by Thomas Tretter

TEACHING ELECTROMAGNETIC WAVES

Used in Communication Technologies

Compared to previous national science education standards (AAAS 1993; NRC 1996), which informed many state science standards over the past two decades, the *Next Generation Science Standards* (*NGSS*) include a stronger focus on electromagnetic waves in modern communication technologies. In particular, performance expectation MS-PS4-3, which is part of the standard Waves and their Applications in Technologies for Information Transfer (MS-PS4), states, "Integrate qualitative scientific and technical information to support the claim that digitized signals are a more reliable way to encode and transmit information than analog signals" (NGSS Lead States 2013). The clarification statement highlights that the emphasis is on waves used for communication, including the conversion of binary patterns. While it can be challenging to teach such a scientifically complex array of concepts in a manner that is conceptually accessible for middle school students, this article describes an approach that systematically builds student concepts in an interactive and engaged manner while simultaneously incorporating a natural connection to the *NGSS* crosscutting concept of Systems and System Models.

The instructional ideas expressed in this article should be implemented over a series of lessons, and additional student tasks and instructional experiences would be needed to fully reach the performance-expectation goal. However, the following set of activities could form the core of an instructional sequence addressing this complex topic. These lessons would typically occur after instruction in wave characteristics such as amplitude, frequency, and wavelength, and the concept that waves carry energy—this set of lessons focuses on the concept that waves can also carry information.

Establishing a model

This set of lessons begins by establishing a physical model for using electromagnetic waves in communication technologies. As is recommended in the *NGSS* crosscutting concept of Systems and System Models, it is helpful to explicitly include in the discussion with students the elements of the model and how these elements are tools for understanding and testing ideas (NGSS Lead States 2013). This supports student development of the crosscutting concept that scientific models are tools for thinking; this physical model will support student thinking about abstract digital wave signals in modern communications. It will also be helpful for supporting the science and engineering practice Developing and Using Models (NGSS Lead States 2013). Among elements of modeling practice specified by *NGSS* Appendix F for grades 6–8, this particular modeling activity is well suited to support student understanding of developing a model to describe unobservable mechanisms (such as communication signals sent via electromagnetic waves) and using a model to describe phenomena (NGSS Lead States 2013). By explicitly highlighting the aspects of scientific modeling students do in this task, teachers can address the *NGSS* goal of seamlessly integrating science content with crosscutting concepts and science and engineering practices.

Wearing safety glasses while engaging in this model, students will use a spring to transmit waves. To reduce the number of springs and amount of space necessary, two student groups (four students per group) can share one long (approximately 2 m unstretched) spring, with each group independently using one end. Student "anchors" are stationed back-to-back in the middle of the spring to hold their group's half fixed on the floor (see Figure 1). A spring like this is often called a "snaky spring," costs approximately $12, and is available from many science suppliers. Alternatively, if there are enough springs and space, each group could have its own spring, or students could use a jump rope (which has greater frictional losses on a carpeted floor) or a regular slinky to transmit waves.

FIGURE 1 Long spring to model electromagnetic waves

Demonstrate the model by having one student anchor the middle and another student slightly stretch half of the spring. The second student generates a sideways wave pulse with a rapid flick of the wrist to the side. If the student rapidly moves his or her wrist only about 10 cm to the right, then the wave pulse generated will have an amplitude of approximately 10 cm. By changing the amount of motion of the wrist, the student can generate different amplitudes of wave pulses that travel down the spring. Typically, on a tile floor, a wave pulse of about 30 cm amplitude is sufficient for the wave pulse to easily travel the length of the spring without excessive frictional loss. For the purpose of modeling digital signals, the specific amplitude is not important; rather, the receiver will be able to sense the wave pulse that reaches the end of the spring by having his or her hand (as described below) close enough to the resting spring to be able to feel the pulse as it passes. It is a good idea for the team to practice the model a few times so that this happens reliably.

The student practices generating a few waves with sufficient amplitude for the wave to easily travel all the way to the second student, who is anchoring a fixed end at the center of the long spring. Because this model will be for digital communications, the wave signal will be sent in pulses (digital, or discrete) rather than continuously (an analog signal). Remind students that this spring represents an electromagnetic wave—an invisible wave of interacting electric and magnetic fields—but this model makes those waves visible.

The student generating the wave signal is the "transmitter"—the component in an electronic system that sends a radio or TV wave out over the air. An option would be to have an index card labeled "transmitter" to hang around the neck of the student as a reminder (with similar cards for the other model components). The student holding the other end is simply there to anchor the spring and doesn't have an analog in the electronic system. In addition to the two students holding the ends, a third student, the "receiver," is now brought into the model. This student either wears a blindfold or closes his or her eyes so that he or she can't see the wave pulse when it arrives. The blindfolded receiver puts the edge of his or her flat hand perpendicular on the floor (pinky down, thumb up) with the palm facing the spring, about 20 cm from the nonmoving spring (that distance can be varied depending on how big a wave the transmitter sends). The blindfolded student who senses the wave when it passes simulates how the electronic components of a receiver react when an incoming electromagnetic wave arrives—the receiver senses that a wave pulse has arrived. Finally, a fourth student on the team is given a clipboard with graph paper and pencil. This student is the "image generator," which simulates the components of the system that translate incoming signals received into an output message for humans to process.

As you orchestrate one group of four students in creating the model for the first time while the rest of the class observes, you can explicitly teach aspects of the scientific practice of modeling through questioning by guiding students to identify what each part of the model represents, the model's strengths and limitations, and how it might help in terms of thinking about the science. Before having students engage in the upcoming small-group activities, you might want to bring a bit of closure to this aspect of the lesson by having students document in their science notebooks this specific model (using sketches and labels) and its strengths and weaknesses.

Tell students they are free to experiment a bit once they begin building the model for themselves with their group of four and that they may decide either larger or smaller amplitudes are better (this depends in part on the friction with the floor—carpet versus tile—and the nature of the spring or rope being used). Having active student involvement in deciding specific details of the model helps reinforce the underlying concept about the use of models: that they should be useful for thinking, and that there may be more than one good way to use them.

Once the model elements and tasks have been established, the team of four students will send a series of increasingly complex digital messages. You can tell students this at the beginning so they are able to put the individual experiences into a schema and expect each cycle to increase in complexity, or you may simply guide students to each aspect of the experience without offering this instructional framework so that they experience each event in turn and use reflection to notice how the complexity has increased over experiences. Either approach can be instructionally beneficial.

These activities can be done in a classroom with adequate space but tend to work best in a long hallway so that student groups have enough room. As students progress through the various parts of the activity, have them rotate among the four jobs in the model to ensure they are all actively engaged with each component of the model. The details below indicate specific tasks students will engage in and highlight outcome goals the teacher can formatively assess by observing groups and asking questions of individuals and groups.

The time spent on each part of the activity can vary depending on a teacher's instructional purpose. For example, the comparison of digital versus analog signals in terms of reliability could be done with multiple cycles of student data collection and sharing with whole-group discussion/debate (taking most of a 50-minute class period), or it could be done briefly to illustrate the point without engaging students in extensive data collection and processing. As teachers develop their instructional units, they can choose which practices to emphasize (e.g., Analyzing and Interpreting Data) and where to spend time.

Activity 1: First message—A digital stream

Ask students what *digital* means in terms of an adjective describing transmitting messages. Through student responses and teacher follow-up questions, guide students to understand that, at its core, *digital* can be thought of as communicating only discrete (rather than continuous) values. The simplest digital signals would therefore communicate only one of two possible values; tell students that in this activity, all waves will communicate one of two possible values (e.g., a digital signal). When the transmitter sends one pulse, that corresponds to a value of 1. Two quick pulses right after each other corresponds to a value of 0 (in keeping with the digital tradition of 0s and 1s rather than 1s and 2s; see Figure 2). Because sending nothing as a 0 leads to confusion about whether something was actually sent or the transmitter is just waiting longer between signals, it is necessary to have something sent to represent 0. I tell students that one way to remember that two pulses represents 0 is to think of the two pulses as canceling each other, which helps them easily recall the coding system.

The amplitude of the pulse does not really matter, as long as it is big enough to reliably reach the receiver at the other end, so it is fine if there is inconsistency in the amplitudes generated. This is one reason why digital systems are more robust than analog in terms of not having static in the picture—by its very nature, either a 0 or a 1 is transmitted, and there are no concerns about in-between values. Understanding this nature of the experience could become a target of structured student-student discussion based on teacher-posed questions, followed by whole-class conversation to ensure that all students have considered these ideas.

The transmitter writes a random string of about 10 0s and 1s on an index card, keeping them secret from the receiver and image generator, and then begins transmitting them. When the blinded receiver feels either one pulse (a 1) or two quick pulses (a 0), he or she says aloud what was received, and the recorder writes it down. Tell the transmitter to wait until the receiver has verbalized the received digit to send the next one to avoid sending digits too fast. After sending the stream of 10 digits, the transmitter says, “End of message,” the receiver takes off the blindfold, and all four team members then compare the original message stream with the recorded one.

Team members switch roles and repeat the activity once or twice until they reliably receive the intended message. Typically, the teams achieve 100% accuracy after the first or second try. The element most important to being accurate is making sure the transmitter sends adequately large pulses and waits for the receiver to verbalize receiving a message before another is sent. Students could be encouraged to develop their own procedures for the modeling to strengthen the reliability of the information transfer, or the teacher could give instructions.

Assessment checkpoint

It is helpful at this point to structure a targeted formative assessment of student understanding before proceeding to subsequent components of this series of lessons. Although the teacher has been informally assessing student groups as they developed, transmitted, and verified streams of digits, having students respond to a short series of prompts offers an opportunity to check that each student understands the lesson so far. These prompts could be assigned as homework or as in-class work (see Figure 3 for sample prompts and a rubric).

Activity 2: Digital versus analog communication

To contrast digital with analog communication systems, reestablish the codes so they are based not on the number of pulses but on the amplitude of the pulse (this is how AM, or amplitude modulation, radio signals work). To model analog wave transmission, the concept is for students to send a predetermined set of different amplitudes of waves, and for the receiver to pick up and identify those various amplitudes. This is

FIGURE 2 **Coding pulses into digital 0s and 1s**

This can also be made into a chart that is hung on the wall to remind students.

Number of pulses	Value
1	1
2	0

different from digital, in which the receiver only had one of two values to indicate a 0 or a 1. For examples of generating analog waves that have a wide variety of possible amplitudes, have students create a code using wave signals with amplitudes in units varying between 20 and 60 cm. For example, the transmitter may intend to send the coded four-value amplitude signal of 10 cm, 40 cm, 30 cm, and 60 cm. As one of those waves comes by, the receiver indicates which amplitude was received. Given the difficulty of precisely sensing a specific amplitude, the receiver might tell the image generator to write down a received code of 20 cm, 60 cm, 10 cm, and 50 cm. In this example, the receiver got none of the four values correct, probably in part due to the spring rubbing on the floor as the wave pulse passed down the line. This imprecision would register as static or a degradation of the signal from the original transmission. Typically, students find it much harder to consistently get 100% accuracy with this analog signal, which represents "static" in the signal. This approach models disturbances to amplitude modulation analog signals in the atmosphere, something most noticeable during a thunderstorm. You may want to show students a video with some static (e.g., the 1969 Moon landing, which is available on YouTube) to provide contrast to the digital TV signals students are familiar with.

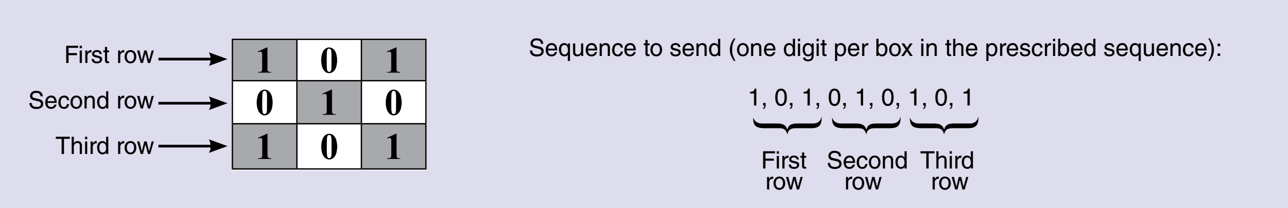
Assessment checkpoint

After students send analog signals and compare their accuracy to the digital ones they sent earlier, assess student understanding of digital versus analog signals using a persuasive paper. This could be structured in collaboration with the language arts teacher, who could connect writing about these science ideas to *Common Core State Standards* in English language arts, specifically standard WHST.6-8.1: Write arguments focused on discipline-specific content (NGAC and CCSSO 2010). A possible prompt could be "Describe similarities and differences between digital and analog signals. In your description, please include information about the reliability of digital versus analog, and circumstanc-

FIGURE 3 Writing prompts and rubric for formative assessment

Writing prompts	Suggested scoring rubric
Describe the function of each of these "communication with waves" model components: transmitter, receiver, image generator.	3 = Core function of each component thoroughly described 2 = General function of at least two of the three components correctly described 1 = At least one component described in general terms 0 = None of the components described
What is the underlying purpose of using models in science? Give the general purpose and then a specific example using the electromagnetic digital wave communication model we used in class.	3 = States models are tools for testing ideas, understanding science, and thinking about how particular parts of science work; concrete example from wave model is given 2 = Makes generic statement(s) about using model to understand science, without explicit example from wave model 1 = Makes statements about imitating or growing/shrinking the "real thing" as the purpose, without a strong example from wave model 0 = No coherent or valid purpose for models is shared, not connected to classroom wave model
Describe how this electromagnetic wave model characterizes digital wave signals instead of analog ones.	3 = Concept of digitization via the transmission of only one of two values, 0 or 1, is clearly explained and contrasted with analog possibilities with many possible values (e.g., amplitudes) being sent 2 = Concept of digitization via the transmission of only one of two values, 0 or 1, is clearly explained, but no contrast or similar description is offered for analog signals 1 = Mentions sending a 0 or 1, but response does not clearly indicate understanding that these discrete values represent the core concept of digitization 0 = Nonrelated response

FIGURE 4 Sending the letter *X*



1	0	1
0	1	0
1	0	1

Sequence to send (one digit per box in the prescribed sequence):

1, 0, 1, 0, 1, 0, 1, 0, 1

es under which each type of signal may be affected in terms of clarity of transmission."

Activities 3–5

At this point in the instructional sequence, I recommend giving students a handout with guidance to independently (in groups of four) complete Activities 3–5 below. It may be best to put directions/guidance for each of these three segments on separate sheets of paper, and as a student group finishes one segment, students in that group bring their work to you for a check to make sure they are on the right track, after which they then pick up the sheet for the next segment and the group continues working independently. This allows student groups to work at their own pace and permits the teacher to freely circulate and give assistance only where needed, while simultaneously having structured end-of-segment checkpoints by reviewing student work at the end of each instructional segment. This facilitates the ability to offer more time and attention to student groups who need that extra input, while not slowing down student groups that are ready to move forward independently.

Activity 3: Second message—A low-resolution letter

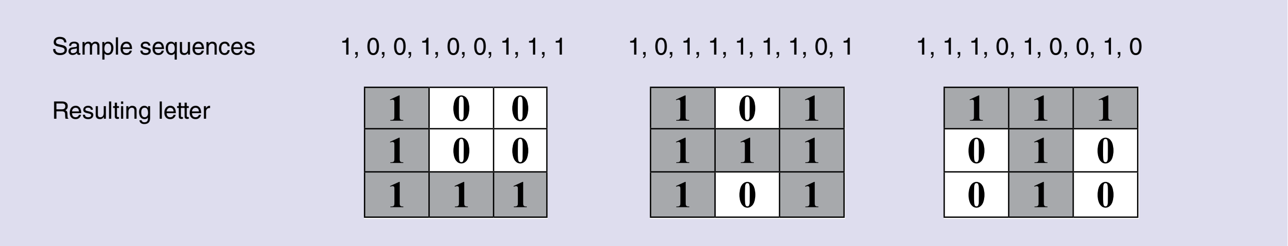
With the communication technology model now firmly established, the next transmission will send the letter *X* (see Figure 4) rather than a random stream of 0 and 1 digits. Students need to all be aware of the sequence for putting either a 0 or a 1 in each of the boxes in a 3 × 3 grid, which is typically done left to right, from top row to bottom. Once that ordering of received signals is clear in students' minds, then their streams of 0s and 1s would be recorded by the image generator in a 3 × 3 box they have drawn on grid paper, rather than recording the stream in one long, continuous line. A nine-digit stream of 0s and 1s will fill this 3 × 3 grid, with each 1 represented by a shaded cell and each 0 represented by a white cell.

After successfully sending the letter *X*, student teams will send out a few more low-resolution letters to each other. Taking turns with each role, a student creates a letter in a 3 × 3 grid by shading in cells to make a letter, such as those shown in Figure 5. The transmitter then generates the nine-digit code for the letter, and that code is sent to the receiver, who then tells the image generator whether to record a 0 or 1 in the "message grid," which is simply a blank 3 × 3 grid on the paper being used by the image generator. Finally, after the image generator shades in all of the 1s transmitted, the message grid should be the same letter as the one originally sent (see Figure 5).

Activity 4: Third message—Higher-resolution text

As a next step, solicit from students how they might be able to send higher-resolution text, and it will quickly become apparent that they need to use grids bigger

FIGURE 5 Sending a variety of letters



Sample sequences	1, 0, 0, 1, 0, 0, 1, 1, 1	1, 0, 1, 1, 1, 1, 1, 0, 1	1, 1, 1, 0, 1, 0, 0, 1, 0
Resulting letter	1 0 0 1 0 0 1 1 1	1 0 1 1 1 1 1 0 1	1 1 1 0 1 0 0 1 0

than 3 × 3. In fact, the more squares in the grid, the more resolution (for example, see Figure 6, the letter *X* on a 5 × 5 grid). Tell students that the technical term for these "squares" is *pixels* (picture elements). Figure 6 has a total of 25 pixels in it. Depending on the display system, pixel shapes can be rectangular, circular, or square. However, because that detail is tangential to the underlying purpose of this sequence of instruction, it really isn't important what shape the pixels are and doesn't need to be explained. It is helpful for the teacher to be aware of this detail, however, because students might bring other examples to show you or the class, such as a color picture made out of lots of tiny dots (in which case the pixels are those circular, tiny dots), but the conceptual understanding is identical independent of the shape of the pixel.

Students might use their spring-wave model to send a 25-pixel letter of their own creation for the experience. But for subsequent refinements in the model, for time purposes, it may be preferable to have students work with paper representations of the text or images they would send rather than actually sending them with the wave model. A student group that is substantially further along than others may be asked to generate and send a second or third 25-pixel letter, whereas student groups not as far along can just do one. Or those groups that are done first can generate the digital stream for a 25-pixel letter (which takes a bit of time) to be used by a subsequent group (it takes less time to simply enter the 0s and 1s in a grid and shade in the 1s). This involves both groups of students in active exploration of this technique for sending digital information via waves but reduces the time disparity among groups finishing the task. As the images continue to get more complex and higher in resolution, the time needed to send even one image grows quickly. Rather than having students actually send many of those signals via the spring-wave model, having them understand how it works and that computers are able to send such streams of 0s and 1s really, really fast might be more fruitful. The next instructional segment shifts student attention to these key features of computers—that they send digital information and can do it very, very fast.

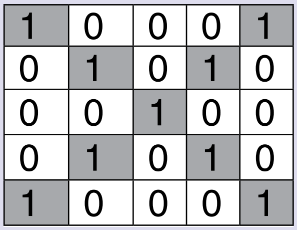
Activity 5: Connecting digital images to computer monitors

An interesting exercise is to have students determine the pixel resolution of a computer monitor. For most computers, this can be accomplished by going into the "Control Panel" and selecting "Display" (or something similar), where students will find a display properties screen with multiple tabs. A tab labeled "settings" or something similar will show the screen resolution in pixels. For example, my large-monitor computer has 2,560 × 1,440 pixels at the highest resolution. This resolution can be modified by the user; on my computer, the lowest resolution I could choose is 800 × 600 pixels. Students can also compute how many 0s and 1s are needed to fill their computer screen (in my case, 2,560 × 1,440 = 3,686,400). It would take over 3.5 million "pulse codes" of the spring to send a static picture to that monitor.

A natural follow-up question is how long it would take the computer to send those codes. If you have students go into "My Computer" and select "Properties," they will find general system properties of the computer, including the clock rate of the computer's central processing unit (CPU), which can be thought of as the computation speed. Although there really is no single speed for a computer (there are speeds for accessing hard drive, for various computer buses, for the CPU clock, etc.), the CPU clock speed is a good way for students to get a sense of how fast computers can send a stream of 0s and 1s. In my computer's case, the CPU clock speed on the "Properties" screen is 3.2 GHz (3.2 billion cycles per second). Dividing this by the number of pixels computed above, my computer could send 868 full pictures (of 3,686,400 pixels each) every second. Some computers employ two or four processors (dual core or quad core) working simultaneously, which means their capacity for computations goes up proportionally.

Some student groups may independently get this far with investigating computer resolution and clock speed, whereas other groups likely will not have time to do this independently as they finish up the prior instructional activities. This is a good point to bring the entire class back together and demonstrate how to find the resolution and clock speed of a computer, and have students do computations (total number of pixels per screen, how many screens per second are possible)

FIGURE 6 A higher-resolution letter with 25 pixels



1	0	0	0	1
0	1	0	1	0
0	0	1	0	0
0	1	0	1	0
1	0	0	0	1

after you have displayed the data for the class to see. This serves as a review for those groups that had the time to explore this independently and illustrates the key points for those that did not get that far.

Activities 6 and 7

For the rest of this instructional sequence, which covers grayscale, color, and digital movies, it may be most effective to primarily use direct instruction and ask students questions. The ideas found in the remainder of this instruction are likely to be new to most students, who will need fairly close guidance to make the conceptual journey outlined below. Interspersing the demonstrations or explanations with questions is an effective way to keep students mentally engaged. Making explicit connections to computers by demonstrating for students with a classroom computer will make the underlying purpose and relevance of the instruction much more obvious. Because some of the following ideas could come across to students as abstract and not very relevant to their lives, the computer connections, which include video games, are a vital element of this instruction.

Use classroom computers to stream a clip from a digital movie and show students current video games that include rich, detailed, 3-D graphics (available on YouTube), and ask them how digital signals are used to create these. Then, for comparison, show students clips of old ("classic") video games to illustrate the blocky nature of the graphics and motions that are very jerky by today's standards—a direct result of low resolution both spatially and in terms of refresh rate because of the much less powerful computers of 30 years ago. For example, a YouTube video called "Game Deaths" is a compilation of classic arcade deaths, including Pac-Man and Asteroids (see Resource). You may also want to highlight the blocky nature of the popular game Minecraft as an ironic throwback to blocky visuals. (The "Game Deaths" video includes cartoon violence; teachers should view it and decide whether it is appropriate to use this example with their students or if there are some students or families who might object.)

The remainder of this article presents the ideas and approaches in an information-delivery context, so that you are equipped with ideas on what to target with your students. Certainly it would be pedagogically valuable to pause at appropriate places to have students do a quick formative assessment—perhaps at a confusing point or point of most significance—or to do a quick-write on a topic you structure. Because teachers already have a wide array of options and experiences incorporating such formative assessment and will naturally incorporate it into the instructional sequence, the text below does not explicitly indicate when or which formative assessments may be used; however, it is helpful to remember to use those pedagogical tools when appropriate.

Activity 6: Beyond black and white—Grayscale and color

To begin leading students from their direct interactive experiences to connect with the state of video/computer digital media, the first step is to consider how to send a picture that is not just composed of black pixels and white pixels, but rather has shades of gray. In that case, a percentage gray could be assigned to each pixel rather than a simple black or white, so that the color of each pixel can be anything from 0% (white) to 100% (black). (To help students understand the concept of percentage gray, I show them the color options for shading cells in a spreadsheet—there is a list of a half dozen shades, with the darker shades having higher percentages [100% = black].) If you want control of the gray in 1% increments, you would need to have 100 different numbers available, each of which would be assigned a shade of gray. To make at least 100 different numbers out of a binary string of 0s and 1s would require a minimum of seven base-2 digits (which would enable 128 numbers to be coded). For historical reasons, and because the binary base of computers naturally leads to thinking in powers of two, a standard "chunk" of electronic information was typically coded in eight digits, called eight bits. A package of eight bits is called a *byte*. Thus, with eight bits, you have the opportunity to code 256 different numbers, from 0 to 255. So instead of each pixel being either black (a 1) or white (a 0), each pixel would be a gray color where the intensity of the grayness would vary across 256 shades of gray.

To send a grayscale picture to a 5 × 5 grid (25 pixels), each pixel would need a total of eight bits of information to know which shade of gray to become. Thus, you would need 25 pixels × 8 bits/pixel = 200-long stream of 0s and 1s to be sent. For my computer screen of 3,686,400 pixels, each pixel needs eight bits; this would require 29,491,200 digits to paint the whole screen in grayscale. At 3.2 GHz, that means it could send 108 screens full of grayscale pictures every second.

But what if we want to send pictures in color instead of grayscale? You can combine the three colors red, blue, and green in different proportions to get any color you want (light combines colors in an additive process, which is different from the subtractive process of color mixing with paints, and so the three primary colors for light are different from those for paint). Thus, you'll need eight bits of information to communicate the intensity of the red color you want for a pixel, another eight bits of information to specify the intensity of the blue color, and a third set of eight bits for the intensity of the green color. Thus, three sets of eight-bit chunks of information for each pixel will permit each pixel to display a desired color. The same display properties screen on your computer where the screen resolution is shown likely also has the color quality options shown (sometimes under "Advanced Settings") in terms of how many bits you'd like to use to specify a color. The more bits you use, the finer your control over the distinction in color intensity.

Activity 7: Beyond static images—Sending digital movies

To send a movie instead of a static image, the basic strategy is to send a quick series of pictures so fast that any changes from one to another will make it look like the picture is moving. This is the same basic principle used in flip-books, where each drawing of a simple picture slightly changes from one drawing to another (e.g., the arm is a little higher, and when flipping rapidly through the pages, it looks as if the arm is moving higher). The more pictures you have with tiny changes and the faster you flip the pages, the smoother the motion looks. If students have not yet been exposed to this idea, it might be useful to have them create a small flip-book so they can better understand how it works to produce the appearance of motion. You might have them begin their flip-books in class with guidance, then finish them for homework.

Standard rates of sending pictures to a computer monitor fast enough so that the human eye perceives it as smooth motion rather than a jumpy set of pictures are 30 or 60 pictures per second (also called "frames per second," which is measured in hertz). This is called the *refresh rate*. You can usually find the refresh rate for your computer monitor in the display properties screen mentioned earlier—sometimes in an "advanced" button.

If you want to send a color movie (three sets of eight bits for each pixel to code for the amount of red, blue, or green) to a computer monitor with 2,560 × 1,440 pixels at 30 frames per second, that would take a total of 2,654,208,000 bits of information per second. It would take a lot of spring shaking to do this using the physical model students started with. It is easy to see how lowering screen or color resolution can be a workable solution to images freezing up if your computer's processing speed can't keep up.

Modern communication

Although technical details of modern communication systems are overlooked with this simple physical model (e.g., compression algorithms that take advantage of the fact that very few pixels tend to change a lot from frame to frame), this modeling approach makes core scientific concepts underlying modern communications accessible to students. Connections to properties students can find on their own computers link *NGSS*'s increased emphasis on modern communication with students' everyday worlds.

As noted above, this set of instructional experiences also includes strong opportunities to seamlessly incorporate instruction on the scientific practice of Developing and Using Models, and with the emphasis on communication technology, there are many connections to engineering, as well. In particular, a key concept that could be included in your instruction could guide students to consider the ways science and engineering interacted historically that led to modern communication systems. As engineers were able to build faster and faster computers, the science of how that speed might be used to generate high-resolution images in full color, and later, streaming video, illustrates how progress in engineering can lead to progress in science. ■

References

American Association for the Advancement of Science (AAAS). 1993. *Benchmarks for science literacy.* New York: Oxford University Press.

National Governors Association Center for Best Practices and Council of Chief State School Officers (NGAC and CCSSO). 2010. *Common core state standards.* Washington, DC: NGAC and CCSSO.

National Research Council (NRC). 1996. *National science education standards.* Washington D.C.: National Academies Press.

NGSS Lead States. 2013. *Next Generation Science Standards: For states, by states.* Washington, DC: National Academies Press. *www.nextgenscience.org/next-generation-science-standards.*

Resource

Game Deaths—*www.youtube.com/watch?v=gJ6APKIjFQY*

Thomas Tretter (*tom.tretter@louisville.edu*) is professor of science education in the Department of Middle and Secondary Education at the University of Louisville in Louisville, Kentucky.