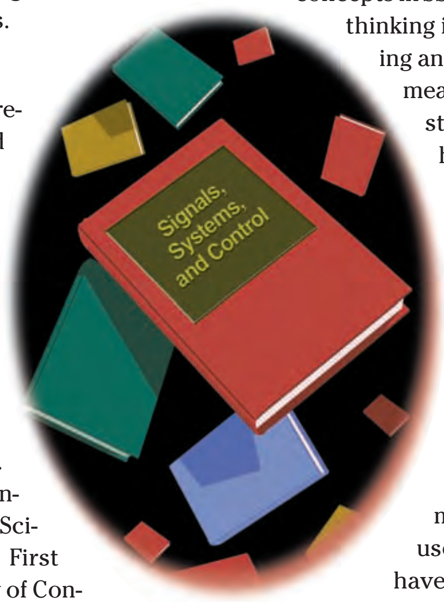
Introducing Signals, Systems, and Control in Grades K Through 12

By Dennis S. Bernstein

Signals, systems, and control (SSC) provide a powerful paradigm for intellectual thought in science and technology, yet these ideas have had virtually no penetration into grades K through 12 education. In this article I provide some suggestions for introducing these concepts into primary and secondary education, thus promoting their diffusion throughout the academic disciplines.

Motivation

This article has several distinct, but related, objectives. First, I have heard many of my signals, systems, and control colleagues describe how their interest and (sometimes irrational) dedication to the SSC field was instantly formed when they first encountered the SSC paradigm. "Everything just made sense" is not an uncommon description of the reaction many of us had when we were first introduced to this conceptual world view.



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Next, during the 2000 American Control Conference in Chicago, the National Science Foundation (NSF) sponsored the First NSF Workshop on Ideas and Technology of Control and Systems in High School Math and Science Education, organized by Prof. B. Pasik-Duncan under the direction of Dr. Kishan Baheti. This workshop provided a unique opportunity for a select group of high school instructors to be introduced to a field of intellectual and engineering endeavor that is invisible to most of our society. Not surprisingly, it became clear to me and many of the "control professionals" who attended the workshop that our SSC world view has had virtually no penetration into primary and secondary education. Yet I see no reason to believe that this must be the case. Certainly, there are concepts from SSC that can readily be appreciated at almost every educational level. Even very young children are entranced by toys that allow them to insert an object and watch another object emerge. Remote-controlled and self-operating toys are among the most fascinating.

Finally, an additional motivation for this article is the fact that the SSC viewpoint has significantly broader usefulness than its traditional home in circuits, communications, and control. Many other disciplines such as the biological sciences can benefit from problem formulations that adopt the concepts and tools of systems theory. By introducing SSC concepts at a younger level, we have a greater chance of broadening their penetration into science and technology at all levels. The time to do this is long overdue.

The purpose of this article is to introduce some basic concepts in SSC at the K-12 level. My goal is to stimulate thinking in the SSC paradigm for classroom learning and science fair projects. This article is not meant to be a tutorial on these topics for K-12 students and instructors, although it is hoped that it will attract the attention of some members of that community. Ultimately, it is the responsibility of SSC students, educators, and practitioners to take the lead in disseminating these ideas within the K-12 world. It is my hope that this article will stimulate the formulation of objectives that our community can pursue in achieving this critical goal.

Throughout the discussion, I have made a deliberate attempt to avoid the use of overly technical language, although I have introduced several terms of fundamental importance. Precise definitions are not provided; rather, the meaning of these terms may be inferred from context.

Signals

When we wave "hello" to a friend we are sending a *signal*. Even our facial expressions transmit signals, showing whether we agree or disagree with what someone is saying. When we talk to someone, our words form a signal. This kind of signal can be transmitted in person, over the phone, through writing on a piece of paper, or through e-mail. These signals can be formulated in many different *languages*.

When we turn on the radio, television, or computer, we are receiving signals. With television and the computer we can receive signals that consist of both audio and video. These signals convey *information*.

But signals can have many forms besides words and pictures. For example, when you put money into a soda machine, you are sending a signal to the machine that you wish to purchase a soda. Presumably, the vending machine has a language of its own, so money does talk.

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A signal can also be *physical*. For example, when you throw a baseball, your arm is sending a signal to the ball, "telling" it which way to go. The signal is a *force* that makes the ball accelerate. Similarly, the engine in a car makes the car move by sending it a force signal as well.

All signals must travel along *channels*, and all channels have a limited *capacity*.

Here are some questions to consider concerning signals and languages:

- Two people are "speaking" to each other using sign language. How is the signal transmitted? Can you think of any advantages of this kind of signal even if the people who are using it are not hearing impaired? Can you think of any disadvantages? (Hint: What is the channel?)
- Is music a signal? What if the music has no words, just instruments? Does music have a language? (Hint: How can you tell when a piece of music is near the beginning or end?)
- Most televisions today have remote control devices. How do these devices use signals? Do they have a language?
- Most sports use umpires or referees. How do these officials use signals? What is their language?
- A police officer is directing traffic. Explain how the officer uses signals and language.
- A person driving a car puts a foot on the gas pedal and then on the brake pedal. Explain these signals.
- Some roads have only one lane in each direction, but some highways have four lanes in each direction. Compare the capacity of these channels.
- If you listen to music through the telephone, it sounds rather poor. AM radio is better, and FM radio is best. Why? (Hint: These channels have a different *bandwidth*, which determines whether the high frequencies in the music can pass through the channel.)

Systems

A *system* is different from a signal. A system usually involves two signals; one signal is the *input* while the other signal is the *output*. The input goes into the system, and the output goes out of the system.

The soda machine is a system. The money you put into the machine is the input, and the can of soda that comes out of the machine is the output. The money and the soda can are signals.

The baseball is a system. The input is the force you apply to the baseball in a particular direction. The output of the system is the way the ball flies, including its speed and direction.

When you speak to someone, the person you are speaking to is a system. The input to the system is the words that you speak and the expressions on your face that the other person hears and sees. The output from the system is the other person's words and facial expressions when reacting to what you have to say.

A car is a system. The input signal is the force provided by the engine, which ultimately makes the car move. The output of this system is the speed of the car, which is measured by the speedometer.

Physical systems have devices to help them respond to inputs. An *actuator* is an input device, and a *sensor* is an output device. The engine of the car is an actuator, and the speedometer is a sensor. A sensor is used for *measurement*.

Here are some questions to consider concerning systems:

- What are some sensors on a car besides the speedometer? (Hint: How do you check how much gas is in the tank or how hot the engine is?)
- Is a flashlight a system? If so, what is the input and what is the output?
- Suppose you open a bank account that pays interest. Is this a system? If so, what are the input and output?

It is useful to analyze systems in terms of their properties. An important system property is *gain*, which compares the size of the output signal to the size of the input signal. For example, imagine a seesaw that is not centered. When the short side of the seesaw moves a certain distance (this is the input), then the long side of the seesaw (the output) moves farther. The gain of the system is greater than one, so it is an *amplifier* of distance. A system with a *resonance* has very high gain for input signals at a certain *frequency*.

- Explain how a seesaw is a force amplifier. Can a seesaw amplify distance and force at the same time?
- A pulley is often used to lift heavy weights. Explain how this system amplifies force.
- A football coach talks into a megaphone. Discuss the gain of the system.
- Turning the steering wheel on a car causes the wheels to turn. What is the gain of this system?
- Someone bought a lottery ticket and won the jackpot. What is the gain of this system? Can it change?

Another important system property is its *phase shift*, which compares the time shift of the input and output signals.

- A mother pushes her daughter on a swing. She only pushes the swing when it is at its highest point. Discuss the gain and phase shift of the system. Does the system have resonance?

A system is *linear* if adding two inputs together gives an output that is the sum of the separate outputs.

- Is the soda machine linear? In other words, if you put in twice as much money, do you get twice as much soda?
- A store has an item on sale: Buy one for regular price, or buy two and get one free. Discuss the gain of the system. Is the system linear?
- An employee gets paid time and a half for working on the weekend. Is this a linear system?

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- You can run a mile in 8 minutes with moderate effort. When you try twice as hard, you run a mile in 7.5 minutes. Is this a linear system? Why?

Control

Control is used to improve the performance of a system. If the output of a system does not follow a desired *command*, then the *error* can be used to change the input so that the output is more desirable. This is *feedback*. For example, consider a car driving on a road. A bump in the road causes the car to swerve slightly out of the lane. The driver sees this and adjusts the steering wheel to return to the center of the lane. This is a *servo* problem: The error between desired motion and the actual motion is used to modify the input to make the error smaller.

- A car has cruise control. How is this a servo system? What is the command? What are the inputs and outputs in the feedback loop?
- A baseball player is trying to catch a fly ball. How is this a servo system?
- A dog is chasing a cat. How is this like a servo system?
- A person is learning to play the piano. How is this like a servo system?

Another important use of feedback control is for *stabilization*. A broomstick standing on its end will fall over unless it is stabilized. Here are some questions to think about:

- When you balance a broomstick, how do you do it? What is the actuator? What is the sensor? Is more than one sensor involved?
- Now try to balance sticks of different lengths. Which ones are harder to balance, shorter or longer sticks?
- Do humans need stabilization to stand up? Try to stand perfectly still. Are you able to do it? How much harder is it to stand still with your eyes closed? What sensors and actuators do you use to stand up?
- If you sit on a bicycle without moving, you fall over. But you don't fall over if you're moving forward. Why?
- When you have a fever, your temperature goes up. Then you take some medicine and your fever goes back down. Is this stabilization?
- A student takes a quiz in school and gets a low grade. The student studies hard for the next quiz and gets the highest score in the class. Is this stabilization? Is it feedback?
- Two people are talking on the phone, but the connection has a *delay*. Soon, they're talking over each other. Why is a delay bad for the stability of a feedback loop?

Conclusions

Although signals, systems, and control ideas are not taught until post-secondary education, I have tried to suggest here that their introduction in K-12 is feasible and desirable. Why do so? Simply put, SSC ideas provide a universal intellectual paradigm that is broadly applicable in both scientific and nonscientific areas of the curriculum. These ideas, which are highly intuitive, can strengthen the traditional K-12 curriculum by providing simple paradigms for exploring a wide range of topics.

Of course, the development and testing of effective curriculum material based on SSC ideas remains to be done. Such development provides an opportunity for the SSC community to contribute to K-12 education by strengthening an institution that is vital to our society.

For Further Reading

The systems point of view was the life's work of the mathematician Norbert Wiener. His classic writings include

N. Wiener, *Cybernetics: Or Control and Communication in the Animal and the Machine*, 2nd ed. Cambridge, MA: MIT Press, 1961.

N. Wiener, *The Human Use of Human Beings: Cybernetics and Society*. Boston, MA: Houghton Mifflin, 1954; reprinted by New York: Da Capo Press, 1988.

N. Wiener, *Invention: The Care and Feeding of Ideas*. Cambridge, MA: MIT Press, 1994.

There is limited popular writing on control ideas. Exceptions are

S.W. Angrist, *Closing the Loop: The Story of Feedback*. Reading, MA: Addison-Wesley, 1973.

K. Kelly, *Out of Control*. New York: Crowell, 1994.

For some thoughts on the teaching of control at the university level, see

D.S. Bernstein, "Enhancing control education," *IEEE Contr. Syst. Mag.*, vol. 19, pp. 40-43, Oct. 1999.

For tutorials on control topics, see

D.S. Bernstein, "A student's guide to classical control," *IEEE Contr. Syst. Mag.*, vol. 17, pp. 96-100, Aug. 1997.

D.S. Bernstein, "The frequency domain," *IEEE Contr. Syst. Mag.,* vol. 20, pp. 8-14, Apr. 2000.

D.S. Bernstein, "What makes some control problems hard?" *IEEE Contr. Syst. Mag.,* vol. 22, pp. 8-19. Aug. 2002.

Acknowledgments

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