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Introducing Feedback Control to Middle and High School STEM Students, Part 1: Basic Concepts ⋆

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Abstract: This paper presents some insights on introducing control concepts to middle and high school STEM students. It summarizes the author's experience in introducing control to such students at multiple workshops preceding control conferences. The author has found that if one understands and works with the most common skill sets for such students, principles of feedback and feedforward control can be introduced to such students with considerable success. The students are always engaged through the talk, with nobody looking at their phones. In Part 1 (this paper), we share here the ideas behind the success of these talks. In Part 2 (Abramovitch (2019)), we show how to discuss control systems math to students who have not had calculus or differential equations.

Keywords: Teaching, education, second-order systems, closed loops, computers.

1. INTRODUCTION

As Dennis Bernstein so eloquently wrote in in his seminal 2002 paper (Bernstein (2002)) feedback is the hidden thread of many world changing technologies of the 1900s. As we progress through our ever automating world of the 2000s, Dennis' insight appears to be the proverbial tip of the iceberg. With agents, networks, robots, self driving cars, smart grids, swarms of drones, etc. the prevalence of human built feedback systems in our lives is increasing exponentially. In parallel, the growing consciousness of the role of feedback in biological and environmental systems – and the need to model and quantify these – cries out for a public understanding of the need for, uses of, and pitfalls in feedback systems.

At the same time, the prevalence of cheap real-time computing platforms and hobbyist accessible programmable cars, houses, robotics, and drones means that there will be a proliferation of computer controlled devices, with most of the code written by people with not even a basic understanding of feedback systems.

One place to address this is with middle and high school students who are taking Science, Technology, Engineering, and Math (STEM) classes already. While we – the controls community – have the domain knowledge to give these students insight and enthusiasm for the world of feedback (and feedforward) control systems, it is critical that we walk the path between oversimplifying our descriptions and acting as if we are presenting to impress our peers in the community. This paper provides some insight based on the author's personal experience at multiple controls seminars for high school students.

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2. UNDERSTANDING THE AUDIENCE

In any attempt to teach material, it is important to understand the level of the audience so as to create an "impedance match" between the speaker and audience. This author has observed that on many occasions, attempts to introduce feedback control to middle and high school STEM students either vastly underestimates or overestimates their knowledge. At one end there are toy problems that never explain how feedback principles are involved and what they do. At the other is a researcher presenting a plot from their last conference paper and using terms such as stability, optimality, adaptation, and robustness without ever defining these for the students. The observed effect is that many students appear to tune out until meal time, looking at their smart phones instead of listening to the speaker. When that happens, we researchers have lost an opportunity to inspire a new generation, and may have done more harm than good.

While middle and high school STEM students are at different places in their educational careers, there are a few common limitations that one can apply for almost all of them.

- With the exception of high school seniors and some select juniors, the students have probably not had any courses in calculus.
- The student that has seen anything about differential equations is the exception rather than the rule, and this probably indicates that they took advanced classes outside of school or had a parent or friend teach them.
- Almost none of them will have seen anything about transform theory.

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- Middle school students have not had any mathematically based introduction to chemistry or physics. High school juniors and seniors are likely to have seen these subjects, but presented without calculus, probability, or differential equations. Most of them have had a biology class; certainly by their first year of high school.

However, there are often positive features that we often ignore, but should not.

- With the exception of students in sixth or seventh grades, one can assume that all of them have had some algebra and have learned about proofs in geometry.
- They are not afraid of math, but they know that they are missing many pieces.
- Many of them have been doing some level of programming from an early age.
- They are completely comfortable with ideas of networks, autonomous agents, robotics, smart sensors, self driving cars, and the like.
- They are a self selecting group and therefore the audience is most likely very bright on average.
- They are as a group, visual and physical in their understanding of things.
- They decide relatively quickly whether someone is worthy of their interest.

How do these "axioms" relate to introducing control concepts to these students? The students in the workshops want to know **what this stuff is**. They have been told that control is an important technology, so they want to know **what makes it important**. Because they are bright and have been taking science and math classes, they believe that they can understand difficult material. Subject to the above limitations, **they want a technical understanding of how it works**. Likewise, subject to the above limitations, **they want to understand how we understand this stuff and make it work**.

At the same time, they have not been to college and so they are unlikely to have deep concerns about graduate school. They rarely care about the details of our lives or our careers, **unless we can relate it to something important in their lives**. They have no fear of robots, agents, networks, etc. but they have no clue what stability, robustness, optimality, etc. are **unless we tell them**.

3. BASIC PRINCIPLES AND TOPIC AREAS

The basic principles for teaching control to these students is – understanding the audience – to start at a high level with physical examples, and follow up with the underlying principles that tie those examples together. The process iterates as we select topics that are of importance in the study of control systems, with each level adding both physical and general insights into some aspect of control systems.

The types of examples should be drawn from both history and everyday life. Since we are all humans in the loop at many points in our daily lives, these systems are particularly helpful. They are physical, they are ever present, and the decision process that humans have to make can be easily visualized. It is a simple step to tell them that what we are really doing is teaching machines to do the same thing.

Likewise, simple mechanical feedback systems provide a very visual understanding of human built feedback systems. They span history, from the earliest outriggers and water clocks (Abramovitch (2005); Mayr (1970)) to the ubiquitous toilet examples. Again, it is a simple process to turn these systems into a block diagram and then discuss how we would teach a machine to make those decisions.

Along with that, there are a list of fundamental topics that need to be covered for the students to begin to have an understanding of control systems. They include:

- Outer loops (big picture) versus inner loops (small picture).
- Discretization: why it's a big deal, what are the benefits, and what are the pitfalls.
- Delay and latency: how it matters little in signal processing and how it is all defining in feedback systems.
- Modeling of systems: how we get models from science and why we need them.
- Math: where does it come in with modeling, and how does it help us understand our systems.
- The math they know and the math they don't know yet.
- What are poles and zeros, and how do we solve problems relating to these?

4. TOP LEVEL: DEFINING FEEDBACK FOR THEM

One of the places where we can lose students is in not articulating a simple definition of what we will be describing to them. Thus, it is good to start with some straightforward definitions, followed by a physical example, followed by an engineering abstraction of that example. We will see this pattern repeat itself in the text. At a top level, we have found the following definitions useful and easy to understand for these students:

Control: Make something move where you want.
Feedforward: Estimate (guess) how to push it but never use where you see it going to adjust how you are pushing.
Feedback: Look at where its going as you push it and adjust how you are pushing.

Without some definitions like these, the poor students have no idea what we are talking about when we start explaining our work, With them, we get straightforward agreement. At the very least, they have a glossary of our terms. Once this has been done, it is important to emphasize the ubiquity of control: that it happens everywhere in nature and that people are doing control all the time (when we throw a ball, ride a bike, drive a car, put a key in a lock, or find a keypad on a phone). With these simple examples from their every day life, we can tell them what we are really doing: teaching machines to do what we humans do all the time and what happens in many natural systems.

The next step is to introduce a feedback loop that all of them should be familiar with. There are lots of choices here, but we have found the shower loop example to be

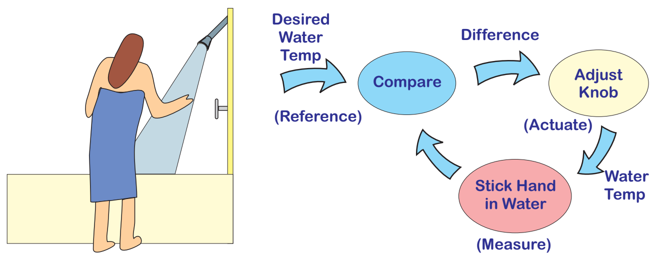

Fig. 1. A common feedback system, and the “loop” abstraction.

most universal (hopefully). This is displayed with the diagram on the left of Figure 1, and the “almost block diagram” on the right. The steps are phrased in both the physical steps that the person takes and in their control system nomenclature. From here, it is easy to explain to them that this is an example of a universal set of steps, that all feedback loops have:

- a reference signal,
- a measurement,
- a comparison element, and
- an adjustment mechanism.

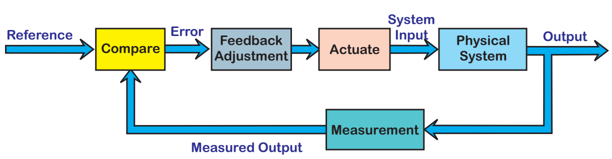

Fig. 2. The basic elements of a feedback loop.

This allows us to move them to what looks like a true engineering block diagram, where the loop on the right of Figure 1 has been generalized into the block diagram of Figure 2. Now, we have named the internal elements of the loop more clearly, as well as added something about its function. Now, we tell them that every feedback mechanism has (Mayr (1970)):

- a sensing element (that which makes the measurement),
- a comparator (that which compares the sensed value to the reference and turns it into an adjustment),
- and an actuator (that which physically makes the adjustment).
- Furthermore, it runs in closed-loop – that is – a portion of the sensed output is fed back into the system.

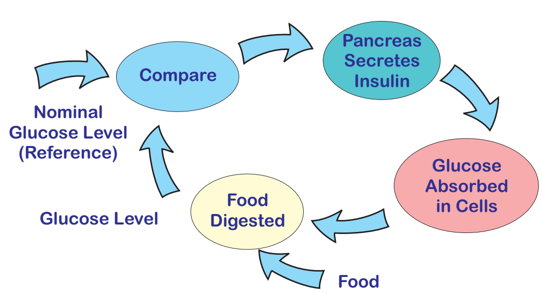

Fig. 3. A simple blood sugar feedback loop.

With the generalization of Figure 2, we can again relate them to something that is universal, the sugar loop in which our bodies regulate our blood sugar, shown in Figure 3. Now, this loop is internal and relates to something that many folks understand, that the pancreas wants to maintain a steady range of blood sugar, despite disturbances (food input, stress, etc.). Historically, understanding relationship between insulin and blood sugar led to first diabetes treatment. As most kids of this age know that diabetics need to measure their blood sugar and adjust (by eating or injecting insulin), we can frame this as diabetics closing the loop themselves. This also brings a natural discussion of sample rates into view, since most diabetics will only do this check 4-6 times a day, while a non-diabetic system will make this adjustment constantly. In the past few decades, insulin pumps have been developed, but this run open loop, that is without being regulated by a measure of the person’s blood sugar. This is a natural segue into the area of artificial pancreas (Haidar (2016)), which are a big topic of controls research and practical application.

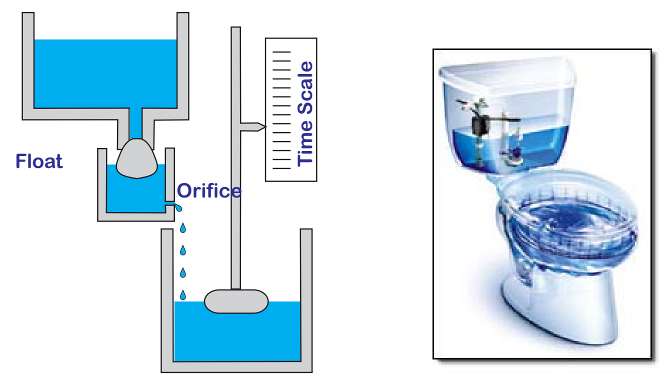

Fig. 4. The float valve of Ktesibios and its modern day descendant.

It is worth mentioning the water clock of Ktesibios, an ancient Greek inventor who lived in Gaza, in the third century B.C.E. (Mayr (1970)) who created a water clock that measured the flow of time by how fast the bottom reservoir was filled from the top reservoir (on the left of Figure 4). The issue is that water flows faster when the supply is higher, meaning the measure of time would not be uniform. Ktesibios clever solution was the float valve, which kept the level of an intermediate reservoir roughly constant, allowing the lower reservoir to fill at a more constant rate. Float valves are still used in the modern day toilets (another ubiquitous example). This example is mentioned because if multiple speakers are discussing control with these young students, they only really need to hear about the float valve once.

We have a particular affinity for the outrigger as an example of ancient feedback, since it is more fun than a toilet, and is at least 1200 years older than the water clock (Abramovitch (2005)). Again, this example is very physical and intuitive, yet provides an opportunity to do analysis that guides the student in how controls work is done. Another great example is the flyball governor (Bernstein (2002)). The main historical note about the flyball governor is that it is when feedback control first “went viral,” at least in the pre-electricity days. Because it

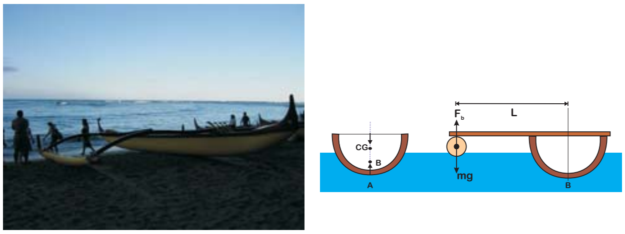

Fig. 5. The outrigger is also a great, physical example, and much older than the float valve (Abramovitch (2005)).

was so useful in the operation of steam engines, and coming right at a time when mathematics was being applied to engineering, it represents the first feedback device for which was studied with significant mathematical analysis.

It is also worth telling the students at this point that there are two types of feedback. Positive feedback in devices as in life, causes something or someone to amplify (or do more) of what it was doing before. Positive feedback will cause a system to amplify the input. If the gain is high enough, the output can grow until one of two things happens: something saturates (hits some limit and then bounces back and forth between limits, which is useful for building devices such as oscillators) or something blows up (which is generally not that useful and can be directly related to such disasters as Chernobyl (Stein (2003))).

Negative feedback (in both devices and life) causes something or someone to deviate less from some desired path than before. Negative feedback will cause a system to become less sensitive to changes. It generally trades absolute gain for stability of gain. For example in building electronic amplifiers, their overall gain is limited by using feedback, but that gain remains steady despite temperature changes, wear, etc. which allows us to build devices that behave reliably the same way time after time.

Finally, we can sneak a reference into what stability analysis is all about by pointing out that bad things happen when negative feedback becomes positive feedback. Chernobyl is the perfect example. A simple explanation for what usually causes this is that the correction lags the error by too much time, a too much too late scenario.

This sequence allows the speaker to go from broad definitions to something that is a current topic of control research and application in a few minutes. Each step builds on the use of physical examples, to abstraction, to application to more physical examples. None of the steps should be difficult for middle and high school STEM students. If we stopped at this point, they would be able to tell someone what a feedback system was, describe its components, and give two simple examples. At this point, we are able to circle back and give them considerably more detail.

5. ABSTRACTION TO BLOCK DIAGRAMS AND THEIR COMPONENTS

Once the overview examples are done, it is useful to take them up a level of abstraction. We have found that the pattern of physical example, abstraction, definition, and detail, can be repeated as we go deeper into the material without loosing the students' interest. Figure 6 is a nice

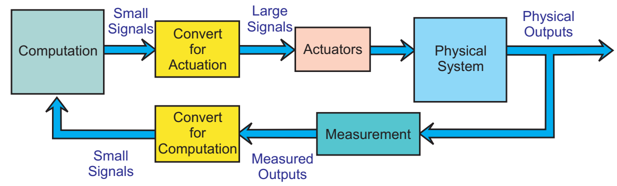

Fig. 6. Expanding the generic feedback diagram to see more of the components needed to make it work.

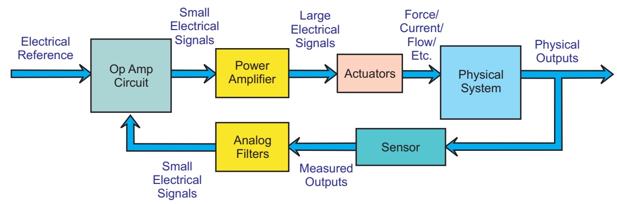

Fig. 7. The diagram of Figure 6 where the computation is done via analog circuitry.

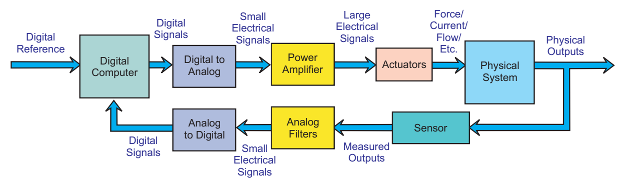

Fig. 8. The diagram of Figure 6 where the computation is done via digital computation.

starting point for a discussion about the components of a control loop and how they affect the size and complexity of systems for which we can build controllers. Each of these components needs to be defined in terms that the students can understand. For example:

Sensors: tell us what is happening.
Converters: change what sensors see into something we can compute with and back again into something that does something about it.
Computation: make decisions about what to do.
Physics: what the real world is really doing.
Modeling: how we describe this to our computation.
Actuators: do something about it.

With these items defined, we can go into a bit more detail. Most middle and high school STEM students have decent familiarity with computing and it is useful to explain how computing is done in control systems. If the speaker has enough time, they can discuss the historical step of using analog circuits for doing the computation, as shown in Figure 7. Depending upon the amount of time the speaker has, this provides a nice chance to describe historical feedback systems. An interesting pair includes the World War II "robot battle" between the German V1 cruise missiles and the M4 Anti-Aircraft gun director which directly linked radar measurements to the control of the gun itself (Mindell (1995)). Analog feedback was significant in the development of telephony, both positive feedback for oscillators and negative feedback for amplifiers (Bernstein (2002)). Again, these are historical touch points that help frame the discussion for the students, but can be omitted in the interest of time.

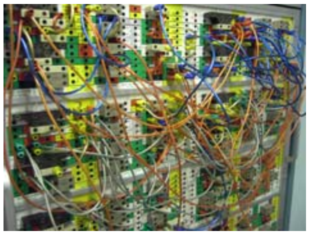

Fig. 9. A "program" on an analog computer.

Analog circuit implementations of control laws are a far less significant part of the modern control landscape than even a few decades ago. An emphasis that makes sense is one that replaces the op-amp circuit computation of Figure 7 with a digital controller shown in Figure 8. For all the potential issues with digital control, showing them a program on an analog computer (Figure 9) should convince them that digital is the way to go. We should point out that even with digital controllers, we still use analog circuits to help us "touch the real world", but they are now signal conduits, not decision engines. Showing the students a picture of an analog computer patch panel makes the reason for this obvious: it is really hard to program and debug anything complex on an analog computer. Here is a good opportunity to make a point about what we do: We are all about teaching a computer to use sensors and actuators to intelligently move stuff around.

6. DELVING DEEPER: FEEDBACK LOOPS OCCUR AT MULTIPLE LEVELS

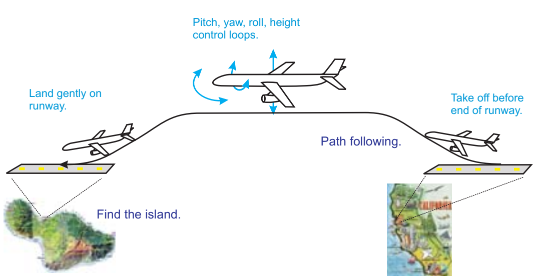

Fig. 10. An example that has loops within a loop.

A useful physical example is shown in Figure 10, which shows a pretty simple diagram of a flight from California to Maui. This diagram is illustrative of the different levels of feedback loops in everyday systems. There is the big path:

- Take off from the runway.
- Find the island.
- Land on the runway.

Within the big path, there are small feedback loops:

- Roll control (dont flip the plane).
- Height control (keep correct height).
- Yaw control (keep right direction).
- Temperature control, engine control, flap controls, etc.

The point is that this illustrates that feedback is something that happens at all levels of engineering systems.

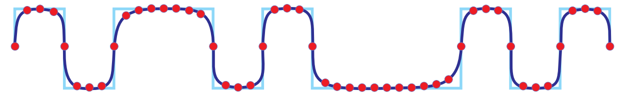

Fig. 11. A pictorial representation of sampling.

Fig. 12. Analog entertainment

Fig. 13. Digital entertainment

7. DISCRETIZATION

The diagram of Figure 8 and the common experience of these students' lives indicates that there is a lot of stuff being done with "digital computers" (or as they would call them, computers), but they really have not been told what is up with discretization. That is, they don't really know how the data gets into and out of the computers.

It is useful to take a Devil's Advocate point of view here, pointing out that digital ("computer") control is bad because:

- Math less like the real world, so modeling is harder.
- Signals approximated by a certain number of bits (Figure 11).
- Signals sampled in time which means that we only look at data every so often and assume it behaves.

Logically, the devices of Figure 13 should never replace those of Figure 12, and yet this has happened. We can then ask and answer as to why this happened, that while sound quality on perfectly tuned, high grade, analog audio, played from reel to real recording beats almost any digital music recording, digital methods allow a cookie cutter approach. Bits are 0 or 1 and we dont care if its a large signal or small so miniaturization happens. Wiring gets replace by computer programs. Copies are exact.

We must remind them that computers must still "touch" the real world to do anything useful, and this is the difference between something happening in computer graphics and in real life.

8. SENSITIVITY TO DELAY: THE DIFFERENCE BETWEEN SIGNAL PROCESSING AND FEEDBACK CONTROL

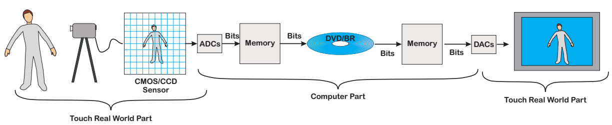

Fig. 14. Discretizing image of human for creating and playing back a DVD/BRD.

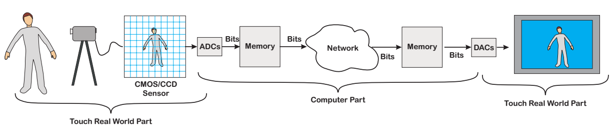

Fig. 15. Discretizing image of human for transmitting across a network.

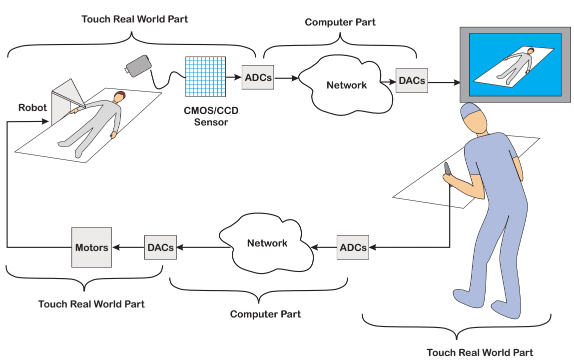

Fig. 16. Remote surgery involves feedback from the images, making latency relevant.

Another useful topic comes out of the whole discussion of discretization and can be easily illustrated to the students using Figures 14 – 16. The top Figure 14 illustrates the process of taking an image or sets of images into an optical disk recording (DVD or BluRay) and playing it back. The important illustration for the students is that the real world images are discretized (using an ADC at a particular sample rate), processed, and stored on the disk. At some arbitrary point later in time, the digital information can be retrieved from the disk, and returned to an analog form (via a DAC) for display on the screen. In the case of a digital monitor, the actual conversion back to analog form is on the screen itself. The individually addressed pixels are integrated by our eyes to produce the analog image that our minds can see.

When we stream these images across a network (replacing the disk, Figure 15) we again have the same discretization and return to analog processes. It's just that the middle part has changed. In either case, there is no great worry about the delay between when a particular image was taken and discretized, and when it shows up on the screen. We don't care whether the delay from the disk to our eyes is 0.1 or 1 second, so long as it is consistent, and while we might want to see some sporting event live, we don't worry whether the screen images are delayed from the stadium on the other end of the world by 1 or 10 seconds.

This all changes when those network images are being used in remote surgery (Figure 16). In this example, the surgeon is operating on a patient far away using a remote robot. Now, it becomes very obvious that any delay in communication of those images to the surgeon and in translation of the surgeon's controller movements to the robot must slow the surgeon down in their movements. We can use this to teach why we are so concerned about delay in feedback systems, while it is a minor annoyance in the first two examples which would be considered signal processing problems.

9. CONCLUSIONS FOR PART 1

This author's experience in giving such seminars to middle and high school students in a variety of pre-conference workshops has led them to believe that this pattern is highly successful and can be adopted by others. The first point is that as technical experts, we must take the Hippocratic Oath towards engaging these students: we must first do no harm by not turning them off to the subject. It takes considerable effort to take this material, interlace it with current pop culture references and examples that relate to the students' experiences to keep them engaged for the time of the presentation.

This material can also be adapted for college STEM students. The difference is that most of them will have had some differential equations, many will have had some transform theory, and some will have had their first controls class. That being said, it is still something that can be used. In Part 2 (Abramovitch (2019)) we will discuss how to talk about control system math when almost none of the students have learned about differential equations.

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