16-299 Spring 2021: Lecture 1
Introduction to Feedback Control Systems

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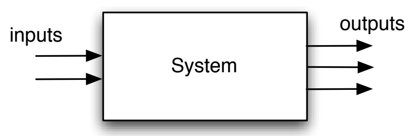
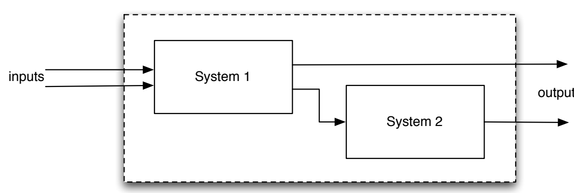
1 Introduction

This class is about **feedback control systems**. Three words: feedback, control, and systems. Let's take them in revese order. **Systems** means that we treat everything as a box that has inputs and outputs, like so:

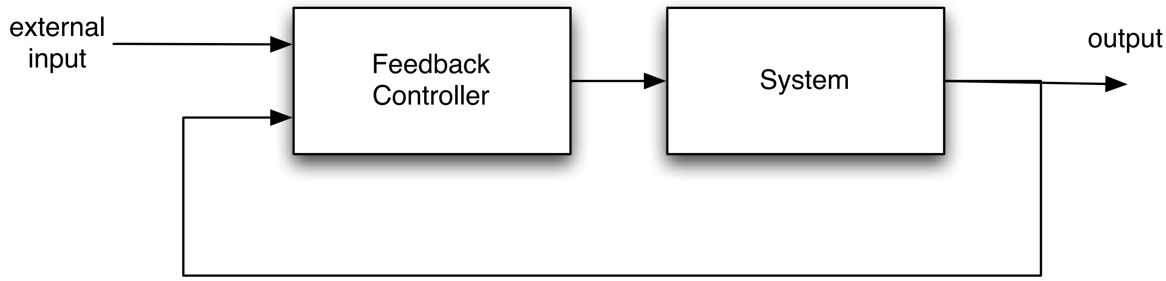


There is a deterministic mapping between the inputs in the outputs, i.e., if we know the input, we know what the output should be. OK, there is a small caveat to this: sometime we need to know something about the internal state of the system when things get started, often called "initial conditions". Note that blocks can be connected together the output of one block to the input of another. The result can be thought of as a bigger, more complex system, but it is still a system with inputs and outputs.



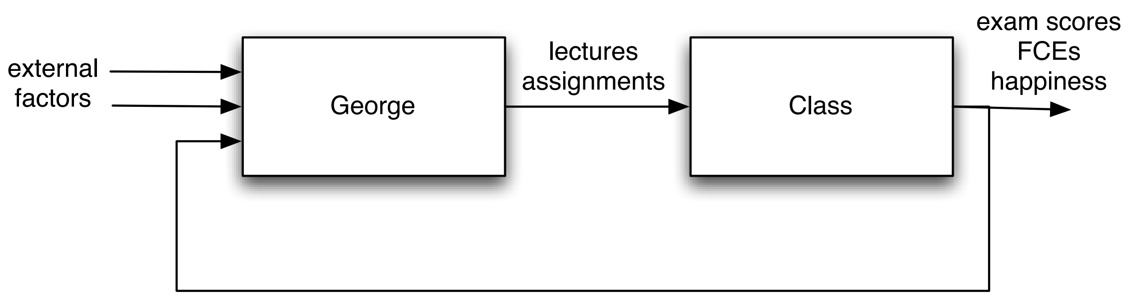
Controls means we'll try to make systems behave the way we want them to. In other words, we try to find an input so that the output tracks some desired behavior. In other words, for some time interval $[t_0, t_f]$, find a control signal $u(t)$, $t \in [t_0, t_f]$, so that the resulting output signal $y(t)$ is identical or very close to some desired output $y_d(t)$ for $t \in [t_0, t_f]$.

Feedback means we'll make the input of the system be a function of its output. This creates a loop, hence feedback control is sometimes called "closing the loop" or "closed loop control". In other words, u becomes a function of both t and y, $u(t, y(t))$. Or in the more usual case of feedback control, u does not explicity depend on time, so we have $u(y(t))$.

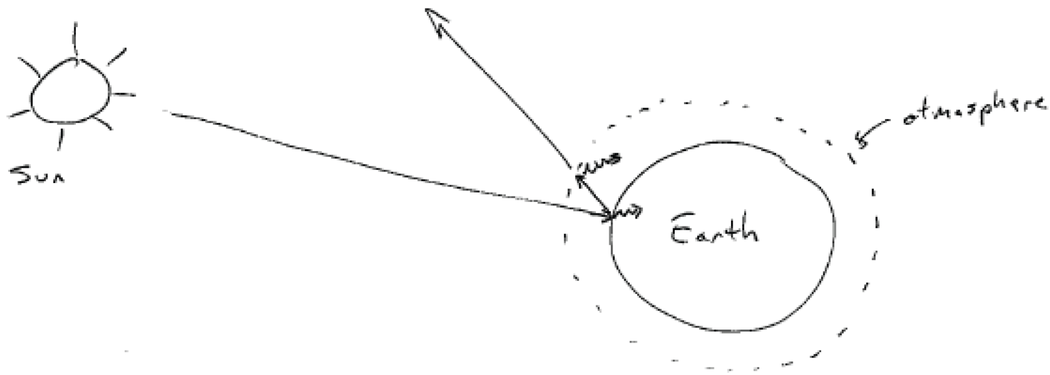


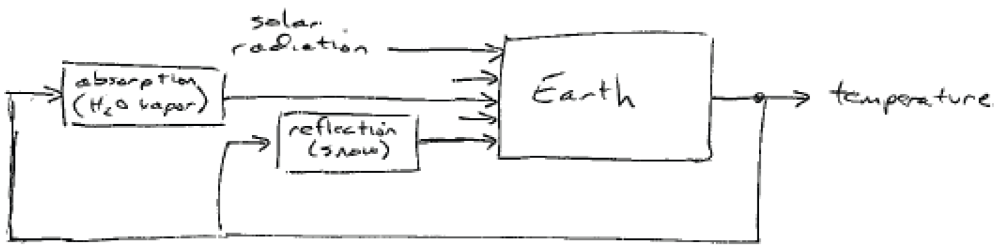
Forget about control for a second – the really interesting thing is feedback. Feedback is everywhere, and it can cause strange and wonderful (and sometimes terrible) things to happen.

Feedback can be good. Consider, for example, the history and evolution of this course. The class can be though of as a system that has lectures and assignments as inputs and exam scores, FCEs, and student happiness as outputs. The instructor can also be though of as a system that has many inputs and generates lectures and assignments as outputs. These systems can be connected together in an obvious way. The exam scores, FCEs, and student happiness from one year influence the lectures and assignements, hence there is feedback. Hopefully, if the instructor does a good job, the class will get a little better every year until it settles into some good steady state.



Feedback can be bad. Consider the Earth. This can be thought of as a system with a bunch of inputs and temperature as an output. Multiple feedback loops exist that can make bad things happen. If it gets colder for some reason, then there will be more snow, which reflects more of the incoming radiation, which makes it colder, and so on. If it gets a little warmer, then the atmosphere holds more water vapor, which prevents heat from being radiated away, which raises the temperature, and so on.





So feedback can be useful to help control and stabilize things, but we have to be careful because feedback can make things go horribly wrong.

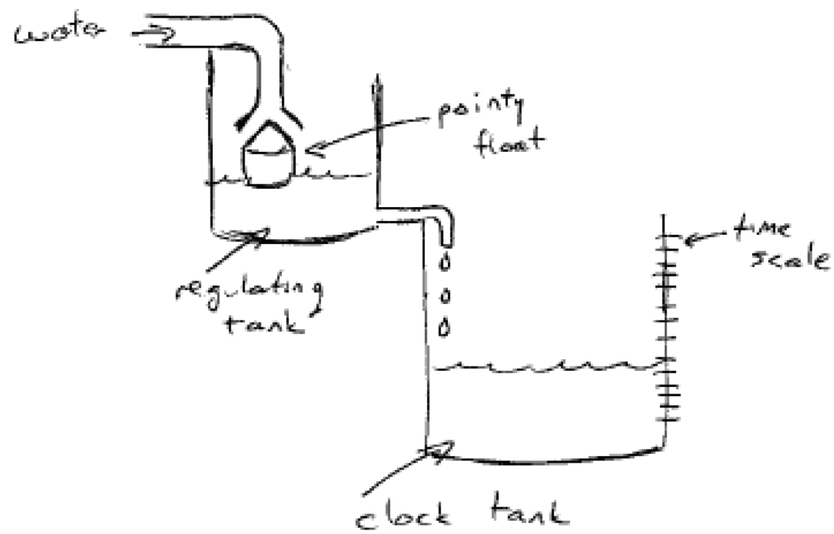
The objective of this class is to learn how to apply good feedback.

2 A History Lesson

The two examples above are examples of systems where feedback just happens naturally or is controlled by a human ("human in the loop"). We want to learn to add feedback to get the system to behave we want it to with out human intervention, hence the term "automatic feedback control". People have been doing automatic feedback control for a long long time. Here are a few examples from ancient history.

2.1 Ktesibios Water Clock

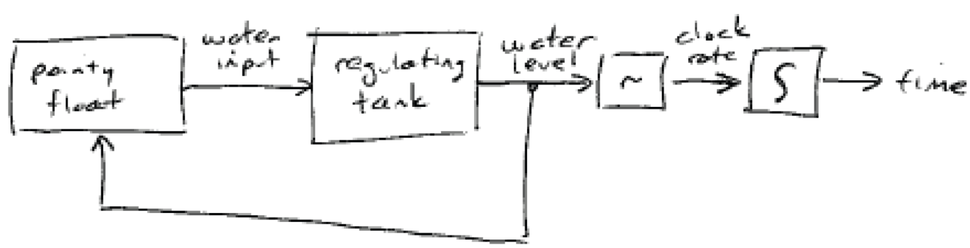
This was invented around 300 B.C. by the greek engineer and barber Ktesibios. It's the earliest example I know of of automatic feedback. Here's a drawing:



And here's how it works:

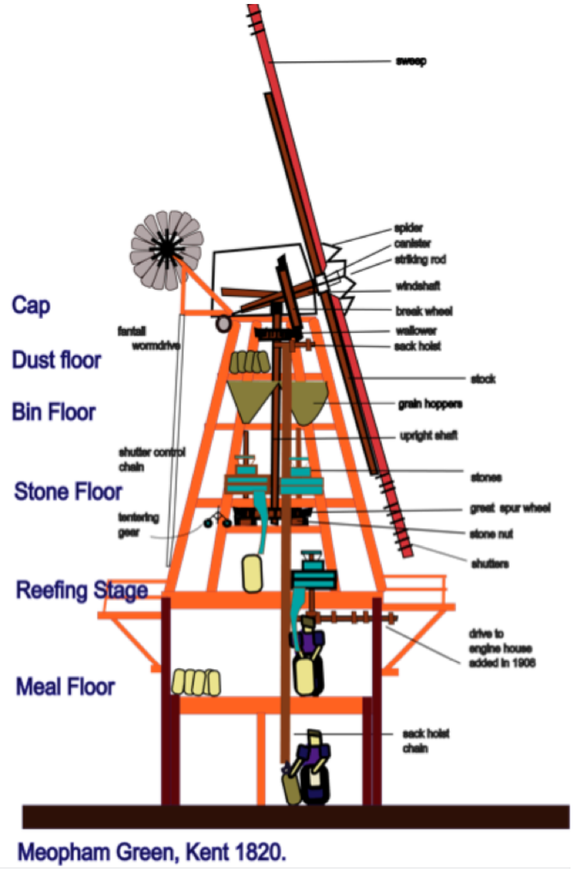
- The key to keeping good time is to have the flow rate into the clock tank be constant.
- It turns out that, if we supply the water for the clock from a second tank (aka, the regulating tank), the flow rate of the water into the clock tank is a function of the water level in the regulating tank.
- Ktesibios invented a simple feedback system to regulate the water level in the regulating tank that was basically just a pointy float directly beneath the pipe that supplies water to the regulating tank.
- if the float is too high, it plugs up the pipe, the flow into the regulating tank is decreased, and the water level in the regulating tank drops.
- if the float is too low, the pipe is wide open, increasing water flow, and raising the water level.

This is an example of hydraulic feedback. We can draw it as a block diagram. In this case, the float acts as both a sensor and an actuator.

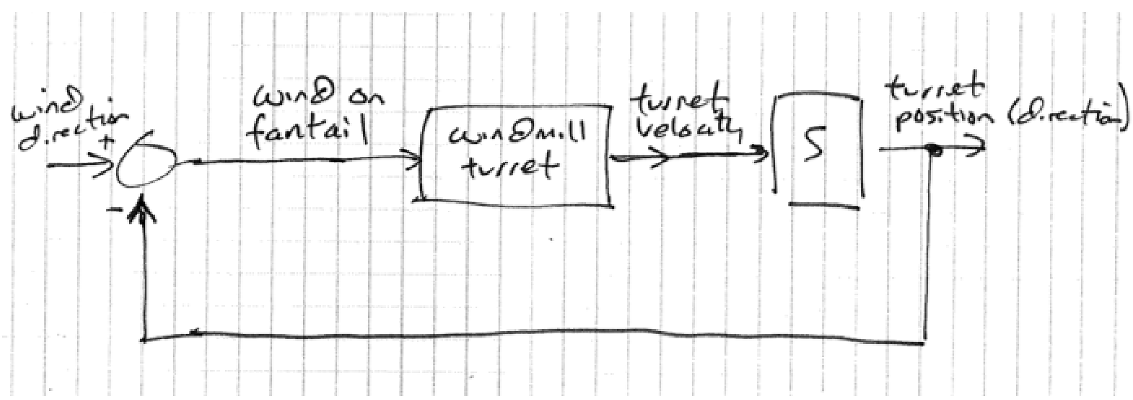


2.2 Self-pointing Windmills

Here's a schematic of a windmill from the early 1800's.

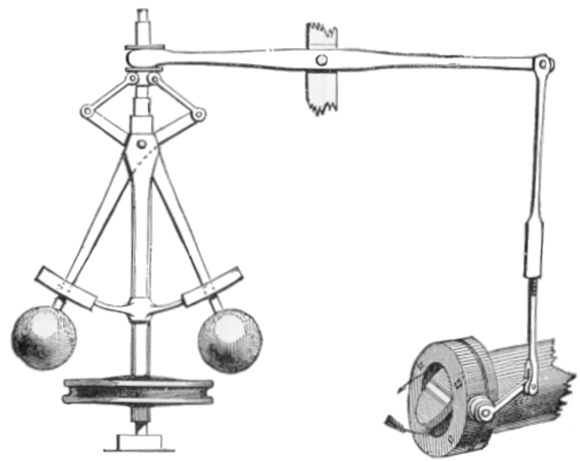
Note that there is small windmill on the back (called a fantail) that is used to point the top part of the windmill so that the big blades face the wind. We can think of this as a system. The fantail is a sensor that senses the amount of off axis wind. The drive mechanism as the base of the turret can be thought of as an actuator that applies a torque to the top part of the windmill. The linkage that connects the fantail to the drive mechanism is the feedback. Here's a block diagram:



2.3 Watt Flyball Governor

Invented in 1788, this famous example is often cited as the first example of automatic feedback in the modern era (though it was invented over 2000 years later than the Ktesibios clock). Watt's steam generator is often credited with spurring the industrial revolution.

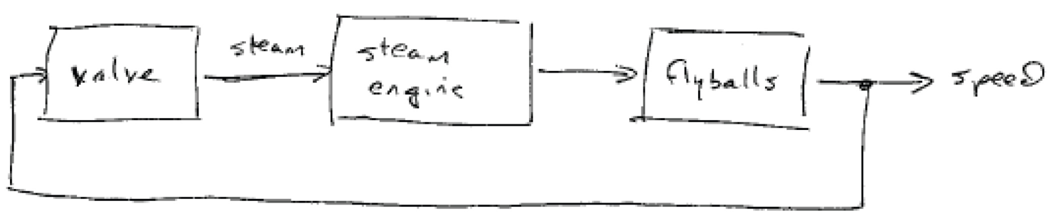
Here's a picture borrowed from Wikipedia, which they borrowed from "Discoveries & Inventions of the Nineteenth Century" by R. Routledge, 13th edition, published 1900.



This is an example of mechanical feedback. Here's how it works:

- if the wheel spins too fast, centrifugal force causes the flyballs to be pulled out and up, pulling the lever top of the flyball mechanism down, pushing the other end of the lever up, causing the steam valve to close off, reducing the amount of steam, reducing the engine velocity.
- if the wheel spins too slow, the opposite happens, causing the wheel to speed up.

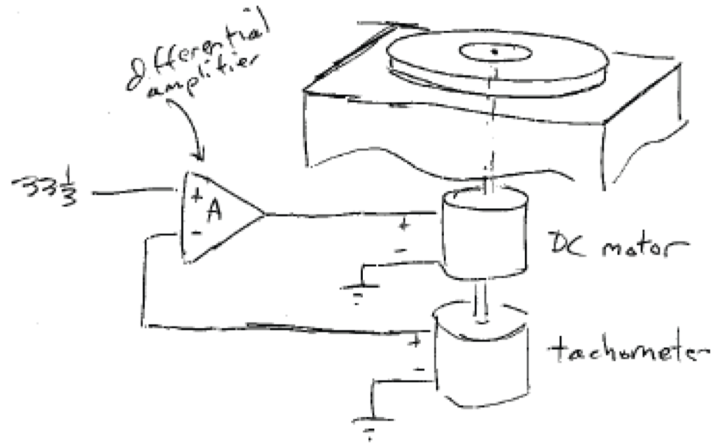
Here the flyballs act as a sensor: they measure the rotation rate of the steam engine. The steam valve acts as an actuator, it provides the input that allows us to control the engine. Here's a block diagram.



A toilet is another example of mechanical feedback!

2.4 Record Player

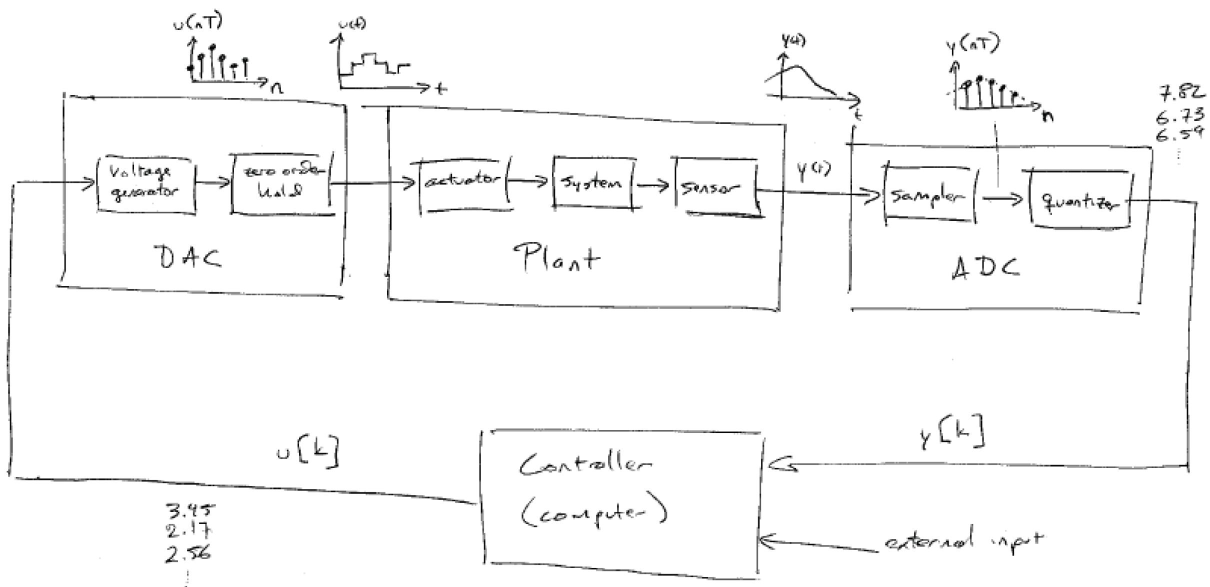
A speed control system for a record is an example of analog electronic feedback. Here's a picture:



2.5 Digital Control via Computer

These days, most feedback controllers are implemented with a computer. This is good, computers are general purpose machines, so the same computer can easily be programmed to control a variety of types of systems.

Here's the standard block diagram:

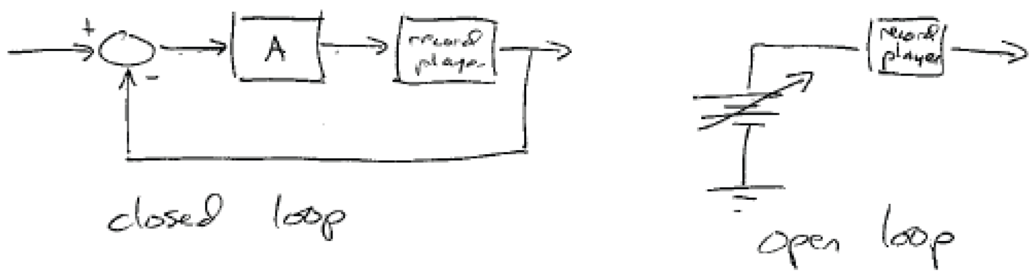


3 Some General Comments

3.1 Why is Feedback Good?

Let's revisit the record player example:

Now compare it to a simpler method of control, just manually adjust the motor voltage until the motor spins at the right speed. This is called “open loop control”.



Why is feedback better?

1. **disturbance rejection:** What if I push on the record? Closed loop system will automatically compensate and make the motor attempt to counteract my push. Open loop will not.
2. **robustness to system parameter uncertainty:** What if the friction changes with time? Or what if I want to build 1000 record players but they don’t all have the same friction? Closed loop will sense that the record is spinning too fast or too slow and counteract it.
3. **set point flexibility** What if I want to play a 45? This can be done easily by changing the set point that we compare the tachometer reading to.

3.2 Postitive vs. Negative Feedback

Note that all of the feedback mechanisms in the previous examples employed negative feedback, i.e., the feedback action worked to decrease the error between the desired and actual outputs. This is in general a good thing, but not always easy to do especially when the coupling between the input and output is complex!

4 Course Preview

see syllabus schedule.