SIGNAL AND NOISE: THE BASICS
TEACHER NOTES

DESCRIPTION

One of the first things that physicists learn is that measurements are not exact. In fact, there can be so much variation in data that it is difficult to decide if any important information is there. The variation in data can result from background "noise" which can be caused by particles entering the detector that we are not studying in a particular experiment or from the settings of the instrumentation. This activity has two sections: analysis of signal and noise in everyday audio and video situations, and an introduction to interpreting instrument data and recognizing when a signal is present above the noise.

STANDARDS ADDRESSED

Next Generation Science Standards

Disciplinary Core Ideas
- PS1.A: Structure and Properties of Matter
- PS2.B: Types of Interactions

Science and Engineering Practices
4. Analyzing and interpreting data
5. Using mathematics and analytical thinking
6. Constructing explanations (for science) and designing solutions (for engineering)
7. Engaging in argument from evidence
8. Obtaining, evaluating, and communicating information

Crosscutting Concepts
1. Patterns
2. Cause and Effect: Mechanism and Explanation
3. Scale, Proportion, and Quantity

Common Core Literacy Standards

Reading
- 9-12.4 Determine the meaning of symbols, key terms . . .
- 9-12.7 Translate quantitative or technical information . . .

Common Core Mathematics Standards
- MP2. Reason abstractly and quantitatively.

IB Physics Standards
- 1.1 Measurements in physics
- 1.2 Uncertainties and errors
- 7.3 The structure of matter
- 12.1 The interaction of matter with radiation

ENDURING UNDERSTANDINGS

Physicists must identify and subtract background events in order to identify the signal of interest.

LEARNING OBJECTIVES

As a result of this activity, students will know and be able to:
1. Describe the similarities and differences between a clear and a noisy audio signal.
2. Sketch waveforms for clear signals and signals with noise.
3. Describe the similarities and differences between a clear and a noisy video signal.

4. Describe the similarities and differences between a graph of instrument data with a clear signal above the noise and data in which there is no signal above the noise.

PRIOR KNOWLEDGE
Students do not need prior knowledge for this activity.

BACKGROUND MATERIAL
This is an introductory activity, so no background material is necessary.

RESOURCES/MATERIALS
We provide links in the implementation instructions.

IMPLEMENTATION
This activity is a tutorial in two parts for developing basic understanding of the difference between signal and noise. Also, students learn about the importance of the signal-to-noise ratio.

PART 1: NOISE IN OUR DAILY LIVES
Noise is a term that we use regularly. Students can easily recognize a sound signal that is noisy compared to a sound signal that is not noisy. We develop this idea using samples of sound files and video stills that are noisy versus clear.

For this activity, divide the students in groups of two or three and allow time for group discussion after each section. Each group can share their thoughts in a class discussion. Students will produce a wide variety of insightful answers. The suggested answers (*in italics*) are examples of possible responses.

A. Sound Waveforms
There are two sound files for this activity. You can use the direct Internet link or you can play the files from the Data Portfolio. One is a regular drum beat (*link to drum file*):

Figure 1. Typical drum waveform.
https://www.soundsnap.com/search/audio/checker+drum/score

and the other a tribal bells ceremony (*link to tribal bells ceremony*):

Figure 2. Tribal bells dance.
https://www.soundsnap.com/search/audio/BTF+06+Tribal_30_Bells-+Dance-+People-+Crowd-General-+Ambience_06/score

Play these files for the students. We give them the following scenario:

Suppose you are on vacation and observe a tribal bells ceremony. You notice it becomes difficult to tell what you are hearing because of the increasing noise from the crowd, so you try to get closer to the ceremony.

- What do you hear? Does moving closer to the ceremony solve the problem?

- Compare the waveform for the drum and the waveform of the tribal bells ceremony. Record the differences and similarities.
- Compare the waveform for the tribal bell ceremony at the beginning with the time when the bells are louder. How did the waveform change? What could have happened to make the tribal bell ceremony seem louder?
- Suppose that the drum track above had a lot of noise in it; what would the picture of the waveform in Figure 1 look like?

B. <u>Video Noise</u>
Display the images of the video stills. Tell the students that each pixel in the image has a waveform. When the signal is boosted, the amplitude of the waveform for the signal is increased, while the amplitude of the noise, or background, remains the same or is decreased.

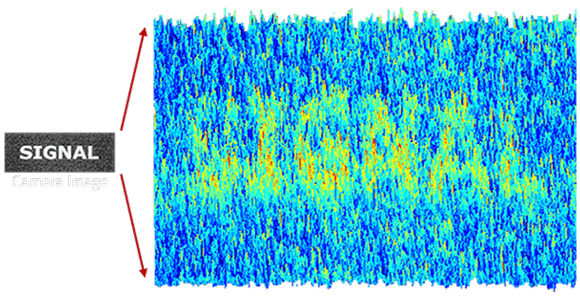

Figure 3.
http://cdn.cambridgeincolour.com/images/tutorials/noise_signal2_new.png

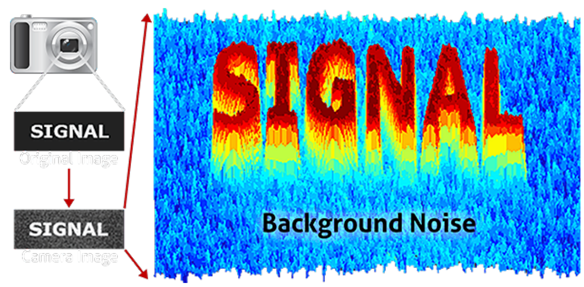

Figure 4.
http://cdn.cambridgeincolour.com/images/tutorials/noise_signal1_new.png

We give them the following scenario:

You are working the video board at the local radio station. You notice that there are controls labeled contrast and gain. Contrast controls the difference between the brightest and darkest the pixel can be. Gain controls the amplitude of the signal for each pixel.

- Describe how the contrast and gain knobs were adjusted to create the image in Figure 4 from the image in Figure 3.

PART 2: NOISE IN AN INSTRUMENT READOUT
Similar to sound waves created by hitting drums, the cosmic ray detector "hears" signals produced by muons that pass through the counters. When the muon passes through the counter, it produces a brief flash of light that is converted into an electronic "signal." The figure below shows what a typical muon signal looks like when plotting PMT voltage vs. time.

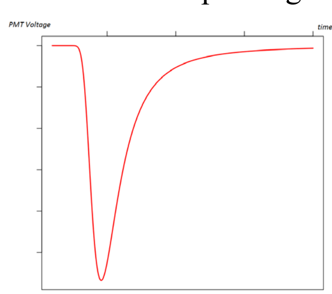

Figure 5. A typical muon signal. https://upload.wikimedia.org/wikipedia/commons/thumb/2/2a/Landau_distribution.svg/1024px-Landau_distribution.svg.png

This plot shows a very smooth curve which is the representation of ideal data. However, there are lots of other things happening in addition to the muon passing through, and all of these things can add noise to the data. Noise could come from a variety of sources and can have a variety of shapes. Below is an example of what a noisy readout looks like, next to a less-noisy readout where the signal is easier to see.

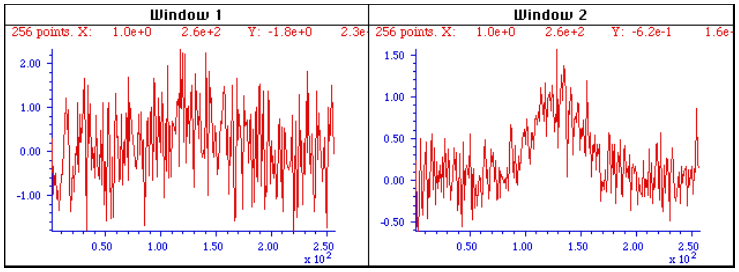

Figure 6. Noisy vs. less-noisy readout.
http://terpconnect.umd.edu/~toh/spectrum/Figure3.GIF

Consider the following scenario:
When looking at the readouts shown above, Student A said that the both of the readouts have so much zigzagging that it is impossible to decide if there is a signal present. Student B said that the zigzags on the right were smaller and the peak was higher than the zigzags on either side, so the readout on the right must have a signal.

- Who is correct, Student A or Student B? Explain your reasoning.
- Describe the details that led you to the claim that a signal is present in a noisy readout.

ASSESSMENT

The questions that are included throughout the activity serve well as formative assessments. After each section, students can discuss their answers with each other, or with you.

A summative assessment can consist of the student responses to the questions in the learning objectives. Sample student answers are listed in italics below.

Suppose you are on vacation and have the opportunity to observe a tribal bells ceremony. You notice it becomes difficult to tell what you are hearing because of the increasing noise from the crowd, so you try to get closer to the ceremony.

- What do you hear? Does moving closer to the ceremony solve the problem?
  - *Moving closer will cause the peaks waveform for the bells to stand out from the background noise. The peaks for the bells will be higher but the waveform will still be messy because the background noise will not vanish; the noise will just have smaller amplitude compared to the bells.*
- Compare the waveform for the drum and the waveform of the tribal bells ceremony. Record the differences and similarities.
  - *The waveform of the drum was very clear. When the drum was not playing, the signal returned to the zero line. The waveform for the tribal bell ceremony was messier. The bells were faint and hard to hear and the peaks for the bells were barely higher than the background noise.*
- Compare the waveform for the tribal bell ceremony at the beginning with the time when the bells are louder. How did the waveform change? What could have happened to make the tribal bell ceremony seem louder?
  - *There was a time in the recording that the bells were louder. At that point, the peaks for the bells were a little higher than the background noise, but the background noise did not disappear.*
- Suppose that the drum track above had a lot of noise in it, what would the picture of the waveform in Figure 1 above look like?

- *The waveform shown below is a typical drum waveform with background noise.*

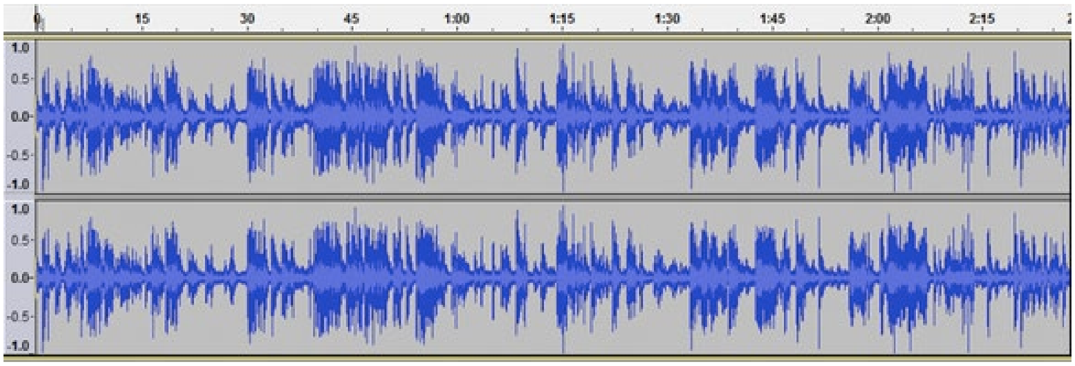

Figure 1a. Drum waveform with background noise.
https://us-758c.kxcdn.com/wp-content/uploads/2015/04/audacity-738x408.png

1. You are working the video board at the local radio station. You notice that there are controls labeled contrast and gain. Contrast controls the difference between the brightest and darkest the pixel can be. Gain controls the amplitude of the signal for each pixel.
   - Consider Figure 3 and Figure 4 above; describe how the contrast and gain knobs were adjusted to create the image in Figure 4 from the image in Figure 3.
     - *In Figure 3, the background and the signal are treated the same. In Figure 4, the input signal is treated separately from the background signal. The signal amplitude was increased using the signal gain control. The background amplitude was decreased using the background gain control. The brightness of the signal was increased using the signal contrast control and the brightness of the background was decreased using the background contrast control.*

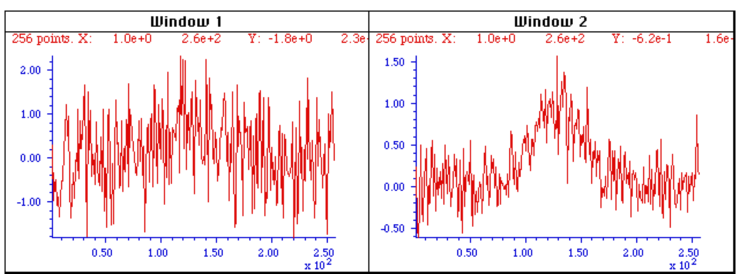

Figure 6. Noisy vs. less-noisy readout.
http://terpconnect.umd.edu/~toh/spectrum/Figure3.GIF

Physicists need to know how well to trust that a signal is present. One measure of this is the signal-to-noise ratio. If the readout is very noisy as in the left readout in Figure 6 above, the signal does not clearly rise out of the noise and the signal-to-noise ratio is small. When the signal clearly rises above the noise as in the right readout in Figure 6 above, the signal to noise ratio is larger. The bigger the signal-to-noise ratio, the more we can trust that a signal is present.

Consider the following scenario:
When looking at the readouts shown above, Student A said that the both of the readouts have so much zigzagging that it is impossible to decide if there is a signal present. Student B said that the zigzags on the right were smaller and the peak was higher than the zigzags on either side, so the readout on the right must have a signal.

- Who is correct, Student A or Student B? Explain your reasoning.
  - *If Student A is correct, then the only thing that matters is the number of zigzags in the signal. Student A's reasoning does not take into account that amplitude differences do*

not matter. If Student B is correct, then there is more to consider than just the number of zigzags. Student B correctly indicates that the size of the zigzags matter in relation to the height of the peak. This is the original of the expression that the "signal rises out of the noise."

- Describe the details that led you to the claim that a signal is present in a noisy readout.
  - *As stated by Student B, the details to consider are the size (amplitude) of the zigzag compared to the height of the signal. Another factor that might matter is how much data is collected. When a large amount of data is collected, sometimes the background noise stays about the same level and, over time, the "signal rises out of the noise."*

2. You attend a party where a singer and a guitar player are quietly playing in a corner. There is a lot of background noise: conversation, laughing, shouts, etc. You move closer to the musicians to be able to hear the music over the noise.
   - What do you hear? Does moving closer to the musicians help you hear the music?
     - *As I walk towards the musicians, I can hear the music more clearly, but there is still background noise.*
   - Sketch a possible waveform for the music when you are far from the musicians.
     - *Use the Tribal Bell Dance waveforms as a guide for appropriate waveforms. The music peaks should be barely above the background noise.*
   - Sketch a possible wave form for the music when you are near from the musicians.
     - *Use the Tribal Bell Dance waveforms as a guide for appropriate waveforms. The music peaks should be noticeably higher than the background noise, but the background noise does not go to zero.*

3. Develop your own scenario using an event from your students' lives.

   A summative assessment can consist of the student responses to the questions in the learning objectives:
   - Describe the similarities and differences between a clear audio signal and a noisy audio signal.
     - *The answers should be similar to the answers for the clear drum wave forms and the Tribal Bell Dance waveforms. Where there is no background noise, the signal will be zero.*
   - Sketch waveforms for clear signals and signals with noise.
     - *See previous examples.*
   - Describe the similarities and differences between a clear video signal and a noisy video signal.
     - *The clear video signal has little or no background noise. A noisy video signal can have background noise that has almost the same amplitude as the signal, so our eye has difficulty finding the brighter signal pixels.*
   - Describe the similarities and differences between a graph of instrument data with a clear signal above the noise and data in which there is no signal above the noise.
     - *Graphs of instrument data have zigzags. When there is no signal above the noise, the zigzags are large and the amplitude does not poke up above the zigzags. When there is a clear signal, the zigzags are smaller and the highest peak has a greater amplitude than any of the zigzags.*
     - *The readout with the largest signal-to-noise ratio has the clearest signal.*

The following teachers were instrumental in developing this activity:

- Jacob Breman, Community Christian School, FL, Florida State University QuarkNet Center,
- Kevin Martz, Richard Montgomery High School, MD, Johns Hopkins University QuarkNet Center,
- Jeremy Smith, Herford High School, MD, Johns Hopkins University QuarkNet Center.