Introducing Signals, Systems, and Control in K-12

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Abstract

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

Motivation

This paper has several distinct, but related, objectives. First, I have heard many of my signals, systems and control (SSC) 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 a not uncommon description of the reaction many of us had when we were first introduced to this conceptual world view.

Next, during the 2000 American Control Conference in Chicago, 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. This workshop provided a unique opportunity for a select group of high school instructors to become 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 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 academic level. Even very young children are fascinated by toys that allow them to insert an object and watch another object emerge. Remote-controlled or self-operating toys are among the most fascinating.

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

The purpose of this paper is to introduce some basic concepts in SSC at the K-12 level. My main goal is to stimulate thinking in the SSC paradigm for classroom and science fair projects. This paper 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.

Throughout the discussion I have made a deliberate attempt to avoid the use of overly technical language, although I have introduced several words 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, though writing on a piece of paper, or through email. 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 receive signals that have 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 soda machine has a language of its own, so money does talk.

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 move. Similarly, the engine in a car makes the car move, and it is sending a force signal to the car.

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?
>
> 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 policeman is directing traffic. Explain how s/he uses signals and language.
>
> A person is driving a car. They put their foot on the gas pedal and then on the brake pedal. Explain these signals.

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 soda that comes out of the machine is the output. The money and the soda 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, height, and direction.

When you speak to someone, then that person is a system. The input to the system is the words that you speak and the expressions on your face, which the other person hears and sees. The output from the system is the words that they speak and the expressions on their face when they react 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 wheels turn. 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?
>
> Is a flashlight a system? If so, what is the input and what is the output?
>
> Suppose that 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 the various properties that they have. For example, a system is *linear* if adding two inputs gives an output that is the sum of the two outputs due to the separate inputs.

> Is the soda machine linear?
>
> A store has an item on sale: Buy 2, get 1 free. Is this a linear system?
>
> A worker gets paid time and a half for working on the weekend. Is this a linear system?
>
> 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?

Another 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 pulley is often used to lift heavy weights. Explain how this system amplifies force.

Turning the steering wheel on a car causes the wheels to turn. What is the gain of this system?

Someone bought a lottery ticket for $1 and won $1000. What is the gain of this system? Can it change?

Control

Control is used to improve the performance of a system. If the output of a system is not as good as might be desired, the output 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 choose the input to make the error smaller.

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 sticks or longer sticks?

Do humans need stabilization in order 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?

Conclusions

Although signals, systems, and control ideas are not taught until post-secondary education, I have tried to suggest here that their introduction is feasible in K-12. Why do so? Simply put, SSC ideas provide a universal intellectual paradigm that is broadly applicable. These ideas are abstract yet highly accessible, and they can significantly strengthen the traditional K-12 curriculum.

References

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

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

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

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

There is limited popular writing on control ideas. An exception is

K. Kelly, *Out of Control*. Reading: Addison-Wesley, 1994.

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

D. S. Bernstein, “Enhancing Control Education," *IEEE Contr. Sys. Mag.*, Vol. 19, pp. 40-43, October 1999.