5E STEM Unit Plan Name
(Time Frame)

Authors

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SUBJECT/GRADE LEVEL

Subject Area: Computer Science
AP Physics

Grade Level: 11th - 12th grade

Materials

- For real-time Analog Computing, the following materials would be needed:
  - The Analog Thing (THAT) analog computer (https://the-analog-thing.org/)
  - An Oscilloscope
  - All electrical jumper cables for connecting THAT to the oscilloscope
- For simulated Analog Computing, the following materials would be needed:
  - Youtube videos on analog computing;
  - Calculators
  - Notebooks

STANDARDS

Next Generation Science Standards

- HS-PS2: Motion and Stability: Forces and Interactions: Students can explore the concept of forces and interactions through the modeling of electrical circuits.
- HS-PS3: Energy: Students can investigate the transfer and transformation of energy in electrical circuits.
- HS-PS4: Waves and Their Applications in Technologies for Information Transfer: Students can explore the characteristics of different waveforms and their role in communication systems.
- HS-ETS1: Engineering Design: Students can apply engineering design principles to create and test analog circuit models.

Mathematics Standards | Common Core State Standards

High School: Functions

- CCSS.MATH.CONTENT.HSF.LE.A.2: Construct linear and exponential functions, including arithmetic and geometric sequences and their sums.

High School: Modeling

- CCSS.MATH.CONTENT.HSF.LE.A.4: For exponential models, express as a power of the same base.

High School: Geometry

- CCSS.MATH.CONTENT.HSG.SRT.A.1: Verify experimentally the properties of dilations given by a center and a scale factor.

High School: Algebra

- CCSS.MATH.CONTENT.HSA.CED.A.1: Create equations and inequalities in one variable and use them to solve problems.

English Language Arts Standards | Common Core State

- SL.9-10.1: Initiate and participate effectively in a range of collaborative discussions (one-on-one, in groups, and teacher-led) with diverse partners on grade-level topics, texts, and issues, building on others' ideas and expressing their own clearly and persuasively.
- SL.9-10.4: Present information, findings, and supporting evidence clearly, concisely, and logically such that listeners can follow the line of reasoning and the organization of ideas.

LESSON OBJECTIVE(S)

Students will be able to:

- Understand the fundamental principles of analog computing and its historical significance.
- Construct simple analog circuits using "The Analog Thing" (THAT) analog computer or virtual simulation tools .
- Analyze the behavior of analog circuits by observing and measuring waveforms.
- Compare and contrast analog and digital signals.
- Apply analog computing concepts to real-world problem-solving.
- Communicate understanding of analog computing through written and visual representations.

CAREER CONNECTION(S)

Mentor Background: David H. Meyer, Ph.D., is a Research Physicist at the U.S. Army Combat Capabilities Development Command Army Research Laboratory. He earned his B.S. from Brigham Young University in 2012 and his Ph.D. from the University of Maryland in 2018.

Dr. Meyer's research focuses on quantum information science and quantum sensing, particularly using thermal-Rydberg-atom-based sensors for radio frequency electrometry and communications. His work includes topics like Electromagnetically Induced Transparency, Rydberg States, Optical Cavities, and Cavity Quantum Electrodynamics.

Dr. Meyer explores advancements in quantum networks, data rates, and error correction, utilizing numerical simulations to study impacts of electric fields, laser pulses, and linewidth. His contributions bridge theoretical physics with practical applications in quantum technology.

STEM Careers:

Engineering Fields

- **Electrical Engineer:** Designing and developing analog and digital circuits, understanding their interactions, and applying them to various systems.
- **Computer Engineer:** Focusing on the hardware aspects of computers, including the design and development of analog-to-digital converters (ADCs) and digital-to-analog converters (DACs).
- **Mechatronics Engineer:** Combining electrical, mechanical, and computer engineering principles to create systems that involve both analog and digital components.

Science Fields

- **Physicist:** Studying the fundamental principles underlying analog computing and its applications in fields like quantum computing and signal processing.
- **Mathematician:** Developing mathematical models for analog systems and exploring the relationship between analog and digital computation.

Computer Science Fields

- **AI Researcher:** Investigating the use of analog computing principles in developing new AI architectures and algorithms.
- **Data Scientist:** Working with large datasets and applying analog computing concepts to data processing and analysis.
- **Computer Systems Architect:** Designing computer systems that effectively combine analog and digital components for optimal performance.

Other Related Fields

- **Electronic Technician:** Troubleshooting and repairing electronic equipment, including analog components.
- **Audio Engineer:** Working with analog and digital audio signals, understanding their characteristics, and manipulating them for various applications.

ENGAGEMENT

Why would I need Analog - Debate:

Teacher Background:

As Artificial Intelligence (AI) is an emerging field within the study of computer science, it has been noticed that digital computers expend a great deal of energy doing AI-intensive calculations. In particular, it is energy intensive for digital computers to do large matrix multiplications in real time in order to process neural networks.

Many CS researchers have posited that analog computing will be the way of doing such calculations in the future, primarily to cut down on the amount of energy that AI processors would consume.

This lesson would introduce analog computing to students (likely as a small module – and not consuming too much time away from the standard AP Computer Science curriculum.

Objectives

- Briefly recap the differences between analog and digital systems.
- Explain the dominance of digital technology in today's world.

Video: Analog vs Digital Computing

Debate Setup

- Divide the class into two groups:
    - **Team Analog:** Advocates for the continued relevance and usefulness of analog technology.
    - **Team Digital:** Argues for the superiority of digital technology and the obsolescence of analog.

Debate Structure

- **5 minutes:** Each team prepares their arguments.
- **5 minutes:** Team Analog presents their case, highlighting the advantages and potential applications of analog technology.
- **5 minutes:** Team Digital presents their counterarguments, emphasizing the limitations of analog and the benefits of digital alternatives.

- **5 minutes:** Open debate and rebuttal. Students can ask questions and challenge opposing arguments.

Potential Arguments (For Teacher ONLY)

Team Analog

- **Reliability:** Analog systems can be more resilient to power outages and electromagnetic interference.
- **Energy Efficiency:** Analog circuits can be more energy-efficient in certain applications.
- **Human-Like Perception:** Analog systems can process information in a way that is more similar to human perception.
- **Specific Applications:** Highlight niche areas where analog technology still excels (e.g., audio equipment, analog photography).

Team Digital

- **Versatility:** Digital systems can perform a wider range of tasks and are more adaptable.
- **Accuracy and Precision:** Digital systems offer superior accuracy and precision in calculations and measurements.
- **Miniaturization:** Digital technology enables the development of smaller and more portable devices.
- **Cost-Effectiveness:** Digital systems are often more cost-effective to produce and maintain.

Conclusion

- Facilitate a brief wrap-up discussion to summarize the key points raised by both sides.
- Encourage students to think critically about the trade-offs between analog and digital technology in different contexts.

EXPLORATION

First "Hello World" Analog Program on an Analog Computer

Brief Description:

- Analog computers and analog programming differ from digital programming in that – instead of using a typical programming language (like Python etc. — that uses pseudo English language) – analog computers use electrical components that need to be "wired" up and run to get "waveforms" on a scope (e.g., an oscilloscope or the like).
- Thus, analog computers are particularly good at simulating physical systems that are governed by mathematical equations, like differential equations. So, such problems as modeling dampened spring systems, exponential decays, quantum mechanical systems would be good problem domains for analog computing. While digital computers may also solve and model such systems/problems, the issues are: (1) computing time and (2) energy consumption.

- Analog computers are able to more closely simulate complex physical systems in quasi "real time" – while digital systems may not be able to simulate systems in real-time (unless one uses supercomputing). In addition, analog computers are much more energy efficient in their modeling as compared with digital computers.
- That is why some scientists and engineers believe analog computing will be used in a "hybrid" system – i.e., a front-end analog computer that models a systems and a back-end digital computer that uses an Analog-to-Digital Converter (ADC) that will sample the analog waveforms and feed in digital data to be used thereafter by the back-end digital computer.
- The goal of this Exploration is to introduce the functional parts of an Analog Computer. Afterwards describe a simple system to model – and describe how to "program" (i.e., wire up) the analog computer to simulate the system.

Procedures:
Students will complete Exploring Waves with an Online Oscillator to learn more about waves.

EXPLANATION

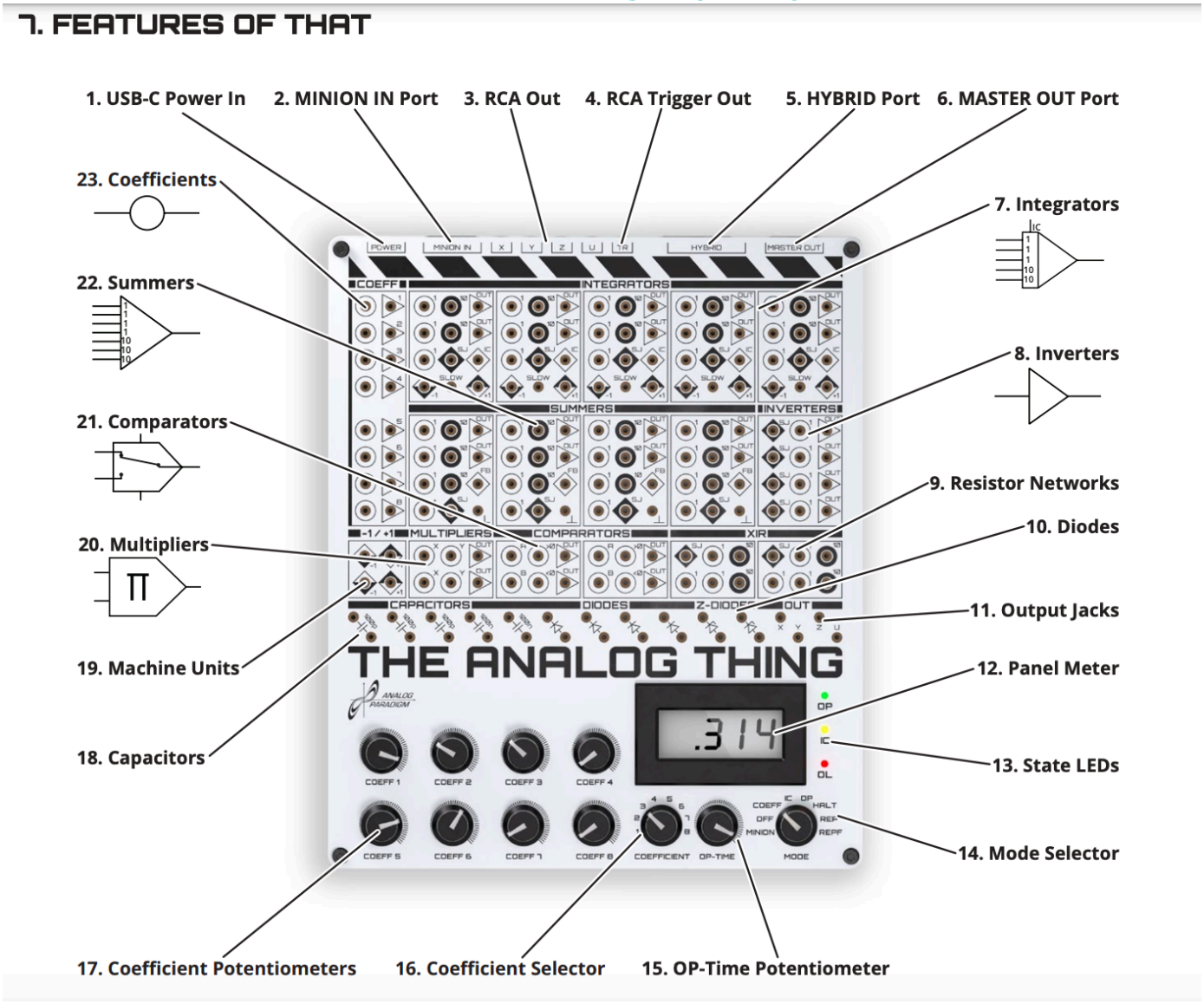
Brief Description:
This section will introduce the student/reader to THAT – a commercially available analog computer (https://the-analog-thing.org/). By completing the steps below, students will become familiar with the THAT computer layout and system.

Afterwards a simple system will be shown how to program on the THAT – and the resulting waveform will be shown that is the real-time model of that system.

Procedures:

- Figure 1 shows the THAT and calls out all of the key modules that are needed to program the THAT while modeling a system.

FIGURE 1 – THAT analog computer layout



- It will be noted that many electrical modules are available to the analog programmer. There is INPUT (23 – Coefficients) and OUTPUT (3 – RCA Out; 4 – RCA Trigger Out). There are also programming modules that do the analog calculations.
- For example, two or more electrical signals can be:
    - ADDED (22-Summers)
    - SUBTRACTED (using 8–Inverters with 22-Summers)
    - MULTIPLIED (20-Multipliers)

    - LOGICAL COMPARED (21-Comparators)
    - INTEGRATED (where integration is used in the calculus sense) – area under the curve calculations over time (7-Integrators)
- All of these modules will become clear in the context of explaining how to program the first "Hello World" program in the Elaborate Section below.

ELABORATE

Brief Description:
Having shown the working panel of the THAT, it will now be explained how to "program" it with a first "Hello World" program. Students will be following the directions below to use the "Hello World" program to model radioactive decay.

Procedures:

- The very first Hello World program is – modeling radioactive decay.
- Before anyone can "program" (i.e., wire up) an analog computer, some thought has to go into the problem itself. Once the problem is defined and understood, then some mathematical analysis needs to be done BEFORE any wiring occurs.
- Typically, the mathematical problem that models a system is in the form of a Differential Equation (DE) – that is, an equation that has a function (say, "y") and y can be a function of one or more variables. In addition, the differential equation expresses a correct relationship between y itself and one or more of the derivatives of y (i.e., y' , y'', y''', etc.).
- Figure 2 shows how to program (wire up) the THAT to model a system involving exponential decay. For more information about exponential decay, the reader is referred to this Wikipedia page (https://en.wikipedia.org/wiki/Exponential_decay)
- In that page, the differential equation is shown and explained in detail. The differential equation in the Wiki page is precisely the one shown below in Figure 2 in red print.

FIgure 2 – HELLO WORLD Program (Radioactive Decay)

9.1 RADIOACTIVE DECAY

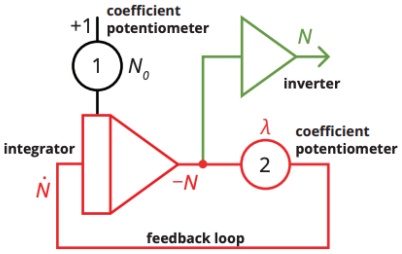
A minimal analog computer patch consists of an integrator whose output is fed back as its input. Imagine rotation *c* in the image in Section 4 being fed back to drive rotation *b*. Depending on the rotational direction of this feedback, *c* plotted over a results in an either exponentially growing or exponentially decaying curve and thus offers a model for phenomena with exponential dynamics. Let's give this a try electronically by setting up an analog computer patch to model the decay in a radioactive sample. Exponential decay can be described with the first-order differential equation shown here.

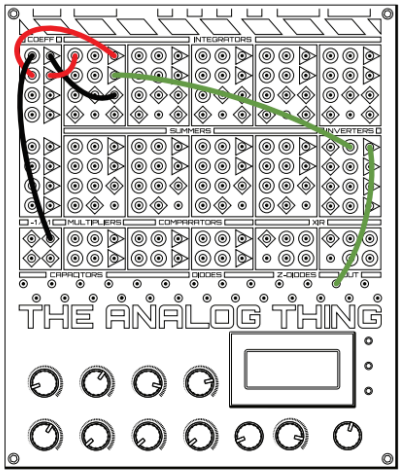
$$\dot{N} = -N\lambda \qquad \textbf{differential equation}$$

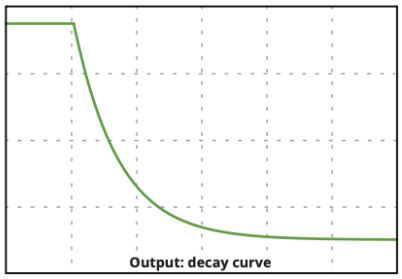
In this equation, λ denotes the decay coefficient. Note that $\dot{N}$ in Newton's notation is the equivalent of dN/dt in Leibniz's notation. To translate this equation into a patching diagram, the Kelvin feedback technique can be used. As a first step, this technique typically requires arranging the equation(s) such that the highest derivative is isolated on the left side of the equal sign. Showing $\dot{N}$ isolated on is left, the equation above is already arranged in this way. Establishing the feedback loop required to solve the equation can now take advantage of the equality of both sides of the equation. For this purpose, the highest derivative on the left of the equal sign is, for the time being, assumed to be known. The term on the right of the equal sign $-N\lambda$ is then modeled with a suitable chain of computing elements. In the radioactive decay example, this is simply an integrator connected to a potentiometer that implements the decay coefficient. The output of this chain of computing elements, known to be equal to the highest derivative, is then connected to the input of the first computing element in the chain, closing the feedback loop. In the radioactive decay example, a second potentiometer is needed to set the size of the sample at the start of the patch run (i.e., the initial condition of the integrator).

As integrators change the signs of their output, feeding an integrator's output back to its input is sufficient to model decay (i.e., negative exponential growth). To display diminishing positive values, however, the initial value of the integrator's output must be negative, and the sign of the output must be changed using an inverter. Two coefficient potentiometers allow the initial number of molecules N_0 and the decay coefficient λ to be adjusted.

To run this patch, put THAT in COEFF mode. Plug cable connections on the patch panel as shown in the patch diagram. Use the coefficient selector to select coefficient potentiometers 1 and 2 in turn and set both to 0.5. Connect your display system to RCA Out X on the back of THAT. Run the patch in REP (repeat) mode to display a flicker-free image on the display system. As the patch runs, change coefficients 1 and 2 and observe how the graph changes. Also, adjust the OP-Time and run the patch in REPF mode to observe how these changes affect the output.





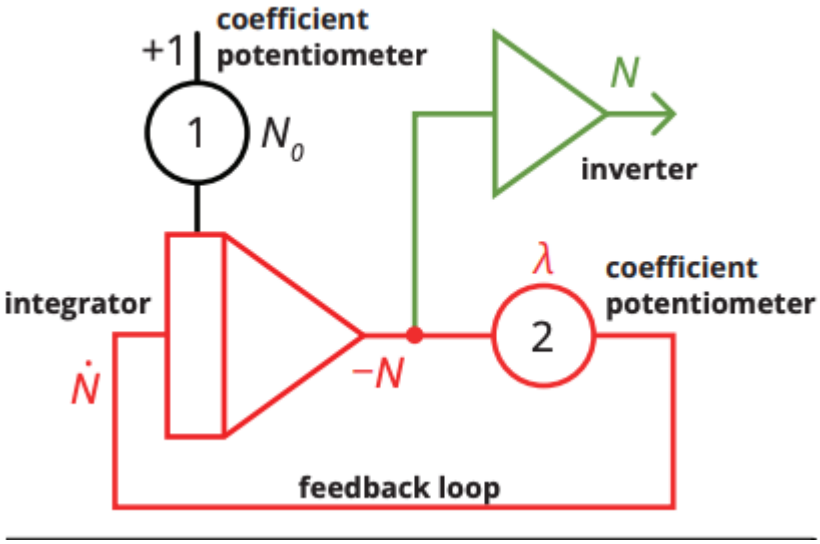


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- Once the differential equation (DE) has been worked out, then the analog programmer needs to understand HOW to map that DE onto the THAT.
- To do that successfully, it is recommended to do an INTERMEDIATE STEP of drawing out the DE processing on the electrical components (that are found on the THAT). This is like FLOWCHARTING a solution program.

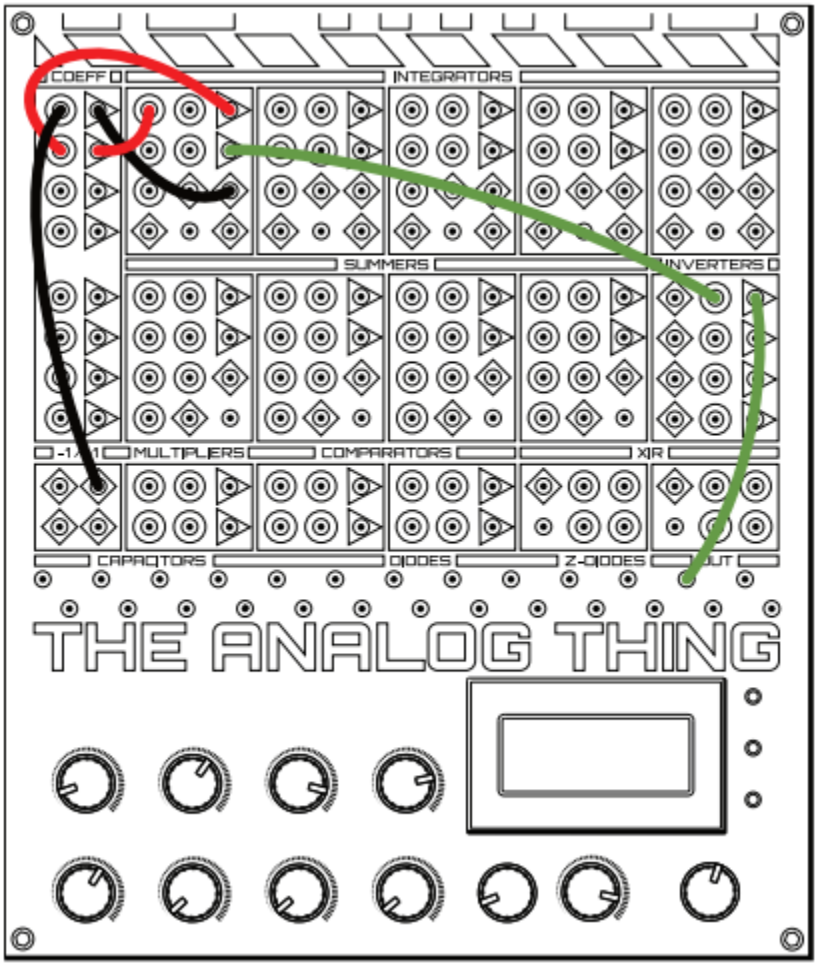
- So, Figure 3 below is the appropriate flowchart:

Figure 3 – Flowchart of the Radioactive Decay DE



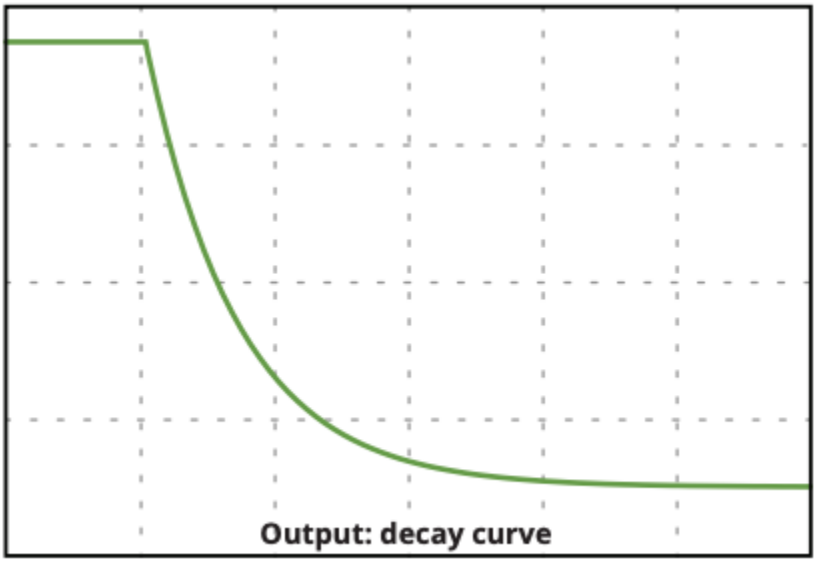
- As can be seen, INTEGRATOR takes as its INPUT two items:
- Initial Condition N_0 – as every system starts with some initial values (in our case, N_0 would correspond to the amount of radioactive material in question)
- N' (Figure 2 calls that "N" with a dot over the "N") – this is the first derivative of the rate of radioactive decay.
- The INTEGRATOR takes those input – and "integrates" N' – to produce N. More precisely, the THAT produces the NEGATIVE of N (-N). This is a peculiarity of the electronic circuit implementing INTEGRATOR. So, it is important that the analog programmer knows that and sends the -N signal into an INVERTER to get -(-N) – or N which is the same thing. It is this N signal (coming from the INVERTER) that is sent to the OUTPUT (which is sent to an oscilloscope for viewing).
- Now the INTEGRATOR, in order to work takes INPUT from the -N signal – which needs to be MULTIPLIED by the LAMBDA symbol. LAMDBA coefficient is related to the half-life decay of the material in question.
- So, it can be seen that this -N x Lambda signal is FEDBACK to the INTEGRATOR ("FEEDBACK LOOP"). This is important as the INTEGRATOR is solving for N by integrating updated versions of N'.
- Once this FLOWCHART is understood by the analog programmer, it is NOW time to "program" (wire up) the THAT.
- Figure 4 shows the programming (wiring) on the THAT that affects the solution to the Radioactive Decay problem.

Figure 4 – Programming (Wiring UP) the THAT



- As may be seen, the wires are COLOR-CODED in the same way as Figure 3's Flowchart is COLOR-CODED.
- The RED lines are lines that are INPUT and OUTPUT of the INTEGRATOR. The BLACK lines set the Initial Condition N_0 . The GREEN lines are the lines that take the - N signal into the INVERTER (producing the N signal) - which is then taken to an OUTPUT (and subsequently sent to an oscilloscope for solution read-out).
- Once the THAT is wired-up and allowed to RUN, then Figure 5 shows the resulting waveform on the oscilloscope that is the SOLUTION to the program that the analog programmer sought to solve.

Figure 5 – Oscilloscope OUTPUT Waveform



- As may be seen the Waveform comports with any radioactive decay – where the Y-axis is the amount of radioactive material (the amount of which decays over time) and the X-axis is TIME.
- The flat portion at the far left side of the curve is the INITIAL amount of radioactive material (set by the N_0 signal on the THAT board). The student/programmer can see (in REAL TIME) how the curve reacts to different amounts of N_0 by turning the dial on the Coefficient 1 on the THAT board.
- Similarly, the LAMDBA coefficient can be altered by turning the dial on the Coefficient 2 on the THAT board. That would correspond with different materials having different half-lifes.
- Success on this Lesson would be to replicate the Waveform in Figure 5.

EVALUATION

Brief Description: The three part activity will assess student understanding of key concepts and procedures involved in programming an analog computer to model a simple system, specifically radioactive decay.

Procedures:
Assessment for Analog Computer Exploration: "Hello World" Program

REFERENCES

Online simulation: https://physics-zone.com/sim/virtual-oscilloscope/

The Analog Thing (THAT) analog computer (https://the-analog-thing.org/)