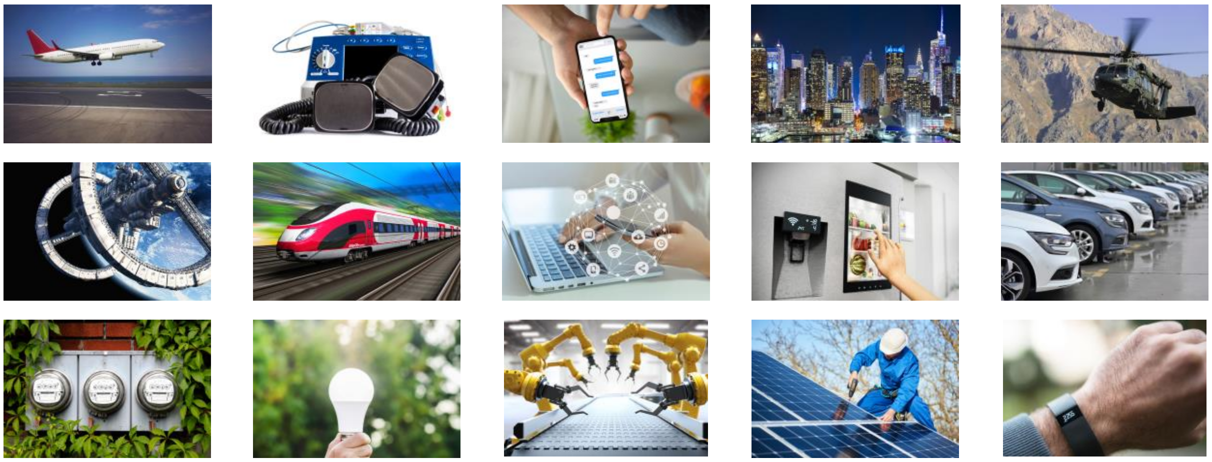
Electronics and Electrical Equipment in the Modern World

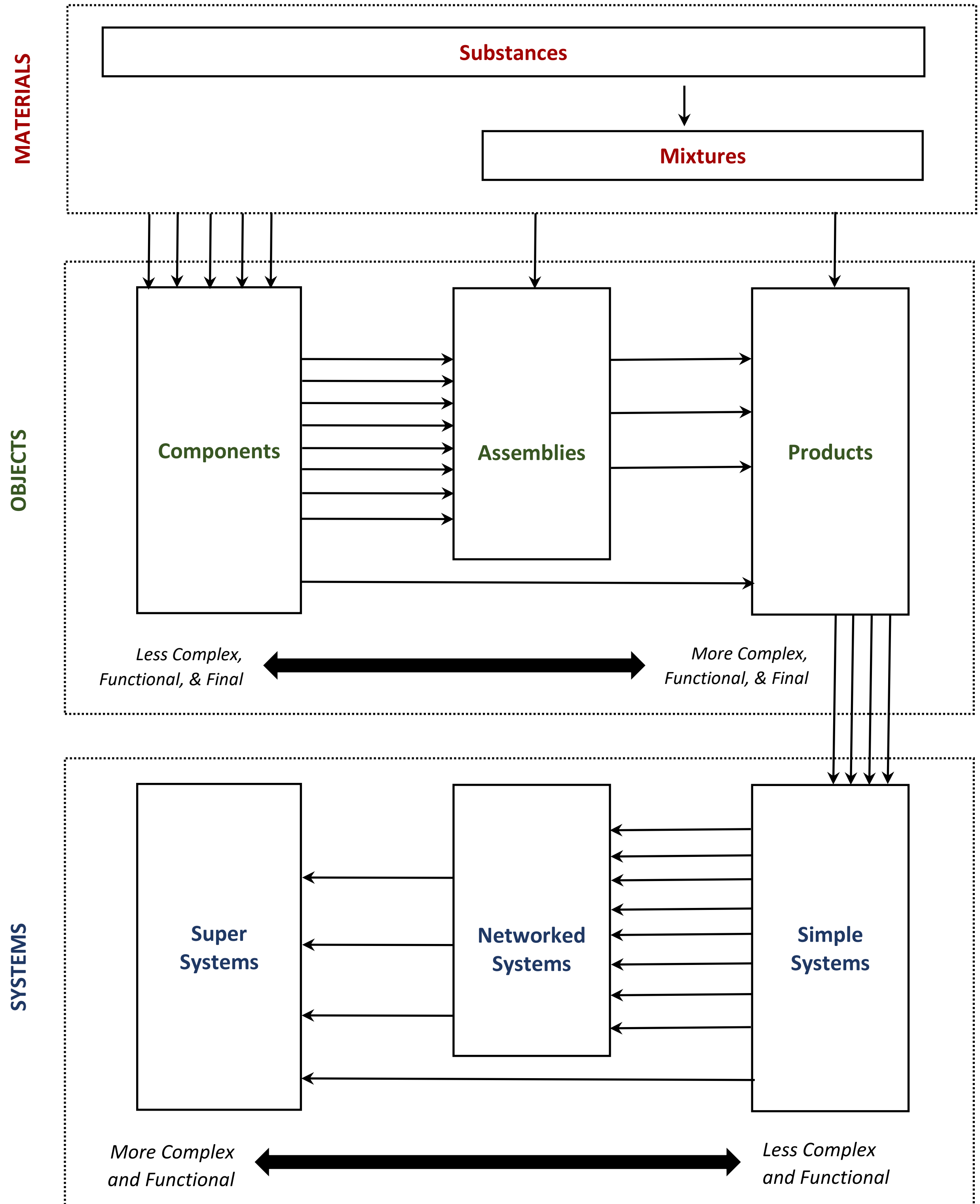


During the Second Industrial Revolution, the development of electricity generation and electric power distribution systems profoundly transformed every aspect of our lives. For the first time in history, electricity was harnessed to light our homes and to power our lives. New technological advancements, such as electrification, ensured access to electricity in individual households and enabled goods to be mass produced on assembly lines. For the first time, industrial machines were used to create products for a mass market. Electricity and electrical devices became central to our lives.

In our modern world, EEE are everywhere from the manufacturing floor to consumer products. We use EEE to create products and systems that make our lives easier. Our homes and offices are filled with electronics from our phones to our fridges. Our transportation and telecommunication systems rely on EEE technologies. We use EEE to keep us safe and healthy. Virtually every item that is mass produced is reliant on EEE. The applications are nearly endless. The technology is incredibly complex. If you are reading this white paper, you may make machines that manufacture products, materials that form manufactured goods, products reliant on EEE technology, or EEE components. You may also simply be interested in learning more about the high-technology sector and how these objects are made.

In this white paper, Vichara Partners will do our best to describe how EEE products are made. Using the Vichara Industry Map on the next page as a guide, we will examine the role materials play in the manufacturing of EEE, discuss the different types of objects contained within EEE products, describe how semiconductors are manufactured and explore how systems are created.

The Vichara Industry Map – An Overview of the High-Technology EEE Sector



Materials Are Used to Manufacture Objects

Throughout time, man has used materials to create objects from primitive tools to the most advanced electrical and electronic equipment (EEE.) All man-made objects are composed of matter and are crafted from *materials* (or *combinations of materials*). Materials are either pure *substances* composed of identical molecules or *mixtures* of substances often called formulations.

When objects are manufactured, the materials from which they are constructed are transformed in some fashion. There are cases where materials are used in the manufacturing of objects, but these materials are not contained in the final object. For example, solvents and cleaning agents may be used during manufacturing, but are not present in any appreciable or measurable amount in the final object. These materials are called *process materials*. Materials intended to appear in the final object are called *materials of construction*. Materials are the building blocks from which an object is manufactured and to a great degree determine the functionality of the end-product.

Semiconductive Materials Revolutionized the Industry

At the beginning of the EEE industry, electrical current was controlled using objects constructed of metal and ceramics. Metal acted as a conductor of electricity, helping electrons to flow. Ceramics acted as insulators, restricting the flow of electrons. Objects were limited in their capacity because of the basic nature of the materials they contained. Discrete objects served very different functions either increasing or decreasing the flow of electrons. The limitations of the materials used led to very large EEE.[1] In comparison to today's technologies, these early EEE objects were quite primitive.

In the 1950s, designers and engineers began to focus on materials, setting the foundation for future innovations in EEE technologies. Engineers discovered the scientific value of a class of materials called semiconductors. These special materials exhibit both conductive properties prone to the flow of electricity and non-conductive (insulating) properties that inhibit the flow of electricity. This discovery resulted in a paradigm shift from separate, distinct objects that had conductive and insulative components to objects that utilized semiconductive materials. Manufacturers could now create integrated components that more accurately controlled the flow of electricity, substantially reducing the size of EEE-related components while increasing their efficiency and adding functionality. Automating the manufacturing

[1] One of the first commercially available computers weighed over 8 tons and required more than 380 square feet of floor space. Imagine putting that on your desk!

process improved product quality and consistency, making it possible for EEE-related objects to be mass produced and considerably reducing costs. Semiconductive materials are so important to the EEE sector that any object created using semiconductive materials is called a semiconductor.

The Smallest EEE-Related Objects Are Called Components

Examining the size, functionality, and use of EEE-related objects can help us better understand how EEE products are made. In the Vichara Industry Map, we define the most basic objects as components.[2] Components are objects which, *by design*, cannot *easily* be broken down into smaller objects. The term *easily* is highlighted because any object could theoretically be broken down into a group of individual atoms via physical and/or chemical means, but nonetheless, disassembly is not a practical option. While a component is the lowest level of an EEE-related object, components play a vital role in constructing EEE products.

EEE Components Control Electrical Current

All EEE components are designed to control or transform an electrical current. The universe of components can generally be grouped into five functional clusters: 1) passive components, 2) active components, 3) electro-mechanical components, 4) opto-electrical components, and 5) bio-electrical components. The functionality of the entire EEE sector is acquired from these five types of EEE-related components. Combining different components within these five categories allows EEE-related products and systems to exhibit a nearly infinite range of functionalities (and therefore value).

Most EEE Components are Semiconductors

Today, almost all EEE components are constructed using semiconductive materials, and are, hence considered semiconductors. Fundamentally, a semiconductor is composed of tiny structures containing conductive and non-conductive elements of different shapes, sizes and distribution patterns. At the most basic level, these structures are created on the surface of a substrate using semiconductor materials. The creation of small structures is the hallmark of all semiconductors and the basis for their functionality – allowing components to control and leverage electrical current.

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[2] Within the EEE sector, there is no universally accepted term to describe physical objects. The term used to describe an object varies from country to country due to differing regulatory definitions and the difficulty of translating terms into multiple languages. In some regulatory regimes (such as the European Union REACH regulations), objects are referred to as articles. For the purposes of developing a common understanding, Vichara Partners propounds that the most appropriate term is *object*.

Major Types of Semiconductor Components

There are several dozen types of semiconductor components. Within each category there are thousands of unique models manufactured by companies around the world. While we would like to provide you with complete information, it is beyond the scope of this document to describe every type of semiconductor being manufactured today. The most prominent and widely used semiconductors include integrated circuits, micro-electro-mechanical systems (MEMS), photovoltaics (PVs), light emitting diodes (LEDs) and liquid crystal displays (LCDs).

Approaches to Manufacturing Semiconductors

All the semiconductor components mentioned above are similar in that each is constructed of tiny structures composed of semiconductive materials. The main differences between the components is in what structures are created, how these features are constructed, and which semiconductive materials are used. The actual building where manufacturing takes place is called a fabrication plant or "fab." While specific techniques used in manufacturing these components may vary, the basic manufacturing process is nearly identical for each component type. To gain a deeper understanding of semiconductor manufacturing, we will look at how an integrated circuit (IC) is constructed.

Semiconductor manufacturing involves creating extremely precise conductive and non-conductive structural elements on the surface of a substrate. The substrate is the canvas for the structural elements. The combination of various types of conductive and insulating structural elements on this canvas are used to leverage the electrical current for either energy transformation or signal processing. Every function of every semiconductor is wholly based on these structures.

Most of these structural elements are very, very small, measuring in the microscale range (1 to 1000 micrometers) or nanoscale range (1 to 1000 nanometers). Semiconductors are routinely called microelectronics and nanoelectronics due to these diminutive scales. Precision and accuracy in the size, placement, and distribution of these structural elements is crucial for the proper functioning of the semiconductor.

These structural elements are like the landscape of cities. Some cities have neighborhoods constructed of duplicate cookie-cutter houses connected by wide boulevards. Other cities have a variety of buildings, from residential mansions and apartment buildings to the corner grocery store, along with small city streets and massive highways. Each semiconductor is constructed with a specific design that allows these multiple structures to provide functionality.

For some semiconductors, the structural elements are extremely simple, consistently repeating across the surface of the substrate. Other semiconductors are incredibly complex with billions of individual structures taking a wide variety of forms. The most advanced, commercially available semiconductors have structures which measure just 7 nm across.

Using materials of construction and process materials, semiconductor manufacturers construct structural elements on the surface of the semiconductor substrate using a variety of chemical and physical techniques. These manufacturing techniques typically include four different processing steps: patterning, materials addition, materials removal and modification of a material's electrical properties.

First, the design schematics of the IC structures are rendered onto the surface of the semiconductor substrate in a critical process step called patterning. After this step, semiconductor materials are added or removed based on the construction blueprints mapped on the substrate surface. For most ICs, the patterning step is executed by shining light through the world's most complex stencil unto light sensitive materials placed on the substrate surface. Patterning processes that employ light are called photolithography. The most advanced methods of semiconductor manufacturing utilize an extreme ultraviolet (EUV) laser light source called an excimer laser. (These lasers are so sharp and powerful that you could be cut in two without even realizing it!) The large industrial machines that utilize lasers to map design elements unto semiconductor substrates are called photolithographic stepper tools.

For most semiconductors, the structural elements of the IC are constructed using repetitive cycles of materials being added while other materials are removed using the above patterning process. The basic process of adding and removing materials creates the microscopic structures inherent in IC semiconductors (as well as all other semiconductors.).

There are multiple methods for adding materials. In the most common method, semiconductor materials are heated until they are in gaseous form and then the gas is carefully deposited onto a solid substrate surface. This process is called deposition. The large industrial machines used in this process step are called deposition tools or equipment. The most advanced deposition tools are capable of adding semiconductor materials several atomic layers thick.

Similarly, there are multiple methods for removing materials. The most common method for removing materials is a process called etching. Under this method, the material is chemically or physically treated to burn away or materially remove the substance. While other methods for the removal process exist, etching is used for most applications.

Lastly, the electrical properties of the materials may be altered using a variety of techniques. The most common method is called ion implantation or doping. In this process, ions in materials are chemically excited and accelerated into the semiconductor substrate, embedding or implanting under the surface of the substrate. Implanting ions in the semiconductive materials changes the electrical properties of the materials, and therefore, enhances the structures.

The four most crucial mechanisms to create features/structures in semiconductors are patterning, addition, removal and altering the electrical properties of materials. Using these four mechanisms, nearly every structural element for all semiconductors can be created. Other semiconductor manufacturing techniques that serve as *necessary support steps* include, but are not limited to, cleaning and polishing.

Importance of Process Materials During Semiconductor Manufacturing

The challenge with using semiconductor materials is that they are not easy to work with in a manufacturing setting. Most semiconductive materials are solid at room temperatures. Extremely high temperatures are required for the materials to change phases. Deposition methods require materials to be in a gaseous form and semiconductive materials are highly resistant to being in this state.

However, it is possible to vaporize these materials by creating intermediate materials that temporarily bind atoms in semiconductive materials to carrier atoms. For example, a silicon atom can chemically interact with four hydrogen atoms to create a gas called silane (SiH_4). Silane is extraordinarily volatile and unstable because silicon chemically "hates" being bonded to hydrogen. As a matter of fact, silane is so chemically reactive that it spontaneously combusts when exposed to oxygen.[3] If no oxygen is present and temperatures are low, silane is stable enough to use in a manufacturing setting provided safety precautions are taken.

Most of the Group III-V semiconductor materials must be transformed into a gaseous state for deposition. For many of these substances, the most effective approach is to temporarily link their atoms to carbon. The resulting highly reactive, explosive and potentially toxic intermediary materials are called

[3] Materials with the propensity to combust on contact with oxygen are called pyrophoric substances and are a subset of high-energy reactive substances.

metalorganics. The EEE industry is wholly reliant on multiple classes of these pyrophoric, highly reactive substances.

All intermediary materials used to temporarily transform semiconductive materials into gaseous form are considered process materials. The importance of these process materials cannot be overstated. Without these intermediary process materials, semiconductive materials cannot be easily controlled or utilized in manufacturing.

These process materials are not just employed in deposition. For example, photolithography would not be possible without the use of process materials. The light-sensitive and light-resistant materials used during photolithography are temporarily employed and do not become part of the final component. Process materials are also used extensively during etching. The types of chemicals utilized differ depending on what types of films are to be etched.

Process materials used to clean are also critically important as they prevent impurities from entering the manufacturing process and ensure product quality. Before each new manufacturing stage, semiconductor wafers are cleaned to remove any remaining unwanted materials from the previous stage. Throughout the entire EEE manufacturing process, several cleaning techniques are employed using a wide variety of solvents and cleaning agents.

While semiconductor materials take center stage as materials of construction for all semiconductors, process materials work in the background and are the real stars of semiconductor manufacturing. Without these supporting actors, it would not be possible to create the structural elements that provide the electrical functionality of semiconductor components. In most semiconductor manufacturing settings, there are at least ten to thirty times as many process materials used than materials of construction. For the most advanced ICs, there are as many as one hundred process materials used. Throughout each stage of manufacturing, a unique set of process materials are used. At times, the process materials are an integral part of the manufacturing technique. Sometimes, the process materials are used in important steps along the way, preventing contamination of the components or adhering components into their proper alignment.

In addition to materials directly related to wafer processing, a wide array of support materials are used in the fab for everything from treating waste by-products to operating the sophisticated machines involved in manufacturing. There is not an official name for these materials, but they could be considered fab support substances. Roughly one hundred substances are routinely employed in this manner.

Important Components Not Constructed of Semiconductor Materials

Several vital components are made using simple conductive or insulative materials. These indispensable components are often passive components manufactured using very basic construction techniques. Examples of non-semiconductor-based components include cables, wires, interconnects, basic circuit boards, resistors, capacitors, conductors, and switches.

While these components are not usually considered "high technology," it is important to note that insulating materials in some of these passive components are designed to provide important safety features such as preventing fire hazards or arc flashes.

In addition to the simple, passive components listed above that are not manufactured using semiconductive materials, *large electromechanical components* such as ***electric motors*** are not typically constructed of semiconductive materials. Instead, these devices consist of a large magnet surrounded by a coil of wires. When electrons from electricity flow through the wire, the coil becomes an electromagnet. The attractive and repulsive forces of the large, permanent magnet cause the electromagnet to spin and the energy of the electric current is transformed into the mechanical energy of movement.

Several dozen types of EEE-related components are based on the electric motor, including heat pumps, vacuum pumps, actuators, and transducers. These non-semiconductor-based electro-mechanical components are extraordinarily valuable in the larger EEE sector and have yet to be replaced in a wholesale manner by semiconductors.

Assemblies of Components

In the Vichara Industry Map, the second most basic object is called an *assembly*. Assemblies are a collection of components connected together to serve a larger purpose. The universe of EEE-related assemblies can be logically grouped together into several functional clusters. From a functional perspective, assemblies are designed to 1) process information, 2) collect information in the real world, 3) provide an interface between humans and EEE-related products or systems, 4) facilitate communication between EEE-related products and systems, 5) provide power to EEE-related products and systems, and 6) transform electrical power into another form of energy. In summary, assemblies are designed to 1) think, 2) sense, 3) interface, 4) communicate, 5) power, and 6) act. These six different assembly types, when mixed and matched, provide a nearly limitless diversity of functionalities that have become the hallmark of all EEE-related product and systems.

The components that make up specific assemblies are all designed to perform one of these fundamental functions. A single EEE-related assembly is usually not considered a final product, because the assembly cannot usually function without other assemblies that provide complementary functions. For example, most EEE assemblies require an electric current or power to function.

Approaches to Manufacturing EEE-Related Assemblies

The manufacturing of EEE-related assemblies is usually less complex than the manufacturing the EEE-related components. Most assemblies are nothing more than collections of components which are physically connected via cables, wires, or circuit boards, and placed into a protective housing. In fact, most components are designed to be easily connected to eliminate the effort required to complete the assembly.

If components are not well designed, assembly manufacturing can be extremely challenging. Most component manufacturers are in constant contact with assembly manufacturers to eliminate any assembly-related concerns. These component manufacturers usually have an in-house engineer who specializes in assembly design and manufacturing. The same is true in the opposite direction. Assembly manufacturers frequently have in-house experts familiar with component design and manufacturing.

For most types of assembly manufacturing, materials of construction are not routinely used in any appreciable volumes since materials of construction are most heavily utilized in component manufacturing. There are, however, several significant exceptions.

One exception involves the external housing that may protect the components as these are often designed to prevent electrical fires, to mitigate heat hazards, and to protect against external electrical field effects. Materials that protect against fire hazards are frequently toxic, posing a potential concern when evaluating for chemical risk. Materials that protect against electrical field effects, such as lead, are also potentially of concern.

Another exception involves the soldering agents used to hardwire components to each other. Some soldering agents contain the hazardous substance lead. While many regions of the world have banned lead, it is still used in industrial applications throughout Asia and may be found in significant amounts in e-waste.

Lastly, adhesives and other bonding materials are often used in assembly manufacturing in place of screws, nuts, and bolts. These substances are incorporated into the final product and have hazard profiles of concern.

In addition to the materials of construction mentioned above, process materials are used to physically clean components to prepare them for assembly. These process materials include some types of hazardous solvents, such as n-methyl-2-pyrrolidone (NMP).

In conclusion, fewer materials are used during the manufacturing of EEE-related assemblies than during the manufacturing of EEE-related components. For every single substance used in assembly manufacturing, there are probably one to two orders of magnitude (10 to 1000) more substances used in component manufacturing. Although there are far more chemicals used during component manufacturing, the hazard profiles of materials used in assembly manufacturing should not be discounted.

Products as Collections of Assemblies

When more than one assembly is connected to produce a coherent function, the resulting item is called a *product*. The term, product, connotes an object that possesses its full functionality and has reached the end of the manufacturing process.

Some products, such as gasoline-powered automobiles, are constructed of groups of EEE-related assemblies connected to each other and to non-EEE-related objects such as the vehicle chassis, drive train, wheels, and a gasoline motor. The final product, a car, contains EEE-related assemblies, but the entire car is not composed of EEE-related assemblies.

Most types of consumer electronics are nothing more than collections of EEE-related assemblies with an external metal or plastic housing designed to protect the internal electronic assemblies. For instance, smart mobile phones are nothing more than collections of EEE-related assemblies which work in concert with each other to produce a wide variety of functions for the end-user. The average smart phone contains several EEE-related assemblies. Each assembly contains several components. The assemblies and components come together to form a product.

Let’s take the real-world example of the 2018 iPhone XS. This particular product contains approximately 35 separate EEE-related components housed in at least five different EEE-related assemblies. Nearly all EEE-related components are semiconductors apart from some switches (i.e. the power button), a couple of circuit boards (to connect components together) and a battery. All the assemblies are housed in a metal, plastic, and glass enclosure to form a finished product.

If you happen to disassemble this phone, you may not be able to identify specific assemblies because to the untrained eye the components seem to be somewhat haphazardly placed on circuit boards. However, the Apple design team absolutely understands optimal placement of components within assemblies for the effective, efficient, and coherent operation of their phones.

Approaches to Manufacturing EEE-Related Products

To fully grasp the high-tech manufacturing process, it is important to understand how products are made. Given the incredible diversity of the universe of EEE-related products, it is nearly impossible to describe, in simple terms, how all EEE-related products are manufactured. This document does not attempt to do so. The process of manufacturing airplanes will be fundamentally different than the process utilized to manufacture laptop computers.

By and large, manufacturing EEE-related products is more complex than manufacturing EEE-related assemblies, but less complex than manufacturing EEE-related semiconductor components. The complex chemistries and industrial processes used in component manufacturing are far more advanced than the process of creating a product. Yet, designing and manufacturing a product is far harder than building assemblies because the final product must account for all the individual traits of each assembly and ensure that each part functions as a coherent whole in the final EEE-related product.

For most types of product manufacturing, materials of construction are not routinely used in any appreciable volumes but there are several notable exceptions. Namely, the external housing that protects the assemblies, soldering agents used to hardwire components to each other, and adhesives and related bonding materials used to secure assemblies and components are all materials of construction that may contain substances of concern and present hazards. Process materials used to physically clean components and assemblies to prepare them for their final placement in the product may also include hazardous substances.

In conclusion, fewer materials are used during the manufacturing of EEE-related products than during the manufacturing of EEE-related components. For every single substance used in product manufacturing, there are probably one to two orders of magnitude (10 to 1000) more substances used in component manufacturing. Nonetheless, the hazard profiles of materials used in product manufacturing should not be discounted.

Extending Beyond Products: Simple Systems, Networks, and Super-Structures

When an EEE-related product needs other products to operate and the products are connected to one another to perform a function, they form a *system*. An example of this would be a desktop computer system, composed of the desktop tower, monitor, keyboard, mouse, connective cables and power cords.

Whether or not a product is considered a product or part of a system is contextual. For example, a laptop computer incorporates the EEE-related assemblies from the desktop tower, monitor, keyboard, mouse and connective cables into one combined unit. Hence, the laptop computer is a product. A desktop tower, monitor, keyboard, and mouse are also each individual, distinct products. However, in the context of the desktop tower, it cannot operate without the related accessories (monitor, keyboard, mouse, connective cables and power cords.) This is the intention of the designers of desktop computers. Similarly, the intention of laptop computer designers is to have all assemblies in one unit instead of creating four separate products which need to be connected for full functionality.

Because the difference between a product and a system of products is contextual, this framework cannot conclude, *a priori*, whether an EEE-related object is a product or system. Each product or system needs to be considered on a case-by-case basis.

When EEE-related systems are connected, they form a network. For example, a collection of personal computers and data servers can be combined to create a local area network. This EEE-related network is the combination of all of the computers, as well as the connections between the computers.

Under this framework, a network of EEE-related networks is called a super-structure. Examples of EEE-related super-structures include the world wide web, mobile phone networks, and extended electrical grids. All super-structures are partly composed of and are reliant on EEE.

Approaches to Building EEE-Related Systems, Networks, and Super Systems

EEE-related systems, networks and super systems are nothing more than collections of products or systems. The building of these systems is beyond the scope of this Vichara Partners project for one very important reason: Virtually no materials are used to build these systems.

The main source of chemical risk would not be in the creation of the systems, but in the maintenance, use or decommissioning of the systems.

Understanding Connections within High-Tech EEE: Materials, Objects, and Systems

In summary, the various EEE-related manufacturing hierarchies are as follows. Materials are used during the manufacturing process to make objects, such as components. Components are used to manufacture assemblies. Assemblies are used to manufacture products. A collection of products that rely on one another to function create a simple system. When more than one system is connected, this forms a network. A super-structure is a network of networks that enables an ecosystem of EEE-related products to provide services and functionality on a large scale.

A Brief Disclaimer

As we end, it is important to acknowledge that the EEE manufacturing process is extraordinarily complicated. A simple smart phone contains as many as fifty to one hundred discrete components. The largest and most complicated EEE-related products, such as airplanes, satellites, and industrial machines, are likely to contain over one million distinct parts. The largest EEE-related *systems* on earth, such as the internet or a continental electrical grid, are likely to contain millions or billions of EEE-related products and, therefore, trillions of discrete EEE-related objects.

Please note that due to the complexity of EEE manufacturing, it is nearly impossible to examine every aspect. Many sections in this document were purposefully simplified. We hope you have found this white paper useful.

If you have questions, please feel free to contact us at questions@vicharapartners.com. We are happy to explain the concepts contained in this document and/or point you in the right direction if you seek more information. We have more technical white papers available. We also have access to experts from around the world!