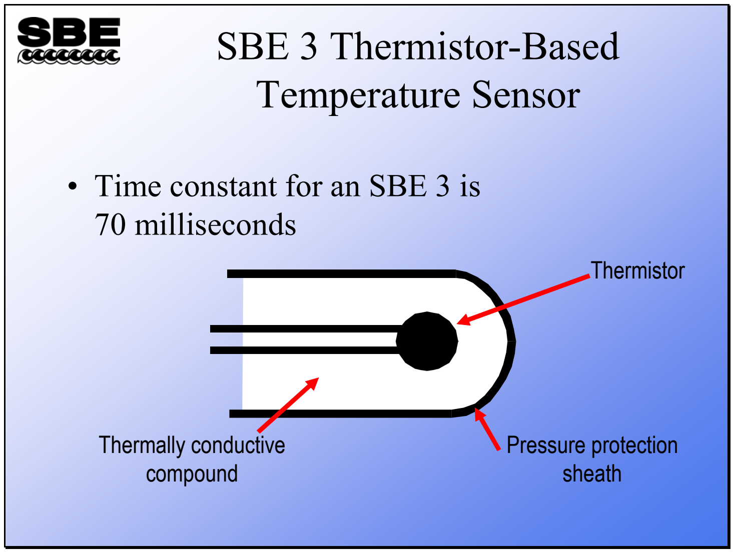
Sensors do not react infinitely quickly to a new environmental condition. For example, let's look at a 2-box ocean, with the top box at 20 °C and the bottom box at 0 °C. If our CTD moved from the top to bottom box, we would see a temperature signal that changed very quickly from 20 °C to 0 °C, but not as a perfectly sharp jump. *The reason for a slower response time for sensors is often found in the packaging of the active element of the sensor.*

For example, a thermistor is housed in a thin metal sheath; the delay in response to a sharp change in temperature from warm to cold is due to the time required for the heat in the thermistor to diffuse into the environment. For a conductivity cell, there is flushing time of the cell. For a dissolved oxygen sensor, there is the time required for the concentration of $O_2$ near the electrode to equilibrate with the environment. *The time constant, or $\tau$, of the sensor is expressed as the time for the sensor to come to 63% of its final value given a step input.*

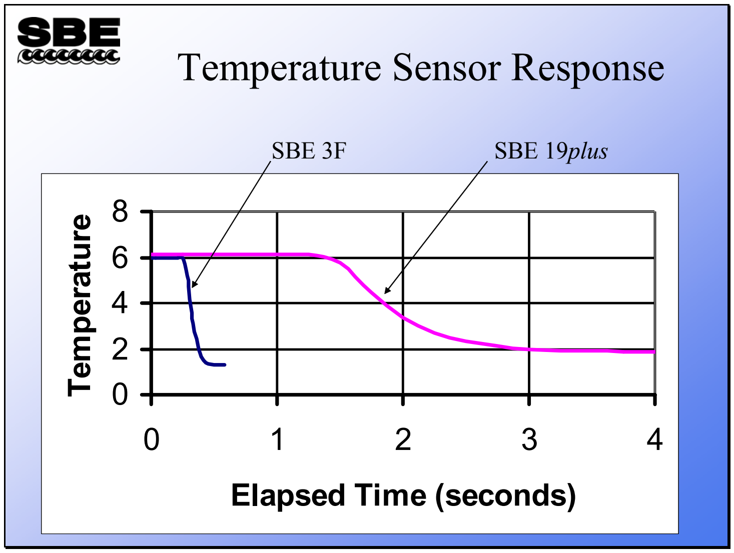
## Sensor Example: a Thermometer



## Sensor Example: a Thermometer (continued)

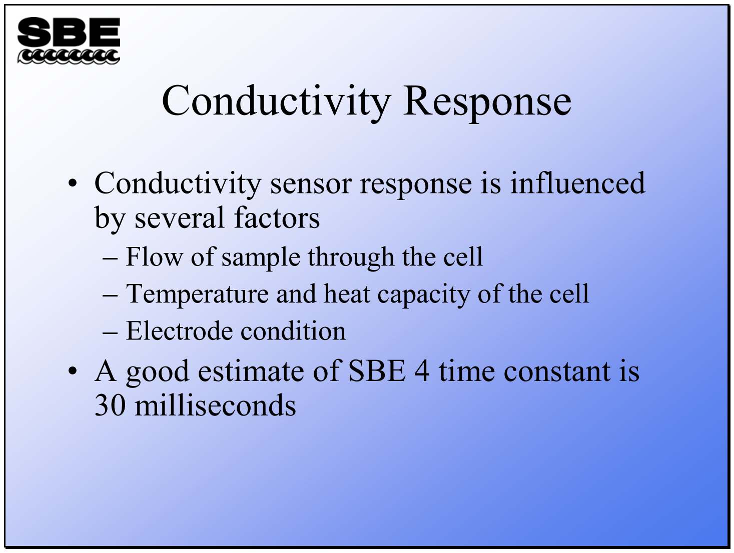


## Thermometer Response Comparison




This plot compares the time response of the SBE 3 with the SBE 19*plus*. The SBE 3 has a smaller thermistor and a smaller needle, giving it a faster response time.

## Conductivity Sensor Response




The measurement of a conductivity cell time constant is a difficult problem. Below are some references to papers that have addressed this problem.

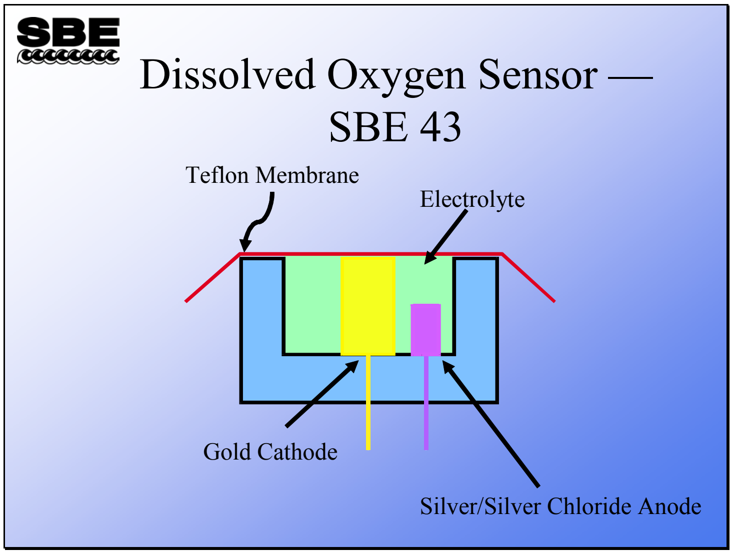
- Gregg, M.C.,T. B. Meagher, E. E. Aagaard, and W. C. Hess (GMAH 1981) “A salt-stratified tank for measuring the dynamic response of conductivity probes”, IEEE Journal of Oceanic Engineering, vol OE-6, 113-118.
- Gregg, M. C., and W. C. Hess (GH 1985) “Dynamic response calibration of Sea-Bird temperature and conductivity probes”, Journal of Atmospheric and Oceanic Technology, vol 2(3), 304-313.

## Pressure Sensor Response

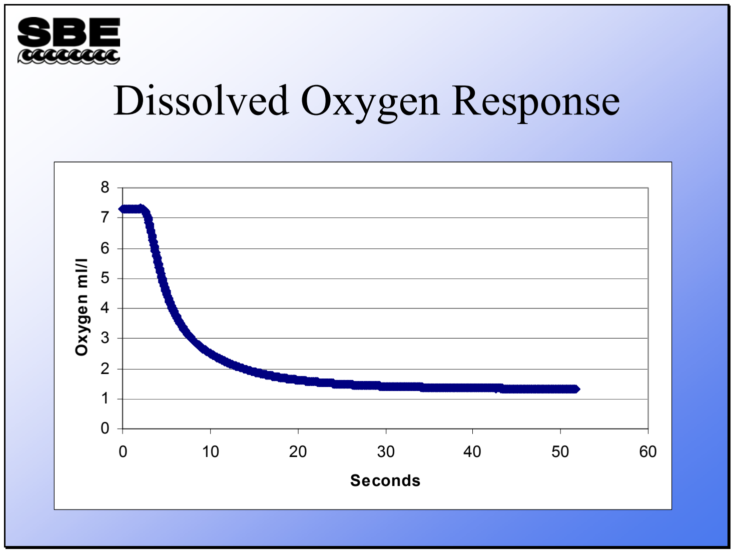
### Pressure Response

- A step change in pressure is not typically seen in the ocean environment
- Pressure sensor time constant is not an issue

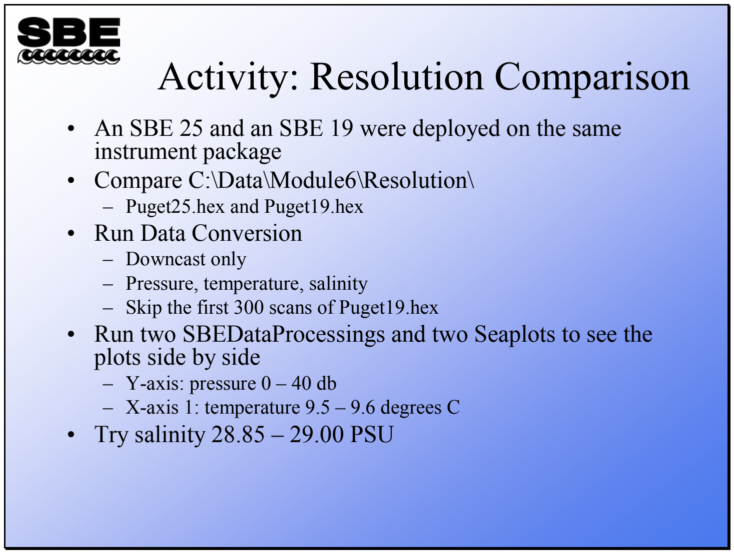
## Dissolved Oxygen Sensor



## Dissolved Oxygen Sensor Response



# Activity

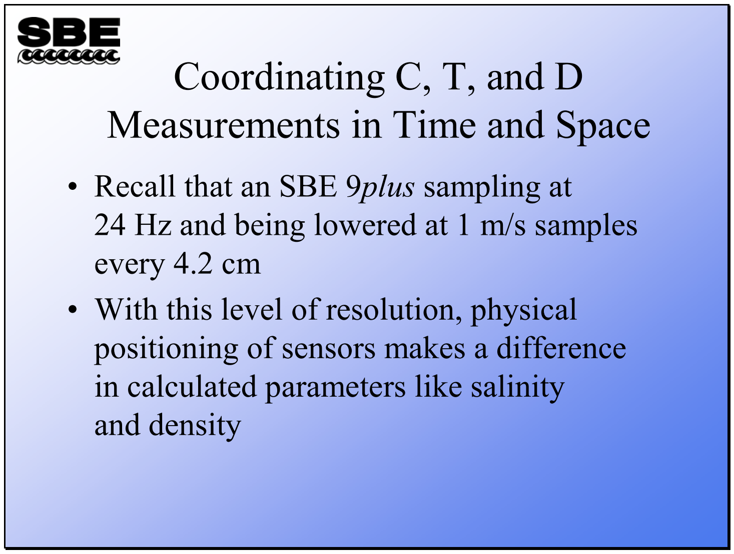



This activity requires some clever use of the processing software. First, use SBE Data Processing's *Data Conversion* module to get a downcast for C:\Data\Module6\Resolution\Puget25.hex. Then run *Data Conversion* on Puget19.hex to get a downcast, but skip the first 300 scans. These are invalid data acquired during the instrument package soak.

Next, run SBE Data Processing's *Seaplot* module, and make a plot of Puget25.cnv as described in the slide above. Adjust the resulting plot so it fills half your screen. Now, open another copy of SBE Data Processing and run *Seaplot* again; make a plot of Puget19.cnv with the same plotting parameters and adjust it to fill the other half of your screen.

How do the plots compare? Try Salinity.

## Coordinating Measurements




Salinity is a function of conductivity, temperature, and pressure. The mathematical relationship that defines salinity in these terms was established in 1978 by a group of scientists working with the international scientific organization UNESCO.

Salinity must be calculated from temperature, conductivity, and pressure measurements made on the same water parcel.

## Coordinating Measurements (continued)

SBE

### Conductivity and Temperature Measurement Revisited

- SBE 3 thermistor is contained in a 0.75 mm diameter needle that senses an approximate volume of 2 ml of seawater around it
- SBE 4 conductivity cell measures the conductivity of 5 ml of seawater
- These measurements are made in different places

The active part of the thermometer is found at the end of the slender needle. The volume of water measured by the end of the needle is approximately 2 ml.

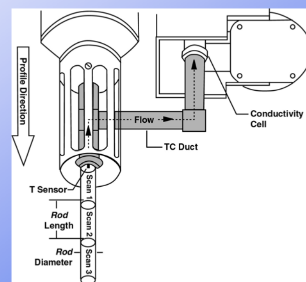
Recall that the conductivity cell is a glass tube containing platinum electrodes; conductivity is measured on the volume of water that the cell contains, approximately 5 ml.

## Coordinating Measurements (continued)

SBE

### Coupling T and C Measurement — the *TC Duct*

- Water is pumped past active element of temperature sensor and into conductivity cell at a fixed, constant rate
- Plumbing set up greatly lessens effects of ship heave (stops *sloshing* through cell)
- Filtering and other data manipulation is much more successful because flow rate is constant

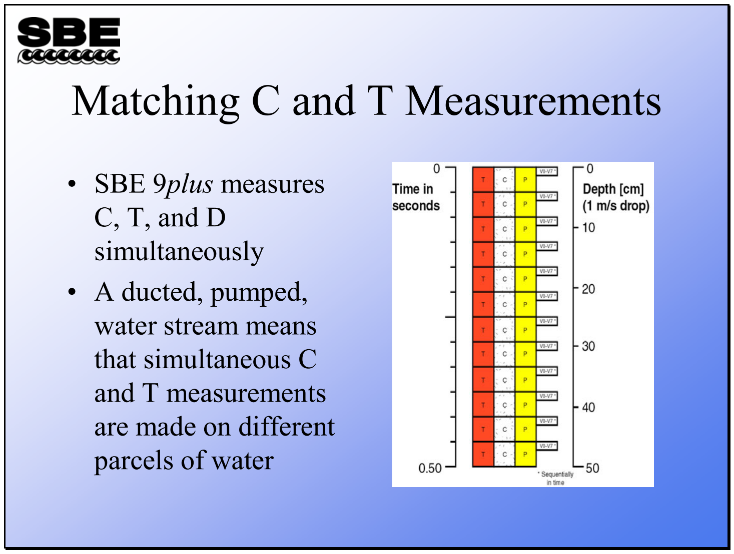



To ensure that the temperature and conductivity measurements are made on a constrained water sample, they are plumbed together and the *T-C pair* has water drawn through them with a pump that moves water at a consistent, known speed.

One way to visualize this is as a *rod* of water that moves into the duct and flows past the thermometer and into the conductivity cell. The diagram above shows the approximate size of the water parcel that constitutes a sample.

Because the water sample is pumped through the duct and conductivity cell, it is not subject to accelerations (sloshing) due to ship heave. This technique of constraining the sample as it is measured greatly improves the quality of the measurement and facilitates data manipulation.

## Coordinating Measurements with the TC Duct (continued)

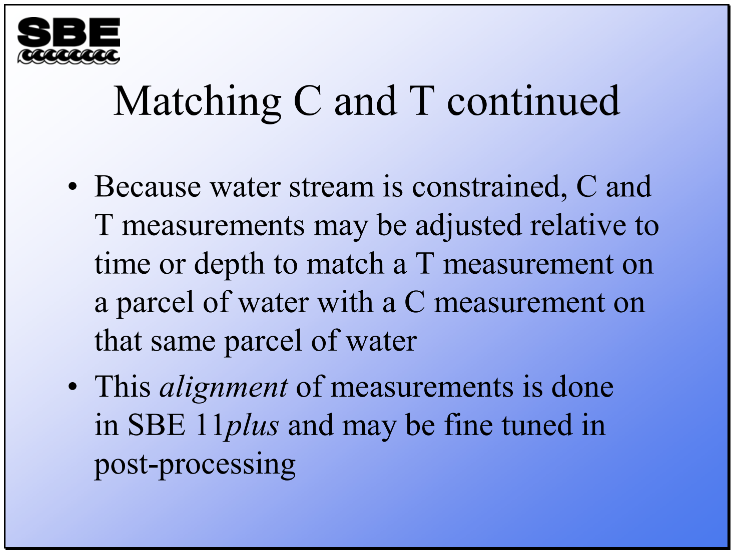



The SBE 9*plus* acquisition architecture measures temperature, conductivity, and pressure simultaneously. Careful examination of the plumbing of the TC duct shows that a water parcel first encounters the SBE 3 thermistor and then transits into the conductivity cell.

For the most accurate estimate of salinity and density, the data stream must be manipulated, moving temperature and conductivity relative to pressure to match the measurements on a parcel of water.

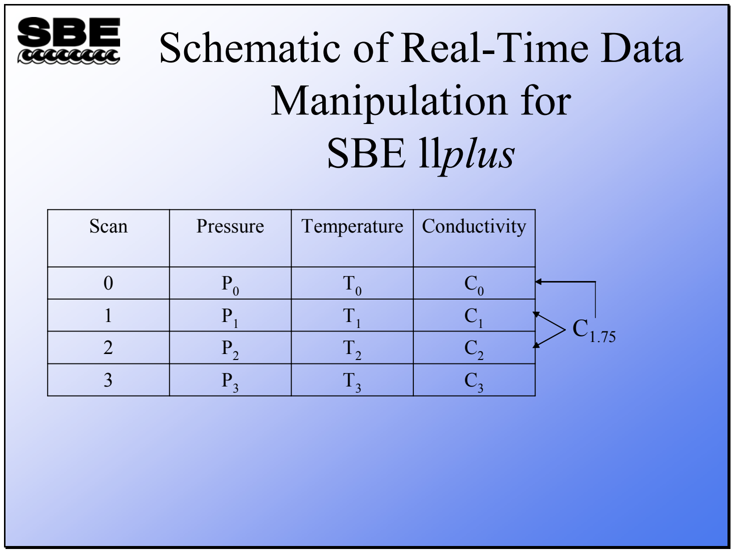
Because the 9*plus* measures T, C, and P simultaneously, and owing to the distance that the sample travels in the plumbing of the TC duct and the conductivity cell, the water that the T sample is taken from at time 0 is actually the same water that the C sample is taken from during time 2.

## Coordinating Measurements




The adjustment of samples in the data stream is taken care of in the SBE 11*plus* deck unit and is termed *sample alignment*. Careful calculation of flow rates, plumbing distances, and sample rates yield a nominal adjustment of 1.75 data scans. Because the conductivity cell is plumbed after the temperature, the conductivity channel must be advanced relative to the pressure and temperature measurements. The next slide illustrates this with an example.

## Coordinating Measurements: Aligning Data



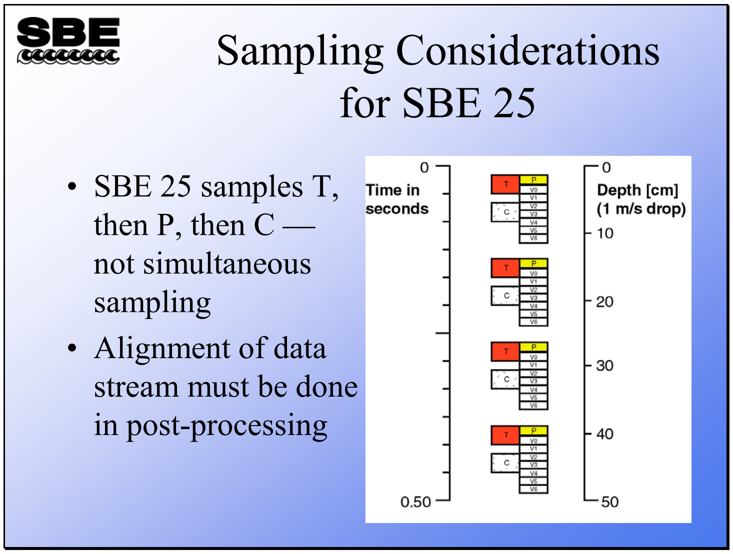

| Scan | Pressure | Temperature | Conductivity |
|---|---|---|---|
| 0 | $P_0$ | $T_0$ | $C_0$ |
| 1 | $P_1$ | $T_1$ | $C_1$ |
| 2 | $P_2$ | $T_2$ | $C_2$ |
| 3 | $P_3$ | $T_3$ | $C_3$ |

For example, a value for conductivity at 1.75 scans, $C_{1.75}$, is calculated by interpolating between the values for $C_1$ and $C_2$. $C_0$ is set to equal $C_{1.75}$. Then $C_1$ is set to equal the value obtained from interpolation between $C_2$ and $C_3$. This process continues to the end.
The 11*plus* can perform this advancement on each of its data channels, with different advancements for each channel. The amount to advance a channel is entered in seconds. Recall that the 9*plus* collects scans at 24 Hz, which equals 0.042 seconds/scan; therefore, a 1.75 scan advancement equals 0.073 seconds.

You might want to enter advancement values for dissolved oxygen sensors or fluorometers as well as for conductivity.

The 1.75 scan advancement is a nominal value; changes in flow rate caused by plumbing changes will necessitate changes in advancement. Similarly, you should consider any advancement that the 11*plus* makes to your other sensors a nominal value and make your final decision based on observing the data.

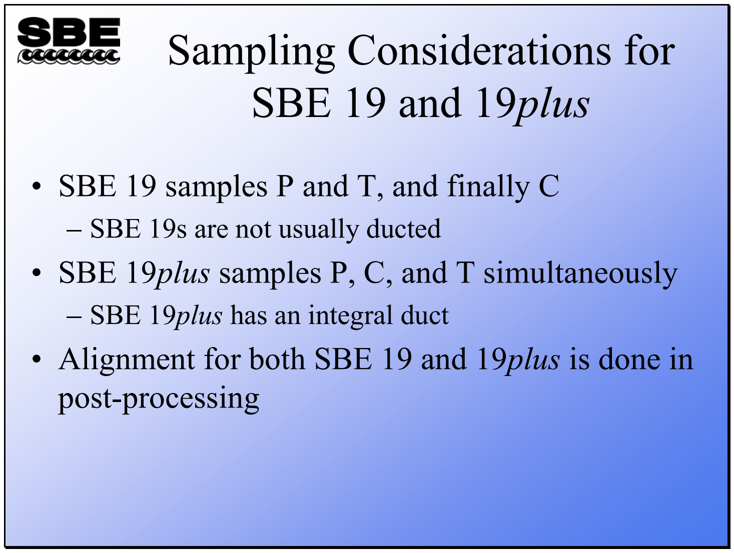
## Coordinating Measurements: Measurement Sequence




The SBE 25 has a different sampling order. With no deck unit, the alignment of T and C must be done in post-processing. As an internally recording instrument, the SBE 25 has the capability of averaging samples to increase the memory endurance. Averaging degrades the resolution of the instrument and makes the alignment of T and C ineffective.

As the diagram shows, T and P are measured simultaneously, with C following. The SBE 25 has the same pump and TC duct as the 9*plus*, yielding the same transit time for water moving past the thermometer and through the cell. A good nominal advance for conductivity is the same as for the 9*plus*, 0.073 seconds.

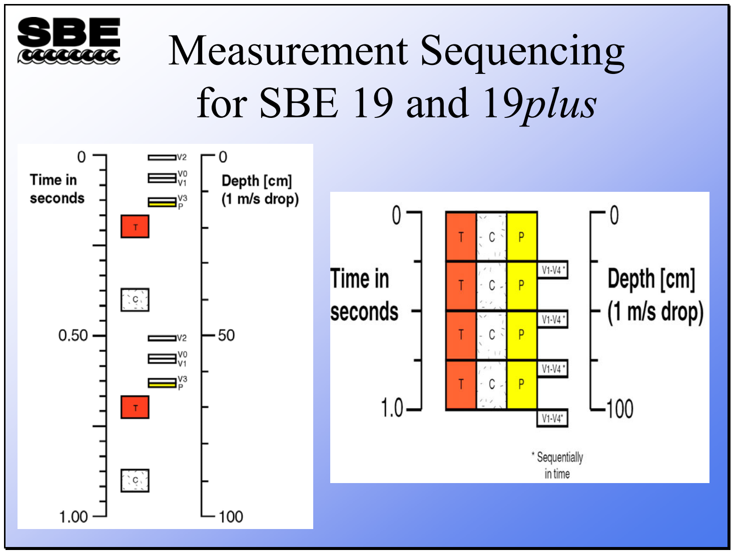
## Coordinating Measurements with the SBE 19 and 19*plus*




The SBE 19 has a different sampling protocol than the SBE 25 and the 9*plus*. The 19 uses the same signal condition circuit, an oscillator, to sample both T and C. A relay switches the oscillator between the thermistor and the conductivity cell. Further, to improve circuit stability, reference resistors are switched into the oscillator every 120 samples.

The SBE 19*plus* samples T, C, and P simultaneously. This is an improved protocol over the 19.

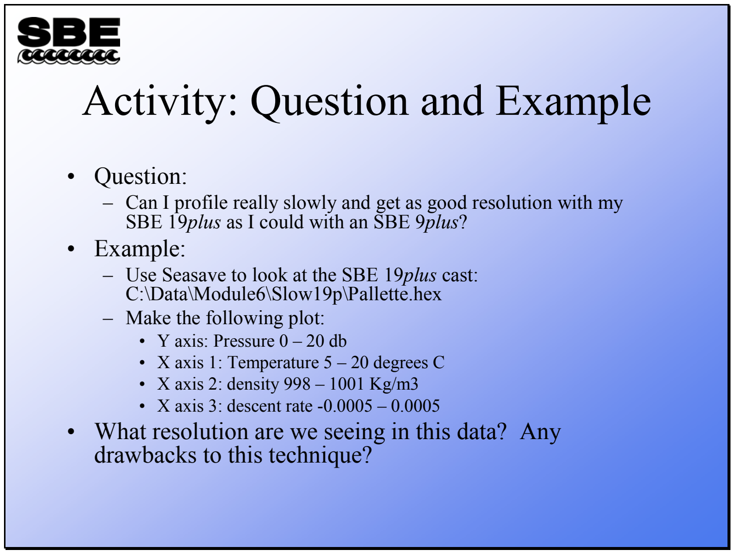
## Coordinating Measurements: Measurement Sequence



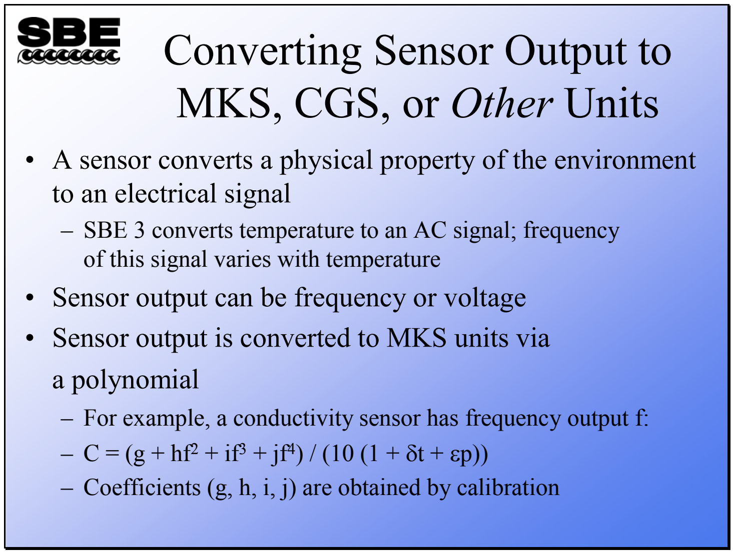

As was mentioned on the previous page, the SBE 19 samples P, then T, and finally C. Because T and C use the same oscillator, there is separation in the measurements to allow time for the oscillator to settle into the new frequency after it has been switched. Alignment of T and C is done in post-processing and, as mentioned earlier, averaging of scans to improve memory endurance tends to degrade the instrument's resolution and make alignment less effective.

The SBE 19*plus* offers simultaneous sampling of P, T, and C, similar to the SBE 9*plus*. It also has a sampling rate of 4 Hz. This sampling schedule is an improvement over the other small CTDs in Sea-Bird's line-up.

## Activity


SBE
Activity: Question and Example
• Question:
– Can I profile really slowly and get as good resolution with my SBE 19*plus* as I could with an SBE 9*plus*?
• Example:
– Use Seasave to look at the SBE 19*plus* cast: C:\Data\Module6\Slow19p\Pallette.hex
– Make the following plot:
• Y axis: Pressure 0 – 20 db
• X axis 1: Temperature 5 – 20 degrees C
• X axis 2: density 998 – 1001 Kg/m3
• X axis 3: descent rate -0.0005 – 0.0005
• What resolution are we seeing in this data? Any drawbacks to this technique?

## Converting Sensor Output to Scientific Units




As we have discussed, a sensor has an active element that interacts with the environment, and a conditioning circuit that converts the reaction into a signal that is measurable with normal techniques (e.g., Analog/Digital conversion or counting of a frequency). Having acquired a digital representation of temperature or conductivity, we need to convert this into units useful to scientists and engineers.

The simplest sensor might have a linear response to the environmental parameter of interest. For example, a transmissometer has a simple relationship between voltage output and percent transmittance of the water within its path:

%T = (slope * voltage output) + offset

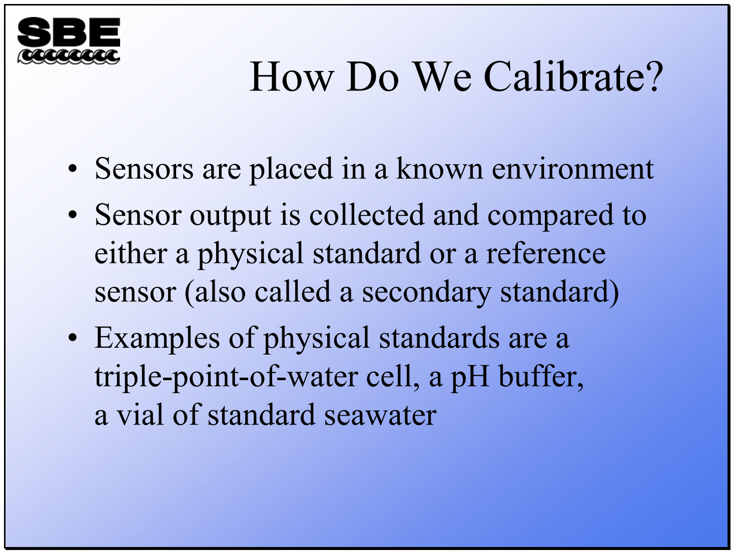
Unfortunately, the output of most sensors in response to environmental parameters is a complex polynomial, often parametric in nature. Consider the equation for conversion from SBE 3 output frequency to temperature. The response is a polynomial because the thermistor responds to changes in temperature in a non-linear fashion:

$$T\,[°C] = [1 / (g + h\ln(fo/f) + i\ln^2(fo/f) + j\ln^3(fo/f)\,)] - 273.15$$

The conductivity sensor's response is a polynomial and parametric, because the sensor has secondary response to temperature and pressure:

$$C = (g + hf^{2} + if^{3} + jf^{4}) / (10\,(1 + \delta t + \varepsilon p))$$

## Converting to Scientific Units: Calibration

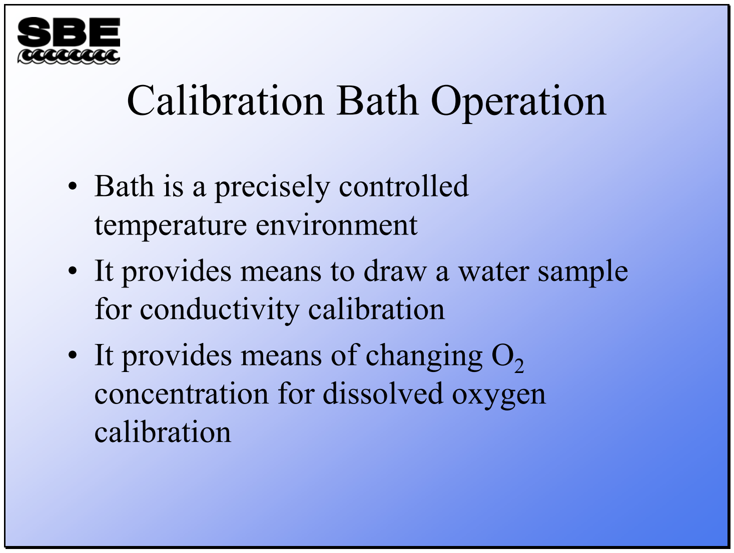



To calibrate a sensor, it is placed in a precisely controlled environment. The output of the sensor is collected at the same time as the environment is measured with a reference sensor. The reference sensor is carefully calibrated and has a well-known history. To gain the careful calibration and history, the reference is calibrated against physical standards such as the triple point of water and the melting point of gallium, or an agreed-upon standard such as IAPSO standard seawater.

## Converting to Scientific Units: Calibration (continued)

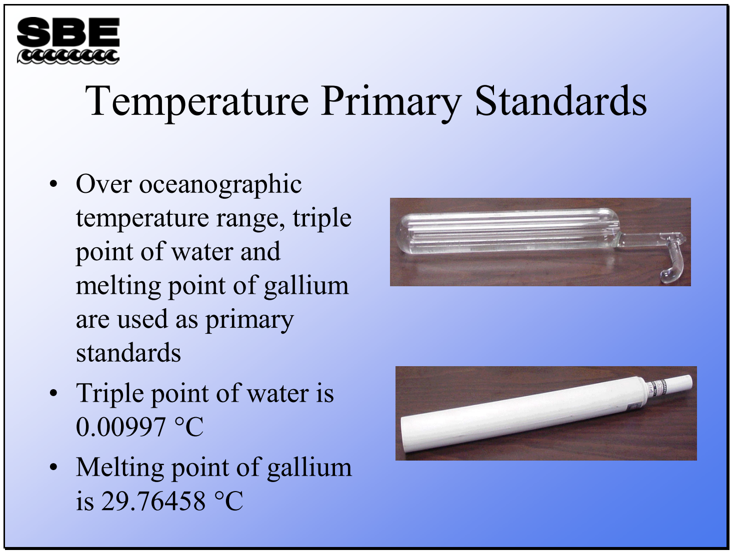

This bath design is common to all of Sea-Bird's calibration activities. They are highly insulated and well stirred, and they typically hold temperature to better than 0.0005 °C.

## Converting to Scientific Units: Calibration (continued)




Baths of this design have been adapted for calibration of all of Sea-Bird’s products. The basis is precisely controlled temperature and the ability to draw a water sample for salinity determination. The means to change partial pressures of Oxygen for SBE 43 calibration has been added.

## Converting to Scientific Units: Calibration (continued)

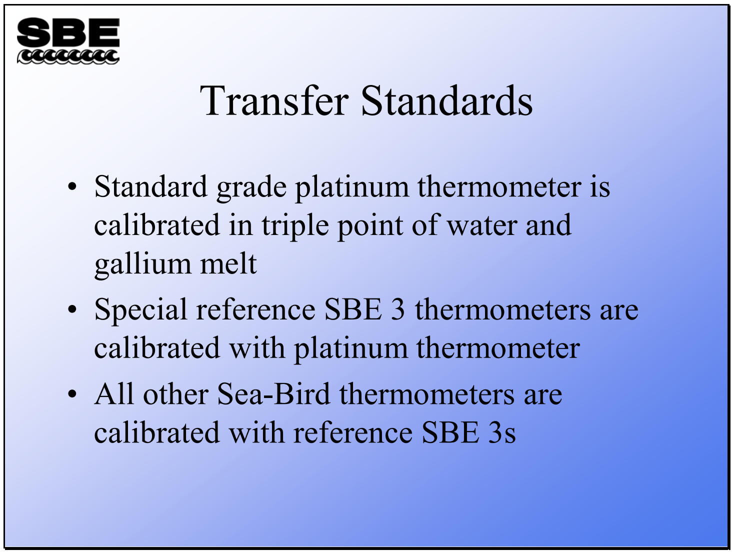



In considering calibration, one runs into the problem of knowing exactly what the temperature of a particular object is. If we only had thermometers to rely on, who is to know which one is right? Instead we use physical standards; the Celsius temperature scale decrees that water freezes at 0 degrees and boils at 100 degrees. However, the freezing point and boiling point are subject to uncertainties such as atmospheric pressure. Instead, we use the temperature at which water exists as a liquid, a vapor, and a solid, the triple point. The triple point of water is measured in a specially constructed cell that contains no air, only $H_20$. The triple point occurs at 0.00997 °C. To pin down the other end of the oceanographic scale, the melting point of extremely pure gallium is used; this occurs at 29.76458 °C.

We calibrate platinum reference thermometers at these points and then calibrate reference SBE 3 sensors with the platinum thermometers. This allows us to trace the temperature measurement used to calibrate all other thermometers back to the physical standards.

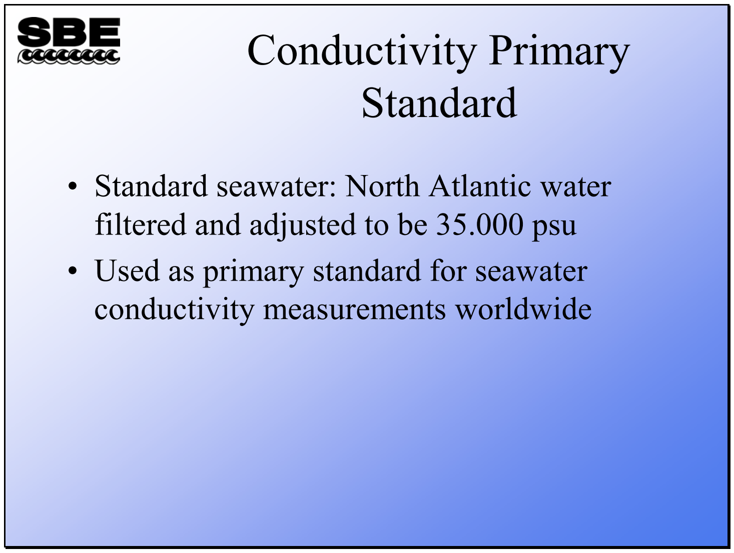
Fixed point cells are called this because when they are in the proper condition their temperature is fixed by the physics of the materials they are constructed of to be a single temperature. The triple point cells are maintained in a water bath very near their natural temperature. This allows them to last a long time. The gallium cells are melted slowly in an oven; the temperature where the gallium changes phase from solid to liquid is used as the calibration temperature.

## Converting to Scientific Units: Calibration (continued)



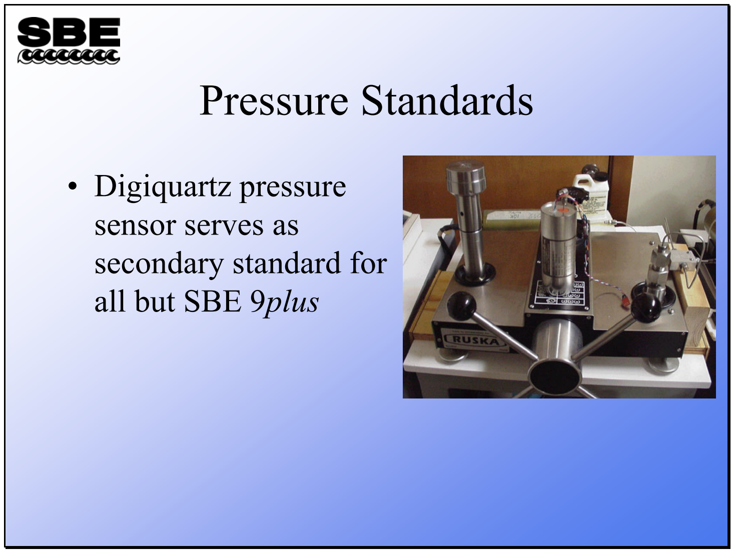

As was previously mentioned, a platinum thermometer is calibrated in the fixed point cells and then used to calibrate the SBE 3 reference thermometers. The platinum thermometer is susceptible to calibration shift due to impact or vibration; because of this it is impractical to use it in routine calibration. The SBE 3s are much more robust. By careful selection of the SBE 3 and the accumulation of a drift history, very accurate calibrations can be accomplished.

## Converting to Scientific Units: Calibration (continued)



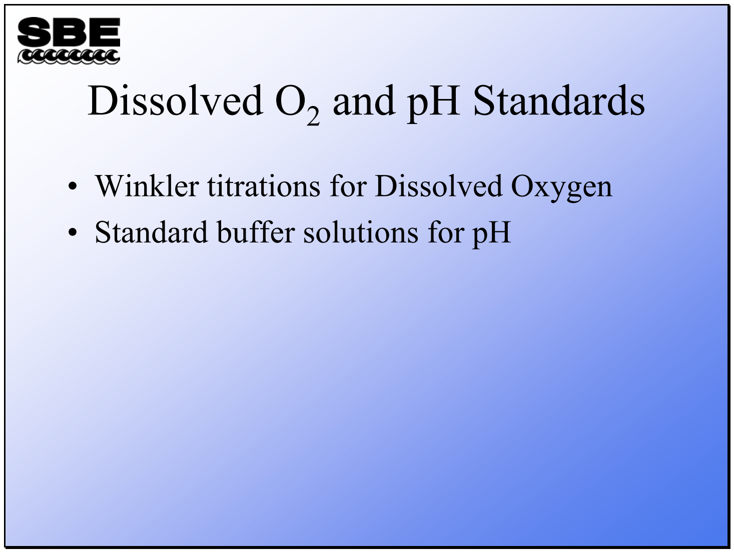

Unlike temperature, a primary standard for the conductivity of seawater is more difficult to come by. In recognition of this, IAPSO commissions the Ocean Scientific International Corporation to provide *standard seawater*. Ocean Scientific sends small ships out into the North Atlantic with large tanks to collect seawater. The seawater is filtered and adjusted in salinity to be 35.000. It is then sealed in vials or bottles and shipped to laboratories worldwide to be used in standardizing laboratory salinometers. Because everyone uses the same water to standardize their salinometers, we are all synchronized with Ocean Scientific. The standard seawater service has been going on for decades under the auspices of various committees of scientists. It was first produced by a laboratory in Copenhagen and was initially dubbed *Copenhagen water*.

## Converting to Scientific Units: Calibration (continued)




Pressure calibrations are performed at Sea-Bird on all instruments except the SBE 9*plus.* The quality of the pressure sensor used in the 9*plus* is such that an adequate calibration would require a local gravity survey and dead weight tester parts that are certified by the National Institute of Standards and Technology. These requirements plus the stability of the Digiquartz sensor make the maintenance of this capability not cost effective for Sea-Bird. For all other instruments, pressure calibrations are made using a Digiquartz sensor as a secondary standard.

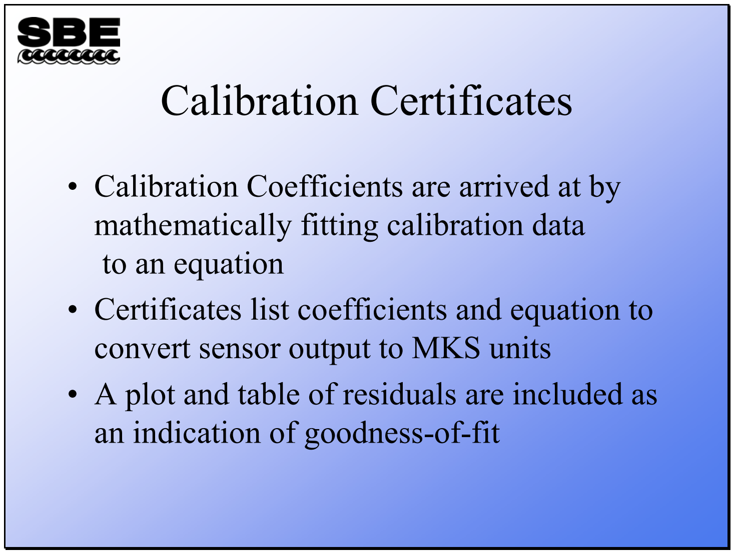
## Converting to Scientific Units: Calibration (continued)




Dissolved oxygen sensors are calibrated in a bath that is plumbed with oxygen and nitrogen inputs. As gas concentrations are varied during calibration, Winkler samples are collected. These are titrated for dissolved oxygen concentration during the time of the calibration.

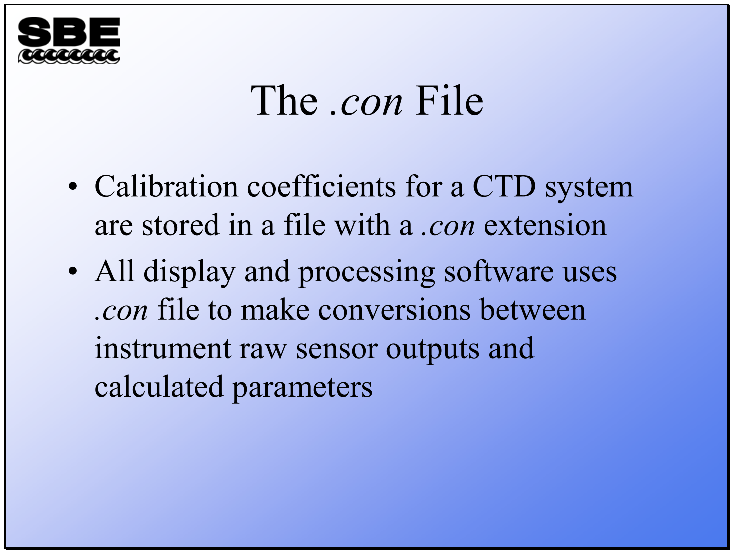
pH sensors are calibrated with commercially available buffer solutions.

## Converting to Scientific Units: Calibration (continued)




The calibration certificate is a listing of all the information required to convert sensor output to scientific units. There is also a table of calibration data and a plot of residuals that indicates a goodness-of-fit. Residuals are expressed as the difference between instrument parameter and bath parameter (residual = instrument – bath). If the residual is positive, the sensor is reading high of reality; if negative, the sensor is reading low.

## Converting to Scientific Units: Calibration Coefficients




Having spent all this time carefully characterizing our sensors, we need to put the data into a format that makes them available to the software for data display and processing. Sea-Bird software, Seasoft, uses a file with a *.con* extension for storage of instrument configuration and calibration coefficients. Before you can do anything with your data, you must have a *.con* file that is correct for your instrument.