incentive to work together to ensure that successful integration occurs.

Assembly permits parts to function by working together as a system. Disassembled, they are just a pile of parts. Furthermore, as we shall see again and again in this book, typical assemblies have lots of parts and several functions. There aren't many one-part products.[1] Typical assemblies consist of *many* parts, each with a *few* important geometric features, *all* of which must work together in order to create the product's several functions.

Assembly is different from traditional unit processes in another important way: It is the key link between the unit processes and top-level business processes. For example,

- An appropriate assembly sequence can permit a company to customize a product when it adds the last few parts.
- Properly defined subassemblies permit a company to design them independently or outsource some or all of them from suppliers, as well as to switch between suppliers.
- A well-defined and executed product development process focused on assemblies can make ramp-up to full production faster because problems can be diagnosed faster.
- Properly defined assembly interfaces can allow a company to mix and match parts or subassemblies to create custom products with little or no switching cost.

TABLE 1-1. Assembly Links Unit Manufacturing Processes to Business Processes

Domain	Context	Example Application
Assembly in the large	Business level	• Market size and production volume • Model mix • Upgrade/update • Reuse, carryover • Outsourcing and supply chain
	System level	• Data management and control • Quality management • Subassemblies • Assembly sequences • Involvement of people • Automation • Line layout
Assembly in the small	Technical level	• Individual part quality • Individual part joining • Part logistics, preparation and feeding • Manual vs. automatic • Economics • Ergonomics

In general, assembly is the domain where many business strategies are carried out, all of which depend on careful attention to the strategic aims during product design. Some of these are listed in Table 1-1. In this table, the terms "assembly in the large" and "assembly in the small" are defined in context by means of the items at the far right in the table. They will be discussed in more detail later.

1.B. SOME EXAMPLES

Let us consider some examples to fix our ideas. The first one is a tutorial using a desktop stapler. The second is a panel meter for car dashboards, a product that illustrates how an assembly can embody the business strategy of a company. The third is a portion of the front end of a car. It illustrates the principle that many parts work together to deliver the functional or operating features of a product, and failure to understand how these parts work together can prevent assembly plant workers from understanding and fixing assembly problems. Some examples of poor assembly-related design are described at the end of this section. The stapler, panel meter, and car front end will be used repeatedly throughout the book to illustrate important concepts.

1.B.1. Stapler[2] Tutorial

Even though a desktop stapler may appear simple (see Figure 1-1), it is in fact a precision mechanism that will

[1]Crowbars and baseball bats are possible exceptions, as is the diamond engagement ring. The ring is really two parts, of which one is overwhelmingly important and the other is there merely to keep the first one from getting lost. Furthermore, that important one has hundreds of features, all of which are necessary to its function.

[2]A complete analysis of a stapler, together with all part and assembly details, is provided in [Simunovic].

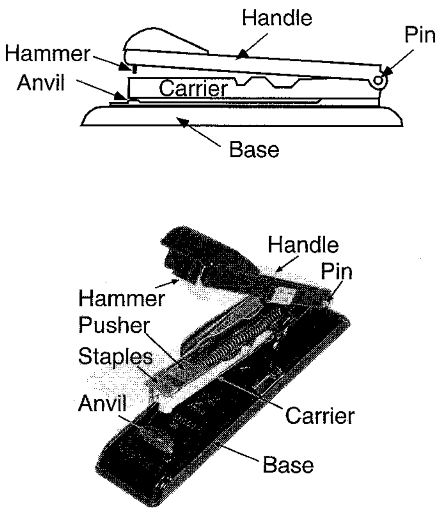

FIGURE 1-1. Desktop Stapler.

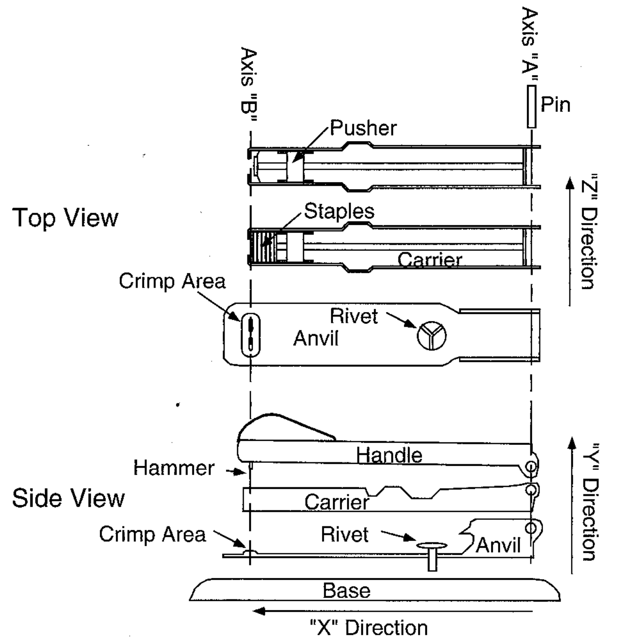

FIGURE 1-2. Stapler Parts. The main parts of the stapler are shown slightly separated from each other in the side view. The top view shows some of these parts plus a few others not visible in the side view. In the top view, the carrier is shown twice, once with staples and once without. The view without staples permits us to see the slot at the left end of the carrier where one staple is pushed out when the user pushes on the handle. The spring that pushes the part called pusher into the staples is not shown. The spring that pops the stapler open after stapling is also not shown.

malfunction badly if its parts are not made to the correct dimensions. A close look at the parts and how they relate to each other reveals why this is true.

The main parts of the stapler, as shown in Figure 1-2, are the base, the anvil (with its crimping area), the carrier (containing the staples and the pusher), and the handle. The anvil, carrier, and handle are tied together along axis "*A*" by the pin. The anvil and the base are tied together by the rivet. Along axis "*B*" we find the slot in the carrier where the last staple will be pushed out, that staple itself, the crimping area of the anvil, and an element of the handle called the hammer, which pushes the staple out of the carrier, through the paper, and onto the anvil, which crimps the staple, completing the stapling operation.

What makes the stapler work? What could cause it not to work? A reader with good mechanical sense can probably figure this out quickly, but products like aircraft and automobiles consist of complex assemblies that are much more difficult to understand. We need help to figure these things out, along with a theory that will help us answer these questions about assemblies that are too complex to be understood just by looking at them.

The way a product is laid out, including which parts perform what functions as well as how the parts are arranged in space, is called its architecture. The architecture of the stapler is relatively simple because it performs only one main function and has so few parts. The architectures of larger products are complex, and the role of architecture extends beyond how the product works into such areas as how it is made, sold, customized, repaired in the field, recycled, and so on.

To simplify this already simple example further, we will consider only one dimension of the stapler, the one called "*X*" in Figure 1-2. The "*Z*" direction in the top view is also important, though not as much, while the direction called "*Y*" in the side view has still less importance. (A thought question at the end of the chapter asks the reader to think more about this.)

In order to understand the stapler, we will use a simple diagram to describe it. This diagram will replace the parts with dots and connections between parts with lines, making a graph called a liaison diagram (Figure 1-3). Using this diagram, we will explain how the stapler works using words and pictures.

Each liaison represents a place where two parts join. Such places are called assembly features in this book.

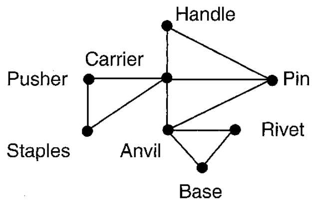

FIGURE 1-3. Liaison Diagram for the Stapler.

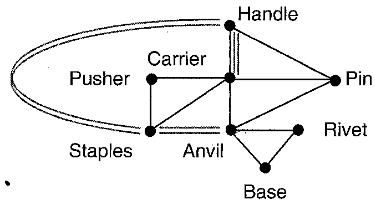

FIGURE 1-4. Liaison Diagram of Stapler with Key Characteristics Indicated by Double Lines.

They serve to position the parts with respect to each other. Some features act to hold a part firmly against another, while other features permit some relative movement between the parts. For example, the liaison between rivet, base, and anvil fixes these parts to each other completely, while the liaison between anvil, pin, and handle permits the handle to rotate about axis A with respect to the anvil.

Using the liaison diagram and the drawing of the stapler, we can make the following statements:

- The rivet connects the anvil to the base.
- The pin connects the anvil, carrier, and handle.
- The carrier connects the pusher and the staples.

In order for the stapler to work properly, the carrier must position the last staple right over the anvil's crimp area in the X direction. In addition, the handle must position its hammer right over the last staple in the X direction so that it strikes it squarely. Also, the hammer must rub against the end of the carrier to gain reinforcement against the buckling force of pushing the staple as well as to guide the end of the hammer against the top of the staple and avoid having the hammer slip off the staple. Finally, the hammer must pass right through the opening in the end of the carrier that the staple passes through, so as to be able to ram the staple firmly against the paper and transfer the necessary staple crimping force through the staple into the crimping area of the anvil. Equivalently, we can say that the operating features (hammer, staple slot, crimp area) must be placed properly inside the parts relative to the assembly features (holes for the pin), and the parts must be positioned relative to each other by the assembly features along axis "*A*," so that all the operating features align along axis "*B*."

This long-winded description is captured concisely and unambiguously in Figure 1-4. This figure is the liaison diagram with the addition of some double lines. These lines indicate schematically some important dimensional relationships between the parts at either end of each line pair (in the X direction only). We call these important dimensional relationships *key characteristics* (KC for short). If we get these relationships right, the product will work; if not, then it will not. It is important to understand that the assembly features play the crucial role of positioning the parts properly with respect to each other so that these KCs will be achieved accurately. That is, not only must each part be the correct length in the X direction, but they must assemble to each other properly, repeatably, and firmly.

Note that this diagram is necessarily simplified. In later chapters we will draw such diagrams in more detail so that each of the important operating and assembly features is shown separately. We will also show how to capture actions and relationships along all the axes, the directions of free motion, and so on.

Now, suppose there is some manufacturing variation in the construction of the handle so that on some percentage of the handles the hammer is located a bit too far from axis "*A*." When staplers are made with these handles, the hammer could strike the end of the carrier instead of sliding smoothly along the inside surface. What if the hammer is located a bit too close to axis "*A*"? In this case, the hammer might slip off the end of the staple; then it and the staple could become jammed together in the slot. Each of these manufacturing variations leads to an assembly variation in a KC. As another example, suppose a hammer is made too thick; it could jam inside the slot as it pushes the staple out. In either of these last two cases, the user would need pliers or other strong tools to open the stapler and undo the jam. After a few experiences like this, the user will throw the stapler away and buy one from another company.

Are there other ways in which the stapler could malfunction, other than due to mislocation of the hammer in the handle? What if the entire anvil is too long, so that the crimping area is not aligned with axis "*B*"? What if

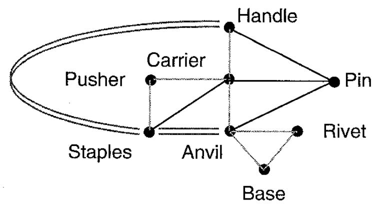

FIGURE 1-5. Liaison Diagram of Stapler with Some Liaisons Grayed Out. The grayed-out liaisons are not involved in delivering the KCs.

the rivet hole is in the wrong place so that the anvil is not where it is supposed to be on the base?

To answer these questions, we need to look more closely at the liaison diagram to determine which parts are really involved in the key characteristics. We will focus on two of the KCs, the one between handle (hammer) and staples and the one between anvil's crimp area and staples. We will assume that the one between handle and carrier is achieved in the same way as the one between handle and staples, using the same parts and assembly features.

With this simplification in mind, consider Figure 1-5. In this diagram, some of the liaisons are shown in gray. We assert that the gray liaisons are not "in the delivery chain for a KC." That is, even if the parts joined by gray liaisons were not installed at all, the key dimensions indicated by the double lines would be achieved anyway. The reader may have to study the stapler in order to be convinced of this. The remaining parts and their black liaisons comprise the parts that are necessary for the KCs to be achieved. The rivet and base are needed to keep the stapler stable on the table during use, and the pusher is needed to force the last staple into position at the end of the carrier, to be sure, but these parts and their relative locations do not affect the KC dimensions.

Not only are some parts not involved in KC delivery, but not all joints in the liaison diagram play the same role in the assembly. Our attention will focus on those joints that link the parts that participate in delivering the KCs. Those joints will be called "mates." Other joints may be important for fastening certain parts to the assembly or for reinforcing the mates. We call these joints "contacts." Knowing which joints are mates and which are contacts is essential in understanding how an assembly works.

The pusher has a *contact* with the staples and pushes them forward firmly against the left end of the carrier. Yet it is the *mate* between the carrier and the staples that positions the last staple properly.

The next step in understanding the stapler is to realize that the two KCs are achieved by different sets of parts, each of which occupy distinct chains. These are shown in Figure 1-6.

From Figure 1-6 we can see that achieving the KC which places the hammer over the last staple requires proper size and relative placement of the staples, via the carrier, the pin, and the handle (which contains the hammer). This chain is shown on the left in the figure. It links the two ends of the double lines that call out the KC. Another way to read this chain is to say that the pin locates the handle (hammer) and the carrier, while the carrier locates the staples. On the right is the chain that places the last staple over the crimping area: The pin locates the anvil (and its crimping area) and it locates the carrier, which locates the staples. Note, too, that both KCs must be achieved in order that the stapler operate properly. Fortunately, different parts are involved in most elements of these chains. This causes the two KCs to be capable of being achieved independently, although we have to be especially careful about the carrier because it is in both chains.

One way to ensure that the stapler achieves the KCs is that both the handle and the anvil be correctly sized and

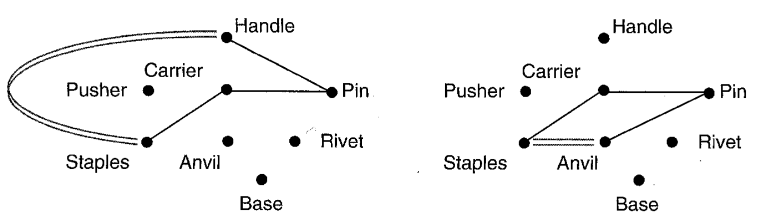

FIGURE 1-6. Delivery Chains for the Two KCs in the Stapler. *Left:* The hammer in the handle lines up with the last staple. *Right:* The last staple lines up with the crimping area of the anvil. Only the liaisons needed to deliver each KC are shown in each drawing. Rivet, base, and pusher are not involved in either KC.

positioned with respect to the carrier. Certainly, the diagram shows that the stapler will not work if this condition is not met. However, we shall see later in the book that it is preferable to be able to make these parts independently of each other, perhaps even to buy them from different suppliers, so that no special selecting, fitting, or measuring is required during assembly. We will also encounter in later chapters many cases where a product has several KCs but the chains that deliver them are coupled. Such situations confront the designer of the assembly with a choice of which KC to favor.

The diagrams in Figure 1-6 can be thought of as the plans for achievement of the KCs. They name the parts in the chain and allow us to identify the assembly features that are involved. These are called *datum flow chains* and are the subject of Chapter 8. When these chains have been designed properly, we can be assured that the assembly has a good chance of working. The chains also tell us where manufacturing or assembly variation could disrupt a KC. If some assemblies do not work, we can refer to the diagram to identify the parts involved, their internal dimensions, and their assembly features, as we search for the cause.

This example has introduced the following concepts and terms. The reader should reread the example if any of these terms are not clearly understood, because they will be used again and again throughout this book:

- Part
- Liaison, and liaison diagram
- Joint, mate, and contact
- Assembly feature
- Operating or functional feature
- Product architecture
- Location of operating feature with respect to assembly feature
- Key characteristic (KC)
- Achievement of a KC
- Chain of parts that achieve a KC
- Manufacturing variation
- Assembly variation
- Customer satisfaction if KCs are achieved; customer dissatisfaction if KCs are not achieved

The topics in the stapler example form the subject matter for Chapters 2 through 8 of this book.

1.B.2. Assembly Implements a Business Strategy[3]

Denso Co. Ltd. is the largest and perhaps the most sophisticated supplier of automotive components in Japan. It designs and manufactures generators, alternators, voltage regulators, fuel injection systems, engine controllers, anti-skid braking systems, and so on, for Toyota and many other automobile builders. Toyota owns 25% of Denso and accounts for almost half its business. Because Toyota manufactures a wide variety of products and wants its components delivered in an arbitrary model mix on a just-in-time (JIT) basis, Toyota puts extreme demands on its suppliers to be responsive and flexible. Over about thirty years, Denso has learned how to use the assembly process to meet Toyota's requirements.[4] Three elements of Denso's strategy are

- The combinatoric method of achieving model-mix production
- In-house development of manufacturing technology
- Jigless assembly methods and minimal changeover time and cost

Denso has applied this strategy to many products over the last thirty years ([Whitney 1993]). One of these is a panel meter for dashboards. This product is mentioned at many points in this book. Here we emphasize Denso's use of the product's architecture to serve the highly variable needs of its main customer, Toyota.

The combinatoric method is the basis of Denso's assembly-driven strategy. A product is divided into generic parts or subassemblies, and necessary varieties are identified. The product is designed so that any combination of varieties of these basic parts will go together physically and comprise a functional product. If there are six basic parts and three varieties of each, for example, then the company could build as many as 3^6 or 729 different versions of the product.

The in-house manufacturing engineering team participates in the design of these parts so that the manufacturing

[3] This subsection is adapted from Chapter 3 of [Nevins and Whitney].

[4] The official corporate slogan at Denso is "Conquer Variety," which means do whatever is necessary to accommodate the model mix demands of its customers. In practice, one could say that the slogan is "Never say 'No' to Toyota."