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A Universe of Systems

Dudley Green

⚙ **Key Concepts**
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The products of technology and engineering have powerful impacts on society—both good and bad. The story you just read about the mass production of the car would convince anyone of that fact. But remember that humans designed manufacturing technologies in the first place. That means we have the power to design products and manufacturing *systems* that minimize unintended consequences. Now, I'm not saying it's going to be easy! I'm just saying it can be done.

Before I go any further, let me tell you about my interest in systems. My name is Dudley Green, and I spend much of my time thinking about manufacturing systems as an engineer for Teradyne, a corporation with offices all of the world. I'm a process engineer, the engineer responsible for creating parts of manufacturing systems.

What Is a System?

The manufacturing systems I work on build printed circuit boards. These circuit boards go into larger machines that test computer chips—the kind of chips you might find in a cell phone, a DVD player, a photocopy machine, a car, or a piece of medical equipment.

I've always been interested in systems—in how the parts of something work together to make something happen. When I was a kid growing up in Dorchester, a neighborhood in Boston, I was always in trouble with my parents for taking my toys apart. I wasn't trying to destroy the toys; I just wanted to see how they worked. My first bicycle, for instance, was a great mystery. But after taking apart the derailer, the chain, then the handlebars and the brakes, I gained a good idea of how my bicycle moved forward, stopped, and turned. The real problem, of course, was putting it back together again!

In high school I learned that taking toys apart was my early effort to figure out how my bicycle parts worked together as a system. Mathematics and science were my favorite classes in high school, but, well…let's just say that my grades did not always reflect my true love of learning. I was captain of the football team, and that focus often took up most of my time.

When I was accepted into Wentworth Institute of Technology in Boston to study mechanical engineering, I took apart all kinds of machines to see how their parts worked. Because I also needed to work full time to put myself through school, I got a job at Teradyne as an assembler on the factory floor. I assembled parts of circuit boards by hand. It was a good job, and it gave me hands-on experience to help me in the work I do now. All in all, it took me about ten years to get my diploma—but it was well worth the time!

Let me get back to telling you about systems because, to understand engineering, it's essential to understand systems. All circuit boards start as sheets of metal—gold, copper, or a combination of materials. Here's a picture of a gold circuit board that's nearly assembled. I'm holding my hand over a part of it because I don't want to give away any design secrets. Who knows? One of you may be working for the competition one day!

Photo taken by Rebecca Pierik

Sorry. Only Teradyne employees can see how our circuit boards are laid out.

A **system** is a group of parts that work together to achieve a specific goal. There are abundant examples of systems in the world; your own body is a living example. It's made up of systems of organs that work together to keep you alive. As Araceli told us, manufacturing technologies are systems that change materials into products. Manufacturing systems include the materials, machines, people, and resources used to mass-produce goods for the market. You'll learn about many other kinds of technological systems later.

Our factory uses an assembly line system. The circuit boards enter one end of the line and move along conveyor belts through machines and past workers. Like all systems, the assembly line can be broken down into inputs, processes, feedback, outputs, and goals.

Inputs include everything that enters the system to achieve the desired goal. To make a circuit board, you need natural resources, such as copper, gold, time, money, energy, labor, information, tools, training, machinery, and more. In a sense, you could even say that my education is an input to the circuit board manufacturing system at Teradyne.

Processes describe the parts of the system that actually change the inputs into the desired products. When you make cookies, your inputs are flour, sugar, baking powder, eggs, butter, and chocolate chips. But you must process these ingredients by mixing them, shaping the batter into cookies, and baking them in an oven. The mixing, shaping, and baking are your processes. No matter how great your ingredients are, if you don't have those processes, you don't have good cookies.

The manufacturing process at Teradyne includes a wide range of parts. In the first step of manufacturing a circuit board, a machine places a stencil over a blank board. The stencil, which I design, is a steel sheet with a cut-out pattern of all the electrical connections. The machine paints a paste made of tin and lead over the stencil. When the stencil is removed, the pattern from the stencil remains on the circuit board. Later, other machines attach the electronic components to this tin-lead paste pattern. All manufacturing processes use an orderly step-by-step procedure to complete an assembly.

Feedback provides information that the system uses to make adjustments during manufacturing. Feedback is critical during the process. Imagine if you put your hand on a hot stove and your nervous system failed to let you know your hand was burning. Your body, or any other system, needs feedback to operate properly.

A **system** refers to a collection of objects that work together to achieve a specific goal. All systems have:

- **inputs**
- **processes**
- **feedback**
- **outputs**
- **goals**

Photo taken by Rebecca Pierik

I designed this stencil to be used in the first part of the circuit board manufactuirng process.

Durable goods are designed to operate for a long period of time.

Non-durable goods are consumable. They may only last for one or two uses.

Likewise, feedback can catch problems during the production process. In our process, the boards are extremely sensitive to temperature. Feedback helps us maintain the correct temperature, preventing cracking or other damage. Sensors detect temperature changes and send signals to the machine to raise or lower the temperature.

Outputs refer to everything the process produces. The desired output of our system is a fully loaded circuit board. Factory processes change materials into outputs that you might see in a grocery store or at the mall. Many manufactured items are *non-durable goods,* which means they are disposable. Disposable cameras, paper plates, or plastic utensils are designed to last only for a short time. Many electronics break or become obsolete quickly as well—even the circuit boards that Teradyne designs. *Durable goods,* on the other hand, stand the test of time. Cars, hand-tools, ovens, and furniture are all durable goods. Goods don't become durable or non-durable by accident. Engineers design goods to have a specific life expectancy. A disposable coffee cup is designed for one use, whereas a ceramic mug may last a lifetime.

There are other outputs to consider—and worry about. In the manufacturing of our circuit boards, flux fumes are an unpleasant output. Flux is a material that we use to clean our components. It has a foul smell and can irritate eyes and skin. If a machine gives off excessive fumes, a special sensor triggers an alarm. People respond like they would to a fire alarm, running for open air outside the building.

Many manufacturing processes produce pollution—noise pollution, air pollution, water pollution, and others—as an undesired output. While designing manufacturing systems, engineers consider these outputs and try to keep them to a minimum. Fortunately, flux fumes don't pollute our office air too often, and never without warning.

The **goal** of a system is whatever that system is meant to accomplish, whether it's producing the best chocolate chip cookies on the block or producing a million cell phones. The goal of our manufacturing system is to efficiently produce high-quality circuit boards. We're constantly trying to **optimize** the system, or redesign it in a way to make it run more smoothly and more economically. When our system falters, we waste valuable time and resources. What would happen if one of our sensors broke down and a machine scorched twenty gold circuit boards? Our company would lose a lot of money! Because we want to avoid waste, we continuously optimize our system to prevent such problems. After all, the more boards we make, the more we can sell.

> **Optimization**
> is the process of making a system as effective as possible. ★ ★ ★ ★

○ Summary of a System ○

	Definition		Example
Inputs ↓	Everything that goes into the system in order to achieve the desired goal	$	Copper or gold, time, money, energy, human labor, information, tools, training, machinery
Processes →	The parts of the system that actually transform the inputs into the desired products	▣	Stenciling, machining
Outputs ↑	Everything produced by the processes		A fully loaded circuit board
Feedback ←	Provides information that the system then uses to make adjustments		If a temperature sensor makes a high reading, it will send a signal to a machine to start pumping in cool air
Goal ✱	Whatever the system is trying to accomplish		Producing circuit boards efficiently

1
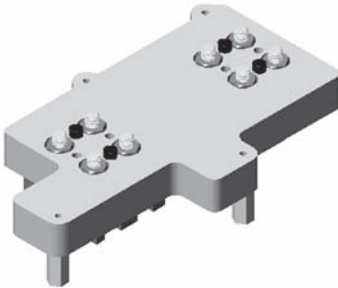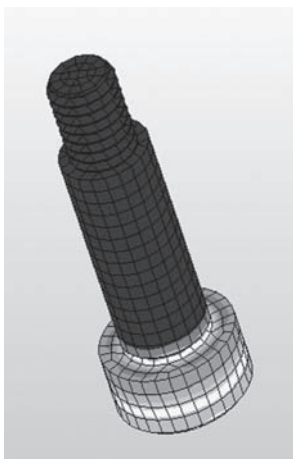
First, I used CAD software to design this piece of tooling, which will attach to a circuit board and protect parts of it from high temperatures.

2

Next, I used the CAD software to see how the components would perform. The lighter areas indicate where this shoulder screw, which fastens the whole piece on to the board, will experience the most stress.

3

Finally, I sent my CAD file to the factory CAM system. That system used it to create this physical copy of my design.

CAD/CAM: New Technologies Lead to New Systems

As you've probably noticed by now, a manufacturing system can be complex, requiring teams of people trained in different tasks, countless machines and controlling devices, and ongoing testing and improvement. Fortunately, some new technologies have emerged in recent years to make engineering manufacturing systems much easier to manage. For instance, I use Computer-Aided Design (CAD) software to create nearly all of my drawings.

CAD systems are a manufacturing engineer's best friend. Take, for instance, the "tooling" that I'm designing right now (figure 1). This piece of tooling will cover and protect the temperature-sensitive components on the circuit board as the board moves through a high-temperature chamber. I must be fairly confident it will work the very first time it's used; otherwise, expensive circuit boards may get destroyed.

With CAD, I can design the tooling to fit the board ahead of time. Then I can simulate how the tooling responds to different factors such as high temperatures or mechanical stress (figure 2). I can tweak the design to meet the process requirements before we build a prototype.

After completing the tooling, I simply send my CAD file directly to our factory's Computer-Aided Manufacturing (CAM) system. The CAM system uses the CAD file to control machines that produce the piece just the way I designed it (figure 3). CAM systems let manufacturers efficiently produce a wide range of goods from metal, plastic, and other materials. There are seldom any surprises, which is good for our golden circuit boards and our company profits.

What's a System Again?

How can you pinpoint exactly where one system begins and another ends? It's very difficult to do that. In fact, when we try to define systems too narrowly, we may face trouble. Let me show you what I mean. CAD and CAM are systems that are embedded in larger manufacturing systems. Manufacturing systems are, in turn, a part of even larger production systems. What about the systems that provide inputs into the manufacturing systems? Or what about the systems that handle the outputs?

Systems That Extract Raw Materials

Trees, iron ore, and oil are examples of raw materials—the natural, unrefined resources of the Earth. Some raw materials come from living things. Leather comes from animals, wood from trees, and cotton from plants. These are examples of renewable resources because they can be replaced in a relatively short time. Non-renewable resources, such as petroleum, coal, or metals, are not replenished after they're removed from a location.

Humans have created a variety of complex systems to find and gather raw materials. We've created systems that mine metals out of the Earth. Systems drill for petroleum and natural gas in deserts and in the ocean. We have systems to harvest plants and trees, and fish the seas.
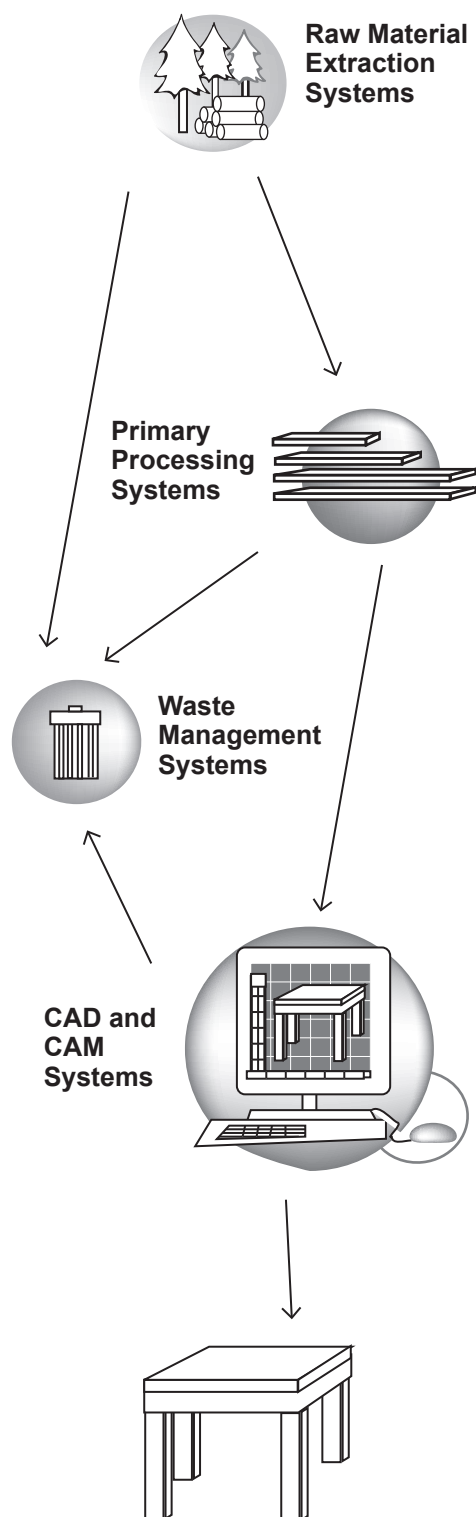
Systems That Make Raw Materials Usable for Manufacturing: Primary Processing

We don't pound gold into sheets at Teradyne. We buy the sheets from other factories located all over the country. Engineers develop systems that add value to raw materials by making them more useful. Systems that add value to natural resources range from cotton gins and fish processing plants to oil rigs and a wide variety of factories that smelt, mill, and refine raw materials.

These factories are responsible for what's called *primary processing*, the first step in transforming raw materials into useful materials. The plants that make gold boards start with either gold ore mined from the ground or recycled pieces of gold from electronics, old coins, and even dental work! Gold from all of these sources contains impurities that must be removed with heat and chemicals. After purifying the gold, the factory then melts it and pours it in a liquid form over large, flat brick molds. Finally, a machine rolls these bricks into sheets, which we buy and cut to the correct size and shape for our circuit boards.

Lumber mills process harvested trees into plywood, particleboard, and the two-by-fours used for construction projects of all kinds. Textile mills take truckloads of raw cotton, clean and dry it, spin it into thread, and then weave the thread into fabrics. Glass mills refine sand, then melt and shape it into sheets of glass.

Systems Working Together

Raw Material Extraction Systems

Primary Processing Systems

Waste Management Systems

CAD and CAM Systems

Systems That Deal with the Outputs: Waste Management

You might be tempted to think that the manufacturing system stops with the finished product, right? Well, I would argue that, given the number of non-durable goods in the marketplace, we must consider the systems that manage the waste resulting from mass production. What happens to the non-durable goods after we throw them away? Think about the complex system garbage collectors use to remove trash and then transport it to a recycling center, incinerator, or landfill. In 2005, U.S. residences and businesses produced more than 236 million tons of garbage, which is approximately 4.5 pounds of waste per person per day. American manufacturing facilities generate and dispose of approximately 7.6 billion tons of industrial solid wastes each year—more than thirty times as much!

> **Primary processing** is the first step in transforming raw materials into products.

Putting It All Together: Life Cycle Analysis

All of the systems I've talked about so far are completely interdependent. Most systems depend on other systems. You'd have a hard time naming a system that functions independently from any other system. That's just how our world works. Fortunately, more and more engineers are designing their products with the big picture in mind.

In recent years, companies and government agencies have begun analyzing the total life cycle of products and services to gauge the true costs of different products by how they affect the environment. *The life-cycle analysis* of a product involves charting all of the inputs and outputs of every system related to its production and use—from extraction of raw materials to primary and secondary processing, use, and finally disposal. The sum of all of these inputs and outputs show what kinds of effects a mass-produced product has on our environment.

So, you can see that many systems are embedded in other systems, making them all interrelated. That's certainly true for natural systems, and it's true for man-made systems. Engineers and non-engineers must consider the impact of a product's life cycle on our environment. Asking ourselves "What is the whole system here?" will help us think outside the box. The more we remember how a system fits into the big picture, the more assurance we have that our technologies will truly help us live better lives.

What's the Story?

1. How does Dudley define the term "system"? What are the parts of a system?

2. Draw a diagram of a system for producing potato chips. Be sure to label the different parts of the system.

3. How do the goals of the potato chip production system differ from its outputs?

4. What raw materials would be necessary for this potato chip production system? What kinds of waste would the system generate?

5. What kinds of primary processing might be required for the potato chip production system?

6. List three durable goods and three non-durable goods that you use every day.

Connecting the Dots

7. What are the inputs, outputs, processes, feedback, and goals of an automobile manufacturing assembly line system that Araceli described in "Bringing Designed Ideas to the Masses"?

8. Conduct a life cycle analysis of an automobile. (List all of the inputs and outputs associated with its production and use.)

9. What does the life cycle analysis of an automobile lead you to conclude about the unintended consequences of the automobile? How might engineers avoid unintended consequences using life cycle analysis?

What Do You Think?

10. Dudley believes that engineers should understand all the processes in a system, no matter what aspect they are specifically involved in. Why do you think he believes this is important? What can this understanding do for the development of new processes and products?