An Introduction to Charge–Coupled Devices

Materials Needed—

- A lot of beans
- 25 small paper cups
- 1 baseball
- Paper & pencil

Objectives—

- Understand how CCDs are constructed, collect light, and create a digital signal.
- Illustrate how a CCD collects photons given a variety of conditions.
- Describe sources of CCD noise (read noise, dark current, cosmic rays) and their causes.

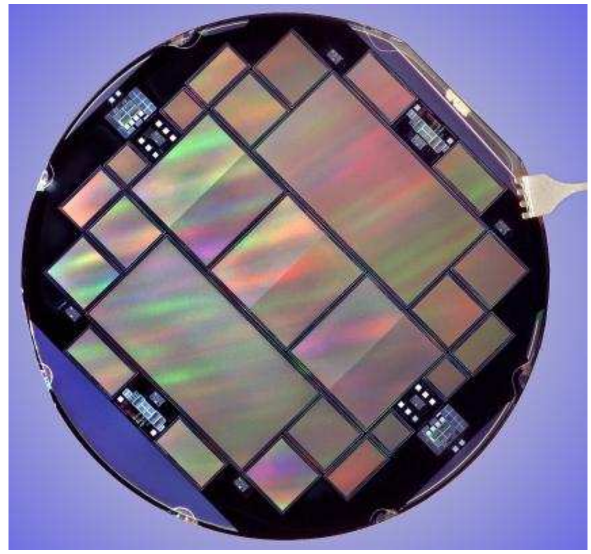

Fig. 1.— A CCD developed at the Lawrence Berkeley National Laboratory for astronomical observations.

Introduction— Charge–Coupled Devices (CCDs) are used in many modern devices to capture and digitize images. Everything from your cellphone camera to a telescope detector uses a CCD of one form or another. The basic design consists of a wafer of silicon crystal onto which "gates" are grown through a variety of processes. This gate defines one pixel. As a photon strikes the gate, it causes one electron to form in the gate. The gate effectively acts as a capacitor and stores the charge. Each pixel collects a supply of electrons that is directly related to the number of photons that have hit the gate. Each gate has a maximum number of electrons that it can hold. The CCD consists of many rows of these gates, forming a grid–like structure over the detector area.

In a CCD for capturing images, there is a photoactive region (an epitaxial layer of silicon) and a transmission region made out of a shift register (the CCD, properly speaking). An image is projected on the photoactive region/pixel array, causing each capacitor to accumulate an electric charge proportional to the light intensity at that location. Once the array has been exposed to the image, a control circuit causes each capacitor to transfer its contents to its neighbor. The last capacitor in the array dumps its charge into a charge amplifier, which converts the charge into a voltage. By repeating this process, the controlling circuit converts the entire semiconductor contents of the array to a sequence of voltages, which it samples, digitizes and stores in some form of memory.

Procedure— We have assembled a grid of paper cups, each representing a pixel. Each bean represents an electron generated by a photon hitting a pixel's gate. For each of the questions below, use the beans and cups to find the answer.

1. In an ideal world, how would the light from a distant star be detected on our paper–cup CCD?
2. In the real world, how will the light be collected? What causes this difference? What role does the atmosphere play in determining how we detect the star?
3. Let's also think about what is going on around the star. Let's say we are observing the star against very dark background. How will this be reflected on the CCD?

Suppose we are now observing a star that emits 3 photons per second, but there is a lot of atmospheric distortion, so this light is spread between four adjacent pixels, creating a square. Also suppose we are observing against a moderately bright background that emits 1 photon per second per pixel over the entire field of view.

4. How will the CCD look after 1 second?
5. After 2 seconds?
6. After 3 seconds?
7. After 10 seconds?

Finally, let's clear out our CCD and observe a very bright star which emits 20 photons per second over a 4 pixel square. Let's say the background is minimal (1 photon per second per pixel), but there is a dim star emitting 2 photons per second in a pixel adjacent to the bright star. Our exposure time will be 60 seconds. Fill up each cup with the appropriate number of beans.

8. What happens to pixels that pick up photons from the bright star?
9. What about the pixel for the moderately bright star?
10. How might this cause difficulty for observers?

You've finished a 10 second observation of a star with a moderately bright background. How will the CCD record the information contained in each pixel in order to quantify and save it? Go back to the Introduction for some hints.

11. Imagine moving the beans from cup to cup while wearing mittens. What might happen?

Read Noise *is the natural error introduced to the values read–out by the CCD itself.* This noise comes from both the CCD and the process of converting the electric charge into the digital signal that is recorded.

Next, we cover the CCD with a lens cap (or in this case, some paper). Even if photons hit the cap, they won't penetrate to the gate and create an electron. Bounce some beans off the paper if you want to test this out.

12. What is the electric current we should measure in this situation?
13. Examine Figure 2. This is the result of a 0 second exposure with a CCD, which in astronomy is known as taking a **bias**[a]. What do you notice?

This is an intrinsic characteristic of the device, and is caused by the spontaneous creation of charges within the silicon, which are then swept into pixels by electric fields which are part of all semiconductors.

[a]Technically this is actually a dark, not a bias. We'll get into the distinction later.

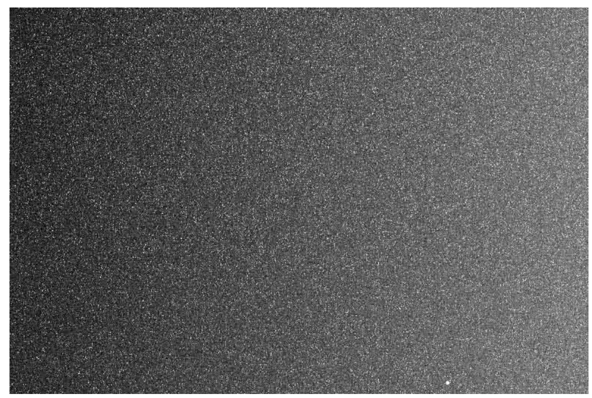

Fig. 2.— CCD image taken with the lens cap on the telescope.

Dark Current *is a direct result of the temperature of the CCD. If we cooled the CCD down, the dark current would also go down. This is why most astronomical detectors are cooled!* To correct for this effect, we take images such as the ones in Figure 2 during observations and subtract them from our data observations.

Cosmic Rays are another source of detector noise. *These are subatomic particles (protons, electrons, etc) that come from a variety of sources in the universe.* They are traveling at great speeds, and thus contain a huge amount of energy. In this exercise, we represent cosmic rays as baseballs.

14. What happens to a pixel if it comes into contact with a slow–moving cosmic ray?
15. What happens if the cosmic ray is moving fast?

On Earth, energetic cosmic rays are usually stopped high in the atmosphere. The ray interacts with atmospheric molecules and decays into so–called secondary cosmic rays. These can still affect CCDs, and are partly to blame for the degrading of CCDs over time.

16. If one cosmic ray destroys a pixel every 3 months, how long until you would find our CCD is no longer usable?

In this exercise, we have assumed that one photon striking the silicon will create one electron in the pixel. This means our **gain** is 1. If we were very starved for photons, we might set a higher gain. If we had a gain of 10, this would mean one photon creates 10 electrons in a pixel. This increases the signal which is read out.

17. When might it be good to have a high gain? Why?
18. When would high gain be bad?