Chapter 5
Fostering Systems Thinking in the Context of Electronics Studies

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Abstract Systems thinking is considered a major higher-order thinking skill essential for successful integration in areas such as science, technology, engineering, or management sciences. However, this term has remained somewhat vague and is defined or represented through diverse models or characteristics lists. In the present chapter, we address this challenge by identifying a cluster of systems thinking characteristics related to learning electronics in school and demonstrate how these characteristics correspond with home appliances familiar to any learner: room heating devices, an air conditioner, and a sound system. For example, a heat projector works without feedback (open-loop control); heat diffusers and air conditioners work with negative feedback, often by a thermostat; an unwanted sound may appear in a sound system due to the positive feedback from a microphone placed in front of the speaker. The final section of the chapter underlines four key aspects of systems thinking: modelling, STEM view; the role of the engineer and the technologist; and innovation. Two instructional approaches for fostering systems thinking in the science and technology, constructivist pedagogy and digital pedagogy are also discussed.

Keywords Air conditioner · Feedback control · Modelling · Sound system · STEM view · Systems thinking characteristics

5.1 Introduction

Four major revolutions in the history of technology development can be identified in the modern era (Pouspourika, 2019). The First Industrial Revolution (from 1760) included the invention of the steam engine, and the use of water and steam power to mechanise production. This caused industry to replace agriculture as the backbone of the societal economy. The Second Industrial Revolution (from 1870) included the emergence of new energy sources—electricity, gas, and oil; the creation of the internal combustion engine; the increasing steel demand and chemical synthesis;

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and the development of electrical energy and communication methods such as the telegraph and the telephone. Finally, the inventions of the automobile and the plane at the beginning of the twentieth century, which are the reasons why, to this day, the Second Industrial Revolution is considered the most important one. The Third Industrial Revolution in the second half of the twentieth century brought forth the rise of electronics, telecommunications, computers, and the Internet. These new technologies opened the doors to many new fields such as space expeditions, biotechnology, cellular communications, robotics, and high-level automation. According to Schwab (2016), the current Fourth Industrial Revolution (IR 4) is fundamentally changing the way we live, work, and relate to one another. This revolution is a fusion of advanced areas such as artificial intelligence (AI), robotics, the Internet of things (IoT), 3D printing, genetic engineering, and quantum computing.

One can see that electricity and electronics are unquestionably at the heart of the last three technological revolutions mentioned above. Teaching electronics plays an essential role as part of technology education which prepares students for the changing technological world, develop learners' systems thinking and foster their often called twenty-first-century skills such as problem-solving and creativity, critical thinking, collaboration, metacognition, and motivation (Hilton, 2010). However, the traditional way of teaching electronics is no longer relevant (Barak, 2018). In the past, analogue electronics courses started with learning about specific electronics components such as a diode, a transistor, and an operational amplifier; digital electronics courses started with learning about discrete components such as OR, AND, and XOR gates or a digital counter. Today, engineers and students are building electronic and control systems, for example, robotics, using ready-made modules such as power amplifiers, electronic sensors, motors, and digital micro-controllers.

The transition from designing electronic circuits having discrete components to the construction of sophisticated control systems with ready-made modules such as microcontrollers, which occurred developmentally in the market and in education, has created a rational basis for fostering students' systems thinking, for example, understanding aspects of energy, power, feedback loop, and dynamic response of technological systems (Barak & Williams, 2007). However, little work has been done to date to identify a cluster of specific systems thinking principles relevant to high school technology and electronics engineering studies. For example, Yakymenko et al. (2020) refer to STEM as a context for developing systems thinking among electronics engineering students; Chen (2003) addresses systems thinking in the context of using the programmable logic controller (PLC) system; Zuckerman and Resnick (2003) write about a physical interface for system dynamics simulation. Holstien and Bode (2015) describe systems engineering as a technique for applying knowledge from other branches of engineering and disciplines of science in effective combination to solve multifaceted engineering problem. However, all these examples of promoting systems thinking do not classify a structured set of systems thinking aspects relevant to the high school students' world.

In the present chapter, we address this challenge by identifying a set of systems thinking characteristics related to learning electronics in school and demonstrating how these principles correspond with home appliances familiar to any learner: room heating devices, an air conditioner, and a sound system. The final section of this chapter underlines pedagogical aspects of fostering systems thinking in the science and technology class.

5.2 Characterising Systems Thinking

Systems thinking is considered a major higher-order thinking skill essential for successful integration in areas such as science (Orgill et al., 2019; Riess & Mischo, 2010), technology (Hallström & Klasander, 2020), engineering (Frank, 2002), and management sciences (Daellenbach et al., 2012). Although this concept has been discussed for decades in the literature of these fields, it has remained somewhat vague and is defined or represented through diverse models or characteristics lists. In this section, we identify several characteristics of systems thinking that will be examined in the context of teaching electronics.

Chan (2015) writes that a system could mean a set of physical parts of a bigger whole, for example, the structural system of a building or the traction control system of an automobile. Therefore, one aspect of systems thinking involves identifying the parts of a whole or the factors that are important for an outcome. According to Amissah et al. (2020), systems thinking aims at understanding relationships between components and their overall impact on a system's intended and unintended outcomes. Systems thinking is also associated with seeing the 'big picture' or macro-view of things as opposed to a more detailed microscopic view, and it allows one to comprehend how all the pieces fit together to explain how all the parts act to produce the intended effect. Chan (2015) stresses that systems thinking has to do with the ability to 'see the forest from the trees' and solve a problem in a balanced and holistic way, rather than focusing narrowly on only one aspect of the problem. Anderson and Schönborn (2008) associate systems thinking with experts' thinking. Barak (2018) suggested that systems thinking involves identifying and understanding concepts such as the parts and structure of a system; the factors that are important for an outcome; the 'big picture' or macro-view; system boundaries; function and behaviour; feedback in a system; system dynamics; and non-functional properties such as safety and reliability that arise from the interaction between parts of a system.

Hallström and Klasander (2020) suggested the following 11 'clustered groups of concepts' that characterise technological systems: (1) the technical core of a system; (2) hierarchies, sub-systems, components; (3) connections and wholeness; (4) system boundary and surroundings; (5) isolated, closed or open systems; (6) control, feedback and flow of information; (7) system functions and behaviour, processes, models; (8) scale and complexity; (9) dynamics, development, change; (10) socio-technological perspectives; and (11) systems for innovation, conditions for productions.

Arnold and Wade (2015) reviewed seven definitions of systems thinking, including those of Richmond (1994), Senge (1990), Sweeney and Sterman (2000), Hopper and Stave (2008), Kopainsky et al. (2011), Squires et al. (2011), and Forrester (1994).

Arnold and Wade (2015) identified 10 aspects of systems thinking recurring in the various definitions suggested by the above-mentioned researchers. They also counted how many researchers out of seven included each aspect in their model, as displayed in parentheses in the following list: Whole rather than parts (4); Interconnections/interrelationships (4); Feedback loops (4); Dynamic behaviour (4); System as the cause of its behaviour; System structure generates behaviour (2); Stock and flow relationships (2); Nonlinear relationships (2); Delays (1); and Acknowledgment that systems are important (1).

In summary, we have seen several lists of aspect of technological systems and systems thinking, even though they overlap to some extent. In the following sections of this chapter, we will address the following seven key characteristics of systems thinking derived from a synthesis of the just cited literature and most relevant to electronics teaching:

W—Whole rather than the parts: recognising system properties that are the outcome of the interaction between system ingredients and cannot be related to a specific component.

I—Interconnections/interrelationships: understudying the flow of information and energy in a system.

F—Feedback loops: realising the process of setting a desired value to a controlled variable, measuring the actual value in real time, and regulating system operation to reduce deviation.

D—Dynamic behaviour: observing change of a variable in a system, for example, an increase or decrease, which depends on time.

B—System boundaries: identifying the border between internal processes and external entities that may affect the system but are unaffected by it.

T—Technological innovation: realising the invention of new products or services that answer needs or may push the market forward.

S—Socio-technological implications: appraising social, economic, or environmental implications of a system.

Figure 5.1 shows that the seven characteristics of systems thinking mentioned above partially overlap and that there is no built-in hierarchy between them. For example, seeing the ‘whole rather than the parts’ is associated with identifying ‘interconnections and interrelationships’ and understanding ‘socio-technological implications’ of a system. It is also worth noting that not all of these principal aspects are necessary to describe a system, but they depend on the complexity of the system in question.

In the following sections, we will explain and demonstrate how the seven characteristics of systems thinking W, I, F, D, B, T, and S presented in Fig. 5.1 are expressed in three technological systems—room heating devices, an air conditioner, and a sound system, and how to teach this subject in order to foster systems thinking in these contexts.

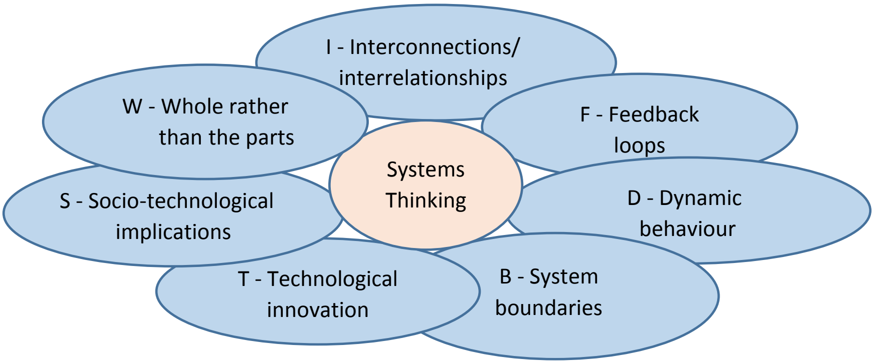


Fig. 5.1 Principal characteristics of systems thinking in a technological context

5.3 Pedagogy for Teaching Aspects of Systems Thinking

It is widely agreed that the traditional teacher-centred instruction contributes very little to fostering higher-order cognitive skills such as systems thinking. Consequently, education today aims at implementing student-centred instruction in class derived from the constructivism learning theory. Constructivist concepts of learning, which have their historical roots in the work of Dewey (1929), Bruner (1961), Vygotsky (1962), and Piaget (1980), call to engage students in problem-solving and critical thinking regarding authentic learning activities that learners find relevant and engaging (Briner, 1999; Brown et al., 1989). Therefore, it is desirable to teach systemic thinking in the context of technological systems with which students are familiar with everyday life. Hallström and Klasander (2020) suggest more specific pedagogies for teaching technological systems to secondary school students:

1. **Interface pedagogy**: starting with the interface between the supposed system and the human being using it, for example, exploring the hidden system in a smartphone or ATM machine.
2. **Holistic pedagogy**: starting with a known technological system, for example, the railway, and moving from the wholeness to identifying sub-systems and significant components.
3. **Historical pedagogy**: following the historical development or changes in a system, for example, the telephone, from a previous point in time to the present, or vice versa.
4. **Design pedagogy**: designing, 'making', and improving a product or a technological system of appropriate complexity (pp. 73–74).

The instructional pedagogies suggested by Hallström and Klasander go hand-in-hand with the broad notion of constructivist pedagogy that has played a key role in the educational literature of recent decades. However, educators should be aware of the limitations and difficulties in implementing students-centred instructional methods in school, and especially the need to adapt instruction to students' prior knowledge and skills, as will be discussed later in this chapter.

The four pedagogies mentioned above (Hallström & Klasander, 2020) guided us in focusing the present chapter on three familiar technological systems: home heating devices, an air conditioner, and a sound system, as discussed in the following sections.

5.4 Aspects of Systems Thinking in the Context of Room Heating Devices

The first example for promoting systems thinking in electricity and electronics we present in this chapter relates to two different room heating devices, the heat projector shown in Fig. 5.2 and the hot air diffuser shown in Fig. 5.3.

Let us look at these devices considering the seven aspects of systems thinking we are addressing in this chapter (Fig. 5.1).

5.4.1 Seeing the 'whole Rather Than the Parts' of Heating Devices

Seeing the 'whole rather than the parts' relates to understanding the purpose of a system, its main components, how it works, and its suitability to user needs. This aspect is central to systems thinking, as has been mentioned by many researchers (Arnold & Wade, 2015; Chan, 2015; Frank, 2002). Comparing two or more similar products (as we often do in a store) and listing their pros and cons may help in understanding the features of each system.

Fig. 5.2 Heat projector

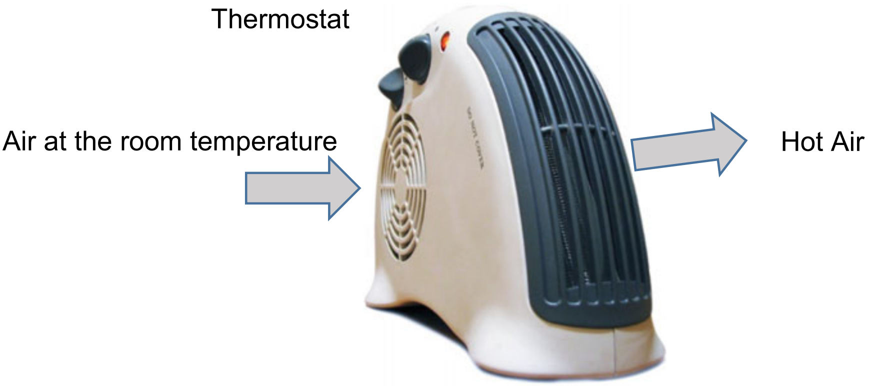
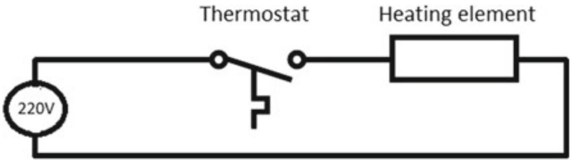


Fig. 5.3 Hot air diffuser with a thermostat

Fig. 5.4 Thermostat control over a heating element



The heat projector main components are heating two elements and on/off switches. The device converts electrical energy into heat energy.

Pros: Quickly heats the air around the device.
Cons: Keeps heating even when the temperature is very high. Could cause a fire.

The main components of the hot air diffuser are a heating element, a blower that draws air at room temperature and dissipates it back to the room at a higher temperature, and a thermostat that stops heating when the temperature reaches the desired value, as shown in Fig. 5.4. The device also converts electrical energy into heat energy.

Pros: Disperses heat over a wide area; stops heating when the air temperature reaches the desired value.
Cons: Does not provide powerful heating near the device.

5.4.2 *Interconnections/Interrelationships Between Components in Heating Devices*

To identify interconnections or interrelationships in a system, one needs to understand how the main components in the system relate to each other, and how information signals and energy flow in the system. In the case of the heat projector, we can describe the flow of energy as follows:

Electrical supply (110 or 220 V) > manual power switch > heating element > heat radiation to the environment.

The interconnections and interrelationships related to the hot air diffuser could be described as follows:

Electrical supply (110 or 220 V) > automatic thermostat switch > heating element > heating air streamed created by a fan > heat diffusing to the environment.

The textual presentation above shows the structure and interconnections of the components in the two heating devices but indicates only indirectly the most important difference between the two electrical devices—the fact that only the hot air diffuser included a feedback loop, as presented in the following section.

5.4.3 Feedback Loop with a Thermostat

The thermostat is the heart of the hot air diffuser control system because it:

- is used to set up the desired temperature by the user,
- measures the actual temperature of air in the room,
- turns the heating element on/off according to the measured temperature.

In the professional language, this is called a feedback loop or a feedback control system, and it is usually described by a block diagram, as shown in Fig. 5.5.

In Fig. 5.5, the minus sign at the feedback signal indicates that when the temperature in the room increases, the thermostat turns the heating off, and vice versa. In other words, the negative feedback stabilises the controlled variable—the temperature.

Although many home or industrial heating or cooling appliances use a mechanical thermostat, this device is frequently replaced by modern electronic sensors and control systems. However, all of them follow the same control process described above.

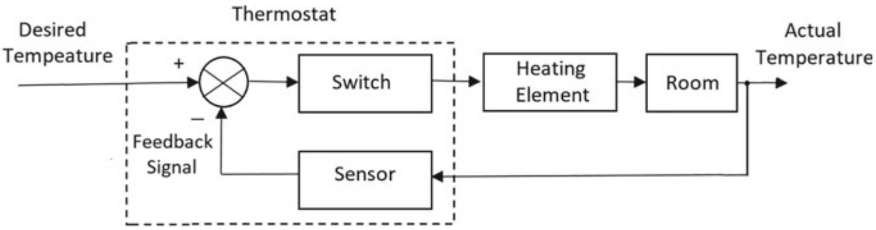


Fig. 5.5 . Block diagram of a thermostat's temperature control system

5.4.4 Dynamic Behaviour of Temperature in a System

The term dynamic behaviour relates to a description of how a system or an individual unit functions with respect to time (McGraw Hill Dictionary of Scientific & Technical Terms, 2003a, 2003b). Barak and Williams (2007) noted that at the heart of systems thinking in scientific, technological, and social contexts lies the analysis of the change with time of physical or social variables, such as the temperature of air or a mass, the volume of water in a tank or the number of products in a warehouse. Analysis of dynamic processes frequently relates to the instantaneous value of a specific variable, its rate of change (derivative), or accumulation (integral) with time. Hallström and Klasander (2020) note that system dynamics is one of the most important characteristics of technological systems.

In referring to temperature control by a thermostat, we have seen that when the air temperature in the room reaches the desired value, the thermostat turns the current to the heating element off; when the temperature drops below the desired value, the thermostat turns the heating on. To avoid turning the heating on and off too frequently, the thermostat has a 'cyclical' range (also called a hysteresis range) of several degrees. For example, as shown in Fig. 5.6, if the required temperature is set to 20 °C (set point) the thermostat holds the heating on until the actual temperature reaches $T1 = 21$ °C and turns the heating off until the temperature decreases to $T2 = 19$ °C.

Regarding the process described in Fig. 5.6, the larger the hysteresis range $T1$-$T2$, the longer the thermostat switching times are on/off. It should be noted that a rise or fall in temperature does not occur at a constant rate but according to an exponential function, according to which the rate of change (rise or fall) decreases depending on time (Barak & Williams, 2007). In summary, we have seen that in temperature controlled by a thermostat, we do not get a constant temperature at the desired value but a dynamic response in which the temperature rises and falls cyclically around

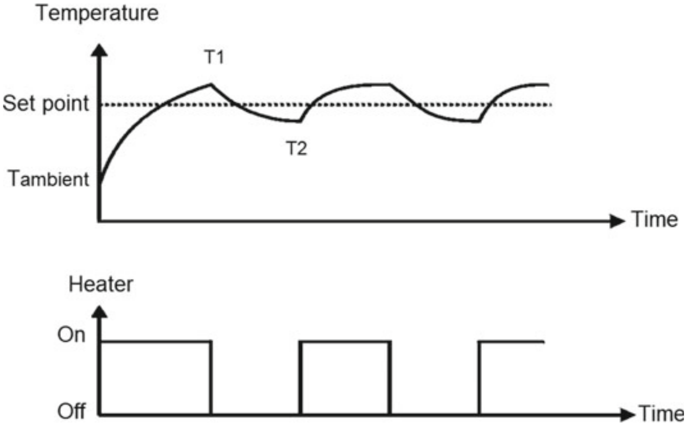


Fig. 5.6 Temperature control by a thermostat with a cycling range

the desired value. This phenomenon also exists in other temperature control systems using a thermostat, such as a baking oven, refrigerator, or air conditioner, as shown in the next section.

5.4.5 System Boundaries

We saw that the term system boundary refers to the border or distinction between internal and external objects or processes in a system. According to Lavi and Dori (2019), external entities of a system are objects and processes that affect the system but are unaffected by it. Internal objects and processes affect system operation and are affected by external entities. With respect to a heat projector and hot air diffuser, external components are, for example, the structure of the room, the outside temperature, and the thermal isolation of the windows, walls, and ceiling. These entities could affect the temperature in a room but are not affected by the heating or cooling devices.

5.4.6 Innovation

The heat projector and hot air diffuser are rather simple devices and have relatively little room for innovation. An advanced heat diffuser may include, for example, a mechanism that rotates the appliance to the right/left for optimal hot air distribution, a water tank to increase humidity in the room, a timer for automatic shut-off after a limited time, and a safety switch to stop heating in case the appliance overturns.

5.4.7 Socio-Technological Implications

The heat projector and hot air diffuser both convert electrical energy into heat energy and are considered heavy electricity consumers. Not only does the user pay a higher price for the electricity consumption of these devices, the devices also contribute to environmental pollution due to electricity production in power stations.

5.4.8 Summary

Up to this point, we have used the examples of a heat projector and a hot air diffuser to illustrate four of the seven concepts related to systems thinking that we are focusing on in this chapter (Fig. 5.1): seeing the whole rather than the parts; interconnection/interrelationships between system components; a feedback loop by the thermostat; and dynamic behaviour of the controlled variable. In the following sections, we will address further aspects of systems thinking in the context of technological systems and discuss how to teach systems thinking in class.

5.5 Aspects of Systems Thinking in the Context of an Air Conditioner

The second example of fostering systems thinking in the context of learning electronics engineering is the case of the air conditioner, a complex electro-mechanical device found today in many homes and offices. We chose to present this example because it combines aspects of energy conversion, control, electricity, electronics, mechanics, and computing. Below we will examine the air conditioner system from the perspective of the seven aspects of systems thinking we are focusing on in this chapter (Fig. 5.1).

5.5.1 Seeing the Whole Rather Than the Parts

A modern air conditioner can be used for cooling or heating a room or larger spaces. Our explanation relates to a split-system air conditioner, as shown in Fig. 5.7.

Regarding the air conditioner, seeing the whole rather than the parts means understanding that when the internal part of the air conditioner draws air from the room and cools it, the heat energy is transferred to an external device, which dissipates it outside. The air conditioner does not transfer air from the room outside, or vice versa.

Fig. 5.7 Split-system air conditioner

5.5.2 Interconnections/Interrelationships in an Air Conditioner

To understand the interconnections/interrelationships between components in an air conditioner, one must identify the main components of the system and how they are connected or related to each other, as shown in Fig. 5.8.

Figure 5.8 shows that the main components of the air conditioning system are:

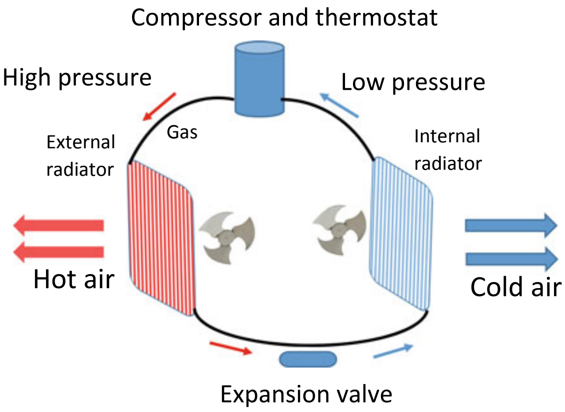
- Internal radiator,
- External radiator,
- Compressor controlled by a thermostat,
- Refrigerant gas,
- Expansion valve.

Understanding the function of each component and their interconnections or interrelationships is a key in understanding how the air conditioner system works.

From physics theory, we know that when a liquid is converted into a gas in a process called phase conversion, it absorbs heat. When a gas is converted into a liquid by high pressure, it emits heat. Air conditioners exploit this feature of phase conversion by forcing a special gas to evaporate and condense periodically in a closed system of coils. The compressor drives the gas in a circular manner between the two radiators:

- On the evaporator side (internal radiator), the compressor sucks in the gas, i.e. creates a low pressure. The gas draws heat from the environment, i.e. emits cold air.
- On the condensing side (external radiator), the gas is compressed to a high pressure and is converted into a liquid. In this process, the radiator emits heat to the environment.

Fig. 5.8 Main components of an air conditioning system



The expansion valve plays an important role in the process described above because it causes the gas to change from a high pressure to a low pressure, as shown in Fig. 5.8.

It is worth mentioning that modern air conditioners are also designed to heat a house on cold days. For this purpose, the gas system in the air conditioner includes a ‘reverse valve’ (not shown in Fig. 5.8) that reverses the gas flow direction between the two radiators so that the inside radiator is the condenser, which emits heat to the room, and the outside radiator is the evaporator unit, which absorbs heat from the environment.

In summary, understanding the interconnections/interrelationships in an air conditioner requires knowing keywords related to an air conditioning system, such as internal and external radiators, gas, compressor, and thermostat. More challenging is understanding the process of gas condensation and evaporation that causes the emission and absorption of heat energy.

The compressor, which does the ‘hard work’ of an air conditioner, includes an electrical motor and a mechanical compressor, as shown in Fig. 5.9.

In Fig. 5.9, we can see on the right side of the compressor the connection points of the pipes for the gas input and output to/from the compressor. On the left side are the wire connections for the electricity supply. The electric power supplied to the compressor motor determines the intensity of the air conditioner. For example, an air conditioner of 1 HP (736 W) power can cool or heat a relatively small room inside an apartment.

Fig. 5.9 Air conditioner compressor

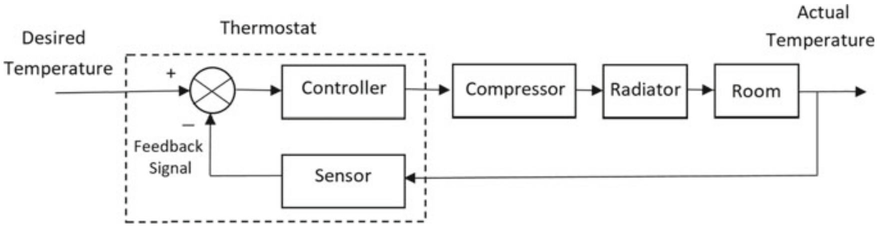


Fig. 5.10 Block diagram of an air conditioner control system with a thermostat

5.5.3 *Feedback Loop with a Thermostat*

Most air conditioners today are controlled by either a mechanical or electronic thermostat. Like in the example of a hot air diffuser we saw in the previous section, the air conditioner thermostat does the three basic actions of a feedback system:

- **Measures** the actual value of the controlled variable—the temperatures.
- **Compares** the measured values to the desired value.
- **Amends/regulates** the process to achieve the desired value.

As we saw in the previous example of temperature control by a heat diffuser, it is common in technology and engineering to represent a system with a block diagram that shows the main components and signals in the system, as shown in Fig. 5.10.

The minus (−) sign near the feedback signal arrow indicates 'negative feedback': when the measured temperature increases too much, the thermostat turns the compressor on to cool the room; when the temperature decreases too much, the thermostat turns the compressor off to stop cooling the room. In other words, the negative feedback stabilises the temperature in a required range.

5.5.4 *Dynamic Behaviour*

In the previous example relating to the hot air diffuser, we have seen that for temperature control by a thermostat, the temperature in the room is not constant but rises and falls in cycles (Fig. 5.6). A similar phenomenon also exists in air conditioner operation. For example,

- A customer adjusts the thermostat to a desired temperature of 24 °C (set point).
- If the temperature in the room is too high, the air conditioner cools the room until the temperature drops slightly below the desired value, for example, 23 °C, and stops cooling.
- The temperature in the room gradually rises until it reaches a level slightly above the desired value, for example, 25 °C, then the air conditioner starts running again and cools the room.

In this case, a graph illustrating the change in temperature versus time will resemble Fig. 5.6, but for the opposite situation: when the air conditioner is on, the temperature drops, and when the air conditioner is off, the temperature rises.

Most air conditioner users are unaware of the phenomenon of cycling described above, also called 'hysteresis' range. However, this phenomenon causes the air conditioner compressor to work for a few minutes and disconnect periodically, causing energy wastage and wear-and-tear of the air conditioner motor. Below we will present an innovative method for controlling an air conditioner that prevents this phenomenon.

5.5.5 System Boundaries

We have seen that the term system boundary refers to the distinction between internal and external objects or processes in a system. In the case of an air conditioner, like a room heater, external factors include the structure of the room, the outside temperature, and the thermal isolation of the building. These entities might affect the temperature in a room but are not affected by cooling or heating by the air conditioner.

5.5.6 Technological Innovation in Air Conditioning Systems

In recent years, technologists and engineers around the world have been investing efforts in refining conventional air conditioners we have known for decades. Below is an example of these developments.

So far, we have seen that the motor of a conventional air conditioner is turned on/off periodically by a thermostat, and the temperature in the room rises and falls cyclically, as illustrated in the blue lines shown in the two graphs in Fig. 5.11. In recent years, modern air conditioners have been increasingly using the electronic inverter technology to substitute thermostat control. The inverter electronic controller provides the motor with a high current only during start-up and then runs the motor continuously at steady low power and low speed, as illustrated in the red lines in Fig. 5.11. This process replaces the thermostat on/off control method, as marked in the blue lines in Fig. 5.11.

Studying the implications of the transition from thermostat-based control to inverter technology-based control of an air conditioner directly relates to the aspect of dynamic behaviour of a technological system. As explained earlier, in a system based on the traditional technology of the thermostat, the air conditioner's compressor is turned on and off periodically and the temperature rises and falls. In a system based on inverter technology, the motor works continuously at low intensity and the temperature in the room (or refrigerator) is constant, without causing fluctuations in room temperature.

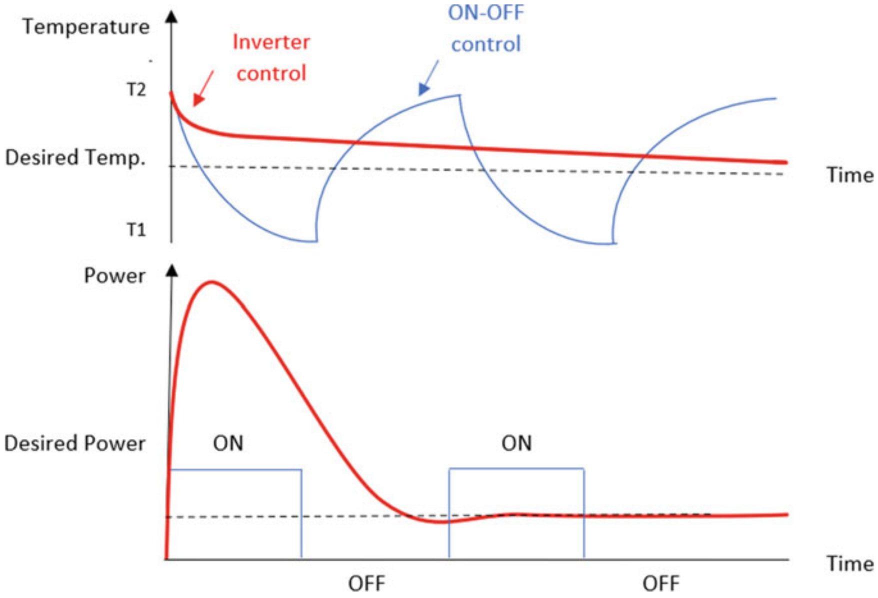


Fig. 5.11 Air conditioner based on electronic inverter control (red lines) versus on/off thermostat control (blue lines) (Izushi, 2018)

The use of inverter technology is expanding to other household appliances such as refrigerators and washing machines. The benefits are not only a smarter and quieter operation of these devices but also low energy consumption. The disadvantages are that inverter-based devices are often more expensive compared to thermostat-based devices, and the electronic circuit may be more fault-sensitive compared to a mechanical thermostat. However, it is likely that these points will improve in the future.

5.5.7 Socio-Technological Aspects of Room Heating Devices and Air Conditioners

De Vries (2005) describes technology as 'the human activity that transforms the natural environment to make it fit better with human needs, thereby using various kinds of information and knowledge, various kinds of natural (material, energy) and cultural resources (money, social relationships, etc.)'. This definition emphasises that systems thinking is about understanding a technological system not only from scientific or engineering aspects but also from the aspects of human needs and aspirations.

In the present study, we have seen that using a modern air conditioner based on inverter technology instead of the old on/off control method may reduce fluctuations in air temperature, reduce noise, and save energy. From another perspective, air conditioner producers are now required to use refrigerant R-32 because it can reduce electricity consumption compared to that of air conditioners using refrigerant R-22 or R-410. Moreover, R-32 has a global warming potential (GWP) that is one-third lower and is remarkable for its low environmental impact.

Although air conditioners consume much less electricity than other heating devices, air conditioners are still among the most significant energy consumers at the home or the workplace and thus contribute to increased energy production and environmental pollution. To deal with this challenge, the ‘green home’ movement (Bonta & Snyder, 2009) recommends designing houses that conserve energy or water, improve indoor air quality, use sustainable, recycled or used materials, use more energy-efficient appliances or building materials that are more efficient in managing temperature. The ‘smart home’ energy network (Han & Lim, 2010) has gained widespread attention due to its flexible integration into everyday life by effectively delivering solutions for diverse areas including consumer electronic device control, energy management, and efficiency home and commercial building automation, as well as industrial plant management.

Up to now, we have seen that room heating devices and air conditioners may serve as rich examples for teaching all attributes of systems thinking to students. The question is which pedagogy is best suited to achieve this goal, as will be discussed in the following section.

5.5.8 Pedagogy for Fostering Systems Thinking in the Context of Room Heating Devices and Air Conditioners

As noted in the Literature Review section of this chapter, educators strongly recommend using a constructivist pedagogy in teaching systems thinking in contrast to the teacher-centred traditional pedagogy. Student-centred pedagogy could be represented by the following four principles: contextual learning; activity-based learning; collaborative learning; and reflective learning. To achieve this end, teachers can engage students in problem-, project-, or design-based learning (Barak, 2020). Below are examples of tasks for students aimed at developing systems thinking in the context of air-conditioning systems while noting the main systems thinking aspects that are most relevant to each task out of W, I, F, D, B, T, S.

1. Investigating the process of choosing an air conditioner for different spaces (main systems thinking aspects: W, B, T, S).
2. Researching the range of temperature change (maximum/minimum) in a room and the frequency of the thermostat on/off switching by a data recorder (main systems thinking aspects: W, I, F, D, B).

3. Exploring the impact of having an open window in a room on air conditioner performance and energy consumption (main systems thinking aspects: W, I, F, D, B, S).
4. Comparing the effectiveness of air conditioners based on mechanical thermostat versus invertor technology in terms of dynamic response and energy consumption (main systems thinking aspects: W, I, F, D, B, T, S).
5. Designing and constructing a micro-controller-based electronics system to monitor and control temperature and humidity in an air-conditioned space (main systems thinking aspects: W, I, F, D, B).
6. Learning from experienced air conditioner installers about issues such as how to choose, install and maintain this device, product quality, common faults in air conditioners, and how to repair them (main systems thinking aspects: W, I, F, D).

In general, it could be said that each of the tasks listed above corresponds with all seven aspects of systems thinking W, I, F, D, B, T, S. Nevertheless, we chose to mark in each task aspects of systems thinking that might have a slightly higher weight in the same task. An additional viewpoint for fostering systems thinking in the technological and electronic class in the context of air conditioners is the four pedagogies for fostering systems thinking proposed by Hallström and Klasander (2020), as noted in the Literature Review section: interface pedagogy; holistic pedagogy; historical pedagogy; and design pedagogy. These steps might complement and take forward the six examples of tasks for students mentioned above.

In summary, we have seen several major characteristics of systems thinking related to heating and air conditioning devices, how to engage students in learning these systems, and thinking patterns in the technological and science class.

5.6 Aspects of Systems Thinking in the Context of a Sound Amplification and Enhancement System

In this section, we discuss how systems thinking relates to systems for sound amplification and enhancement, with a focus on the seven aspects of systems thinking W, I, F, D, B, T, S we are discussing in this chapter (Fig. 5.1).

5.6.1 Seeing the Whole Rather Than the Parts

A simple example of a sound amplification system that includes a microphone, amplifier, and loudspeaker is shown in Fig. 5.12.

Seeing the whole rather than the parts in this system means recognising the role of the system, its main elements, and how it works in general. From the user's viewpoint, the system includes microphones, some electronic instrumentation inside

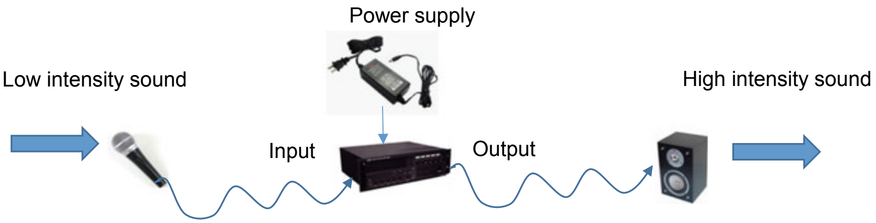
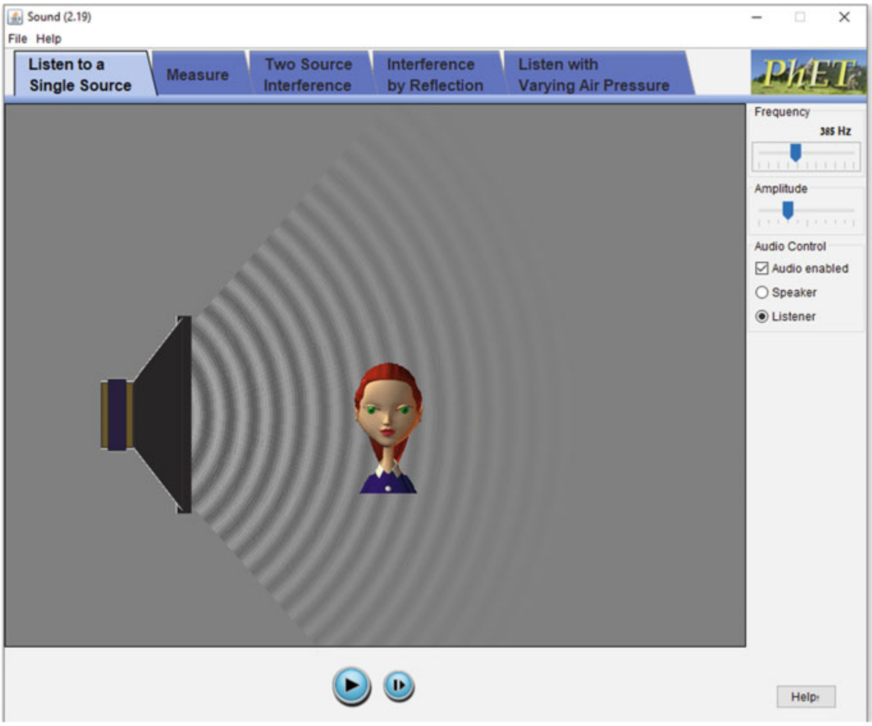


Fig. 5.12 A basic sound amplification system

the box and a loudspeaker. In this case, seeing the whole means understanding that the microphones convert the voice to an electronic signal, which the box amplifies. It also includes an intuitive understanding that the singer's voice spreads through the air, for example, to the microphones and from the speaker to a listener. Many people are familiar with the term sound waves, which is somewhat vague. Figure 5.13 shows a simulation of sound waves created by a loudspeaker.



Frequency 385 Hz

☑ Audio enabled

○ Speaker

● Listener

Fig. 5.13 Simulation of sound waves. *Source* PhET free interactive simulations, University of Colorado Boulder https://phet.colorado.edu/. *Licensing:* https://phet.colorado.edu/en/licensing

5.6.2 *Interconnections/Interrelationships in a Sound Amplification System*

This aspect of systems thinking takes us one step further in understanding the phenomena associated with a sound system physically and technologically.

From physics, we know that sound happens because something makes air (or other material) molecules vibrate. When we strum a guitar string, the string oscillations vibrate the air molecules around it, which vibrate other molecules nearby, and so on. Each particle vibrates locally but the vibrations propagate in the air, a phenomenon that we call a sound wave, which is shown in Fig. 5.13.

From the technological perspective, sound systems deal with transforming sound to an electronic signal, amplification of this signal and transforming it back to sound, as is shown in Fig. 5.12.

As we have seen in the air conditioner section, it is common in technology and engineering to represent a system with a block diagram that shows the flow of signals and energy in a system. The sound amplification system could be represented by a three-stage block diagram, as shown in Fig. 5.14.

In the block diagram, each of the three main blocks represents a component (or sub-system) in the system, and between the blocks are the main signals (variables) in the system. To understand the interconnections/interrelationships in a system, one must know a little about the signals characterising the system. For example, in the system shown in Fig. 5.14:

- The microphone might provide an electrical signal of 1 millivolt (mV) and a current of a few microamperes (uA) to the amplifier.
- The amplifier would provide a signal of 1 V and a current of a few milliamps (mA) to the loudspeakers.
- An amplifier requires an energy source such as batteries or an electric power supply.
- Sound intensity is measured in dB (deci-Bell) (Berg, 2020). For example, absolute silence (threshold of hearing)—0 dB; home/office background noise—50 dB; rock

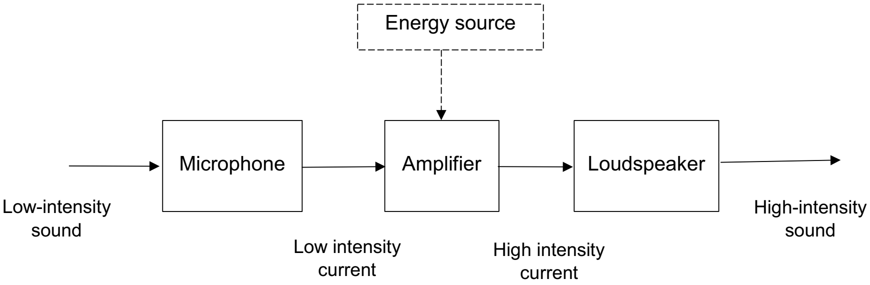


Fig. 5.14 Block diagram of a sound amplification system

Fig. 5.15 A sound intensity metre

music—120 dB. Sound intensity could be measured by a sound metre, as shown in Fig. 5.15.

It is important to note that the term sound system has to do with the amplification and enhancement of sound for many uses such as theatre and musical performances, or a public address system. In these cases, a sound system could be quite complex and include an advanced power amplifier and several loudspeakers of different sizes. Such a system often includes a 'mixing console' that enables connecting to the amplifier sound from different devices such as singers' microphones, electronic guitars, a CD player, or a computer. The sound console is the major tool for the sound person to adjust the intensity and enhance the quality of sound from each input device (Fig. 5.16).

Drawing a block diagram for an advanced sound system as described above is a challenge for the teacher and the student.

5.6.3 Feedback Loops: Unwanted Sounds Due to Positive Microphone Feedback

When we use a sound amplification system such as a karaoke system, at first glance this looks like an open-loop system, that is, without feedback. However, an unwanted high-pitched jarring sound is often obtained when the microphone is placed in front of

Fig. 5.16 Sound console

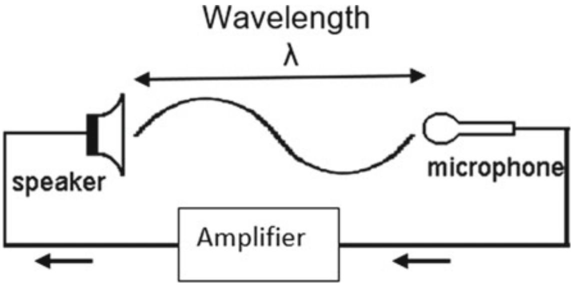
the speaker, as shown in Fig. 5.17. This phenomenon is called microphone feedback. In this case, the microphone signal is amplified through the amplifier and speaker, and the sound from the speaker is picked up by the microphone and then amplified again.

A block diagram of the microphone feedback system is shown in Fig. 5.18.

The phenomenon of microphone feedback is defined as ‘positive feedback’, which causes instability or self-oscillations in a system. In contrast, we have seen earlier in this chapter the case of ‘negative feedback’, which stabilises the temperature in a room controlled by a hot air diffuser or air conditioner (Figs. 5.5 and 5.10).

Positive feedback from the microphone to the speaker occurs when a sound signal repeats itself and is received in the microphone in the same phase each cycle. From a physical viewpoint, this happens only if the microphone is placed at exactly one

Fig. 5.17 Microphone feedback that causes unwanted sounds



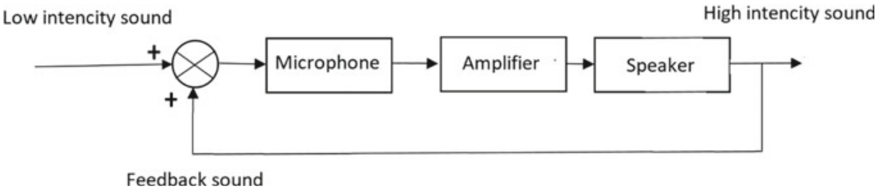


Fig. 5.18 Block diagram of unwanted positive feedback from a microphone

wavelength λ (or a whole number of wavelengths n•λ) from the loudspeaker, as shown in Fig. 5.17.

From physics, we know that sound wavelength is calculated by the formula $\lambda = V/\mathrm{f}$ (m), where V (m/s) is the sound velocity of propagation and f (Hz) is the sound frequency. For example, the sound propagation in air is $V = 343$ m/sec, and for a sound of 1 kHz, the wavelength is $\lambda = 34.3$ cm.

If the microphone is placed at distance of 34.3 cm from the amplifier, an unwanted sound will appear at a frequency of 1 kHz. If we move the microphone closer to the amplifier, the sound frequency will increase. A simple way to avoid microphone feedback is to change the location of the microphone. Professional sound people have practical experience in how to resolve this issue.

The phenomenon of positive feedback that causes instability or unwanted oscillations is a major challenge not only in a sound system but also in designing control systems such as robots or airplanes. Regarding the characteristics of systems thinking, this issue clearly belongs to the aspect of understanding feedback loops.

5.6.4 Dynamic Behaviour: Frequency Response of a Sound System

Dynamic behaviour of a sound system is associated with its frequency response, namely the audible frequency range that a sound system can reproduce. Audio frequencies are measured in Hertz (Hz), and the theoretical range of human hearing is from about 20 Hz (the lowest bass tones) to 20 kHz (the highest treble tones). Frequencies at the low end of this range are typically referred to as bass, the higher end is called treble, and those in the middle are called mid-range. However, considerable variation exists between an individual's hearing, especially at high frequencies, and a gradual loss of sensitivity to higher frequencies with age is considered normal.

Good speakers are the key to getting high-quality audio from a sound system. Ideally, a single speaker would be able to play sounds at all frequencies 'equally', meaning it would not make certain frequencies louder than others would. Typically, a sound system and the speakers create lower intensity sounds at low frequencies, for example, below 100 Hz, and at higher frequencies, for example, above 15 kHz, as shown in Fig. 5.19.

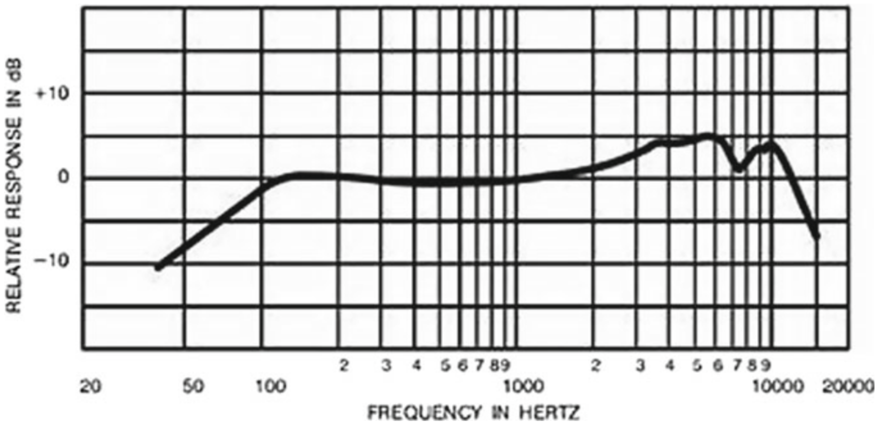


Fig. 5.19 An example of frequency response of speakers

In the case of a sound system, the aspect of system dynamic behaviour is crucial. In practice, it is very important to check the frequency range of a sound system or headphones that we are considering purchasing.

5.6.5 System Boundaries: Noise Accompanying a Sound System

As previously mentioned, system boundaries are defined by external objects and processes that affect the system but are unaffected by it (Lavi & Dori, 2019). In a sound system, the main factor that defines system boundaries is the noise from external resources that accompanies the sound, as shown in Fig. 5.20.

The phenomenon of unwanted noise is a major problem in electronics systems, for example, in radio and television broadcasts or digital communication networks. Common external noise sources are low-quality wires or cords, loose contacts, and noise from the 50/60 Hz power system that adds to the sounds. One can find websites on the Internet that advise how to eliminate noises in sound systems, it is often impossible to eliminate noise completely.

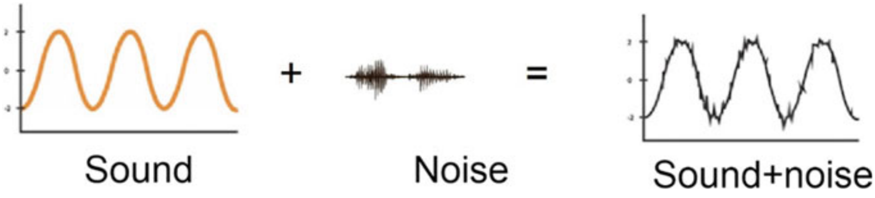


Fig. 5.20 Sound with noise

5.6.6 Technological Innovations in Sound Systems: Active External Sound Cancellation

Innovation is at the heart of technological development. The sound system we purchase today is much more sophisticated than what we knew 10 or 20 years ago. Over the years, new components and features have been added to sound systems, such as using a remote control, connecting the sound system to a TV using an optical audio cable, or listening to music on our smartphone by Bluetooth connection to headphones. All these enhancements have been developed by the initiative, creativity, and imagination of engineers and technologists. In many cases, consumers get to these innovations quickly and start thinking about how they had managed without them before. One of the innovations in sound systems is an active noise-cancelling technology, as shown in Fig. 5.21. This system includes a microphone that detects incoming noise and introduces a second opposite sounds in sync with the problem noise. This has the effect of reducing the problem of external noise.

Another area of innovation in the field of sound is that of hearing aids. A traditional hearing aid is based on analogue electronic technology and includes a microphone, amplifier, and tiny speaker, like the audio system we have seen. In recent years, hearing aids based on digital technology have been developed. The tiny digital processor installed in the hearing aid makes it possible to better adjust the sound amplification to frequencies where there is a hearing impairment, increase speech

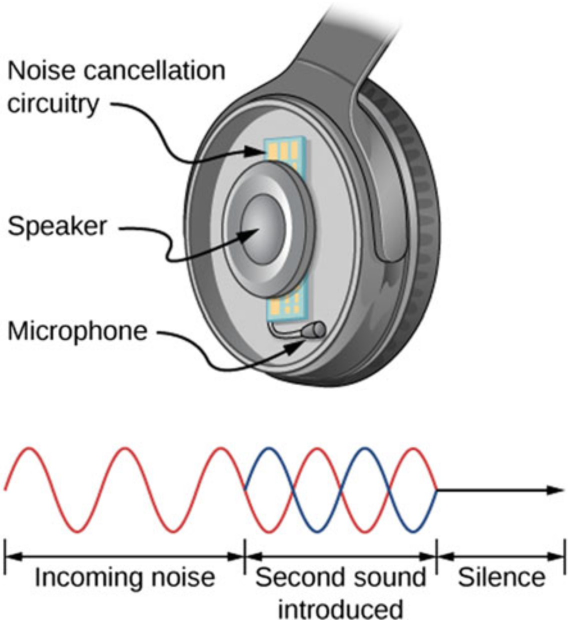


Fig. 5.21 Headphones with active noise cancellation

sounds, mute background noise, and eliminate beeps due to positive feedback from the microphone.

5.6.7 Socio-Technological Aspects of Sound Systems

Sound has played a key role throughout the history of humankind, including hearing sounds from nature, animals, human speech, and music. The technology of recording and re-playing sound has evolved since the invention of the vinyl disk in 1897. The use of magnetic tape for sound recording originated in the 1930s, and the compact disc (CD), which is a digital optical technology for data storage, was invented in 1982. Today, we are experiencing the revolution of storing huge amounts of data, including sound and movies, on digital databases, and listening to sound or watching movies online anywhere, anytime. It is a cultural revolution that affects not only the listeners but also the artists who create music and movies of all kinds. It would be interesting to explore aspects of systems thinking related to new technologies for sound storage and playing but lying at the end point of the new systems is still the fundamental sound amplification system discussed in this chapter.

5.6.8 Pedagogy for Fostering Systems Thinking in the Context of Sound Systems

As previously noted, educators strongly recommend moving from teacher-centred traditional pedagogy to student-centred constructivist pedagogy, which could be described by the following four principles: contextual learning; activity-based learning; collaborative learning; and reflective learning. Below are examples of applying these principles through problem-, project-, or design-based learning to cultivate systems thinking in the context of sound systems. For each example, we mark the most relevant systems thinking aspects of W, I, F, D, B, T, S.

1. Investigating the factors affecting the quality of sound in a stage performance, for example, the components of the sound system; the role of the sound mixing console; the process of adapting a sound system to the environment of a stage performance or to individual singers, actors, or a musical band; observing the work of a professional sound person (main systems thinking aspects: W, I, B).
2. Exploring the quality of sound produced by a common home sound system; measuring the sound intensity depending on the frequency; drawing a graph of the system frequency response; identifying noise sources in the system (main systems thinking aspects: W, I, D, B).
3. Designing and constructing a digital micro-controller-based device that measures sound intensity and alerts in case of excessive deviation (main systems thinking aspects: W, T, S, B).

4. Investigating the phenomenon of microphone feedback; exploring the relationship between the distance of the microphone from the loudspeaker and the frequency of the sound generated; discovering the sound wavelength; discovering how to prevent unwanted sound (main systems thinking aspects: W, I, F, D, S).
5. Investigating the process of adapting hearing aids to a person; addressing the advantages and limitations of a digital hearing aid compared to a traditional analogue device (main systems thinking aspects: W, T, S).

In conclusion, we have seen that sound systems are a rich technological field that is very close to a student's life and that exposes learners to all the principles of systems thinking we mentioned earlier in this chapter (Fig. 5.1).

Following the previous two chapters dealing with systems thinking in the context of the air conditioner and sound system, the next section will discuss key teaching and learning aspects related to fostering systems thinking in the science and technology class.

5.7 Fostering Systems Thinking in the Science and Technology Class: Key Teaching and Learning Characteristics

In this chapter, we address four key aspects of teaching and learning related to fostering systems thinking in the science and technology class, as shown in Fig. 5.22.

5.7.1 Modelling and Systems Thinking

Modelling relates to the generation of a physical, conceptual, graphical, or mathematical representation of a real phenomenon, process, concept, or operation that is difficult to observe or represent directly. Chan (2015) asserts that systems thinking is about building conceptual models that explain the complexity of the real world in terms of structure and behaviour. Scientific models explain and predict the behaviour of real objects or systems and are used in diverse scientific disciplines, including technology and engineering. Hallström and Schönborn (2019) assert that models and modelling are considered a fundamental aspect of STEM education, can be used to increase the relevance and authenticity of STEM disciplines, and contribute to the integration of STEM components in teaching and learning.

This chapter includes about 25 pictures, diagrams, drawings, and mathematical equations that represent different types of modelling, without which it would be almost impossible to present the aspects of systems thinking in electronics studies discussed here. However, creating or drawing a model of a physical, technological, or social system is not a simple task. Barak and Williams (2007) note that the process by

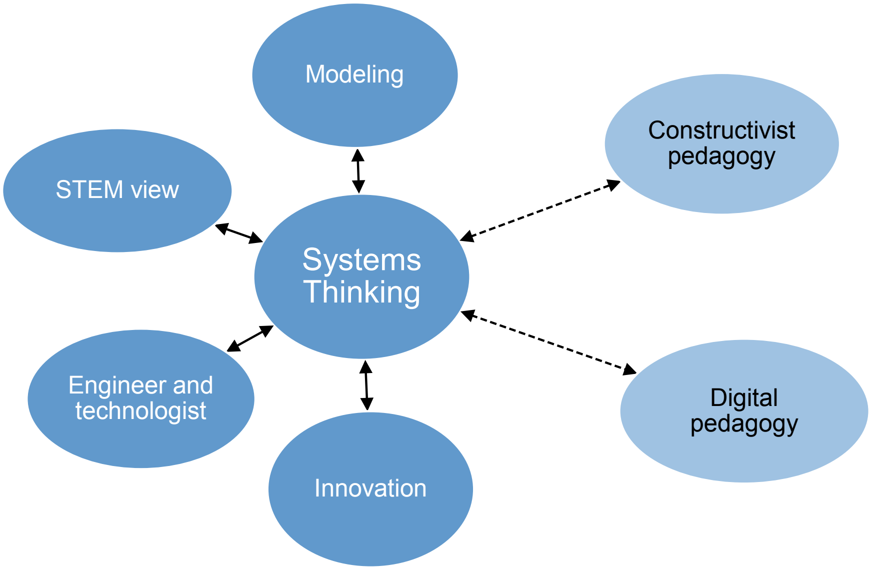


Fig. 5.22 Key characteristics of systems thinking and the instructional approach in the science and technology class

which people learn to use models or build their own models is a relatively unresolved issue in the psychological and educational literature. Therefore, it is important that the application of models to the teaching and learning of system structure and dynamics should be carried out gradually, with lots of examples from the simple to the complex. For example, the teacher can present in the class the block diagram of a heating device with a thermostat (Fig. 5.5) and ask the students to draw a block diagram of an air conditioner (Fig. 5.10).

5.7.2 STEM View and Systems Thinking

The term STEM—Science, Technology, Engineering, and Mathematics education—was proposed in the 1990s by the American National Science Foundation (NSF) and has been adopted widely by many countries around the globe. Sanders (2009) noted that although NSF has used STEM simply to refer to four separate and distinct fields, many educators and researchers have suggested that STEM education implies interactions between S, T, E, and M in the sense that 'the whole is greater than the sum of its parts'. On the other hand, STEM educators have established and consistently defended their sovereign territories (Kelley & Knowles, 2016). The two examples discussed in detail in this chapter—the air conditioner and the sound system—demonstrate the integration of STEM aspect in daily life. For example, learning that the air conditioner is based on concepts such as liquid evaporation and condensation and energy conversion, refers to science; concepts such as feedback, on/off control, and continuous control are about technology and engineering; concepts such as sound as a mechanical wave, frequency, and wavelength have to do with science; concepts such as electronic amplification and positive feedback relate technology, engineering, and mathematics. High school science and math courses should provide a sufficient foundation for STEM learning.

5.7.3 The Engineer, the Technologist, and Systems Thinking

Systems thinking is closely associated with the concept of engineering design, which usually includes the stages of identifying a problem or need, investigating, planning, constructing, evaluating, and improving. A major aspect of engineering design is the process of optimisation, which generally involves choosing the optimal solution from several options while balancing different requirements, for example, how to achieve high-quality outputs with minimum use of equipment, materials, or energy. Technology is a broader term than engineering, and engineering could be viewed as a branch of technology in which professionals use mathematics and scientific knowledge for the systematic design of products and systems. Kelley and Knowles (2016, p.6), based on De Vries (2011) and Barak (2012, p.138), write:

> Engineering can differ from technology in that engineering only comprises the profession of developing and producing technology, while the broader concept of technology also relates to the user dimension. Technologists, more than engineers, deal with human needs as well as economic, social, cultural or environmental aspects of problem solving and new product development.

Systems thinking is essential for both the engineer and the technologist since they must each understand how a system they are addressing works and its advantages and limitations. For example, engineers might face the challenge of developing an efficient, reliable, and relatively inexpensive air conditioner. The technologist deals with adjusting an air conditioner to an apartment, considering the customer's needs, the apartment size, the size of the windows and doors, the directions of the sun, and the typical weather in the place. An engineer engaged in sound system design is required to address several properties of the system, for example, the power of the amplifier and the loudspeakers, the system bandwidth, the quality of the microphone, mixer, amplifier, and loudspeakers. A technologist will deal with many factors associated with the users and the setting, for example, the type of music to be played, the audience, the environment, and how to avoid microphone feedback. Both an engineer and a technologist are required to address the seven aspects of systems thinking we discuss in this chapter: the whole rather than the parts, interconnections/interrelationships, feedback loops, dynamic behaviour, system boundaries, technological innovation, and socio-technological implications; however, the last three aspects might interest a technologist more than an engineer. Understanding the focus of an engineer versus a technologist may help educators develop systems thinking in the classroom.

5.7.4 Innovation and Systems Thinking

In the Introduction section of this chapter, we mentioned that we are currently at the beginning of the Fourth Industrial Revolution (IR 4), which is fundamentally changing the way we live, work, and relate to one another (Schwab, 2016). An interesting question is how new technological systems and devices are born. The traditional method for developing new products has been inspired by notions such as 'the voice of the customer' (VOC) or 'the voice of the market' (VOM). However, VOC and VOM may reflect only minutely customers' hidden wants and needs, especially in the case of a truly novel product, that is, a product that has never existed before. Abramov (2015) proposed supplementing VOC or VOM with the more objective 'voice of the product' (VOP), which shows that innovative products such as the iPhone were born from the knowledge, imagination, and initiative of the inventors and not due to a market survey. Innovative products are likely to create a market that did not exist before and often make the consumers say: 'how did we manage without that before'.

Systems thinking goes together with the innovation route mentioned above. To develop an innovative product or service, the inventor must have a broad view of the cultural, economic, and technological system for which the new product is intended. In our study, for example, it is natural that engineers would try to improve an air conditioner's technology, such as using inverter control technology. On the other hand, adding Wi-Fi to the air conditioner or an application that allows the consumer to operate the air conditioner via a smartphone is an innovative service that probably surprises and attracts customers. To what extent may this addition interest consumers and strengthen the product? How could we adapt the product to a wide audience? Dealing with such questions requires systems thinking related to the seven aspects discussed in this chapter by the company's designers and marketers.

5.7.5 Instructional Approach for Fostering Systems Thinking

5.7.5.1 The Role of Constructivist Pedagogy

Throughout this chapter, we have mentioned the advantage of constructivist pedagogy in the science and electronics class and presented some examples of how to apply these principles for fostering systems thinking in the context of an air conditioner and a sound system. However, educators are increasingly aware that at the beginning of learning a new subject direct instruction by the teacher might be more effective than constructivist pedagogy such as project-based learning because at these stages, the notion of minimal guidance during learning works only little (Barak, 2020). Some supporters of PBL (Hmelo-Silver, 2004; Savery, 2006) stress the need to tailor the scope and complexity level of assignments to students' prior knowledge and skills and provide instruction and support, to reduce the cognitive load and enable students to learn in a complex domain (Kirschner et al., 2006). By giving appropriate conceptual and representational scaffolding in the learning environment, students should be able to tap into their everyday experiences and channel and enhance these experiences to construct understandings of complex systems that are cognitively robust (Jacobson & Wilensky, 2006).

5.7.5.2 Using Digital Pedagogy

Educators and students now have diverse technological means at their disposal for teaching and learning technology and developing systems thinking. For example, in learning the subject of sound, students can use the Audacity free software to record and analyse the signals of different sounds. Figure 5.23 shows the electronic signal of two short beats in flute sounds recorded by a computer microphone.

Figure 5.24 shows the vibrations of the sound by zooming to a section of the signal seen in Fig. 5.23. From these two figures, students can learn to record and analyse analogy and digital signals, for example to identify the duration of each beat, the time difference between the two beats and the sound frequency. Students can accomplish this experiment with any laptop at school or at home, without the need for additional equipment. With appropriate instruction, the teacher can engage students in hands-on rich experiments, which are the key for learning all the seven aspects of systems thinking, for example, modelling, feedback loops, dynamic response, noise, and system boundaries.

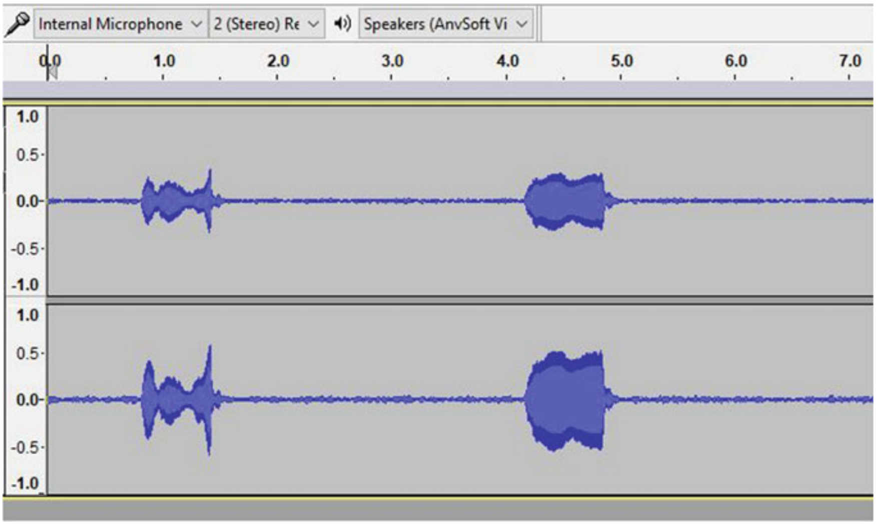


Fig. 5.23 A signal obtained from two short beats in a flute

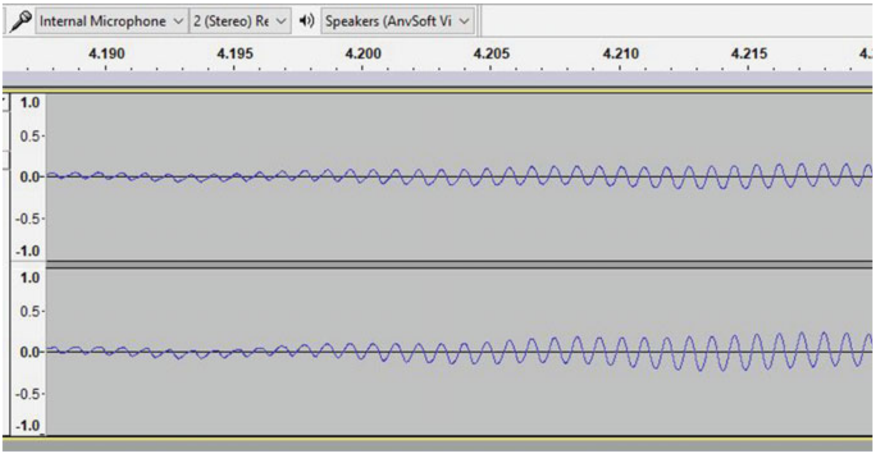


Fig. 5.24 Zooming into a section of the sound signal

5.8 Concluding Remarks

In this chapter, we have seen that systems thinking aims at understanding relationships between components in a system and their overall impact on a system's intended and unintended outcomes. This is an abstract, complex, and somewhat vague topic associated with terms such as higher-order thinking and experts' thinking. Electricity and electronics, which are at the heart of the latest technological revolutions, can serve as a good platform for fostering systems thinking in a technological context. To exploit this potential, we identified a cluster of seven aspects of systems thinking that correspond well with the electricity and electronics domain. We also investigated how these aspects are reflected in devices and electronic systems close to everyday life: home heating devices, an air conditioner, and a sound system. Following this analysis, we emphasised four key aspects of teaching towards systems thinking: modelling; STEM view; the role of the engineer and the technologist; and innovation. Instructional aspects concerned with achieving this goal, constructivist pedagogy, and digital pedagogy, are also discussed. It is hoped that this chapter may serve as an example of how to teach systems thinking aspects in the context of other technological and engineering fields, for example, mechanical engineering or communication systems.

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