CHAPTER 11

Product Evaluation: Design For Cost, Manufacture, Assembly, and Other Measures

KEY QUESTIONS

- What is Design For Cost, DFC, and how can costs be estimated?
- What is Design For Value, DFV, and how is value different from cost?
- How can a product be easy to manufacture (DFM) and assemble (DFA)?
- How do Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and Design For Reliability (DFR) help eliminate failures?
- Can products be designed that are easy to test (DFT) and measure (DFM)?
- What can a designer do to protect the environment (DFE)?

11.1 INTRODUCTION

In Chap. 10 we considered the best practices for evaluating the product design relative to performance, tolerance, and robustness. Also of importance are the evaluations for cost, ease of assembly, reliability, testability and maintainability, and environmental friendliness, all covered in this chapter. These evaluations have come to be known as Design For Cost (DFC), Design For Assembly (DFA), DFR, DFT, and so on, or generically—DFX. This is the TLA (Three Letter Acronym) chapter.

11.2 DFC—DESIGN FOR COST

One of the most difficult and yet important tasks for a design engineer in developing a new product is estimating its production cost. It is important to generate a cost estimate as early in the design process as possible and to compare with the

> Eighty percent of the cost is incurred by 20% of the components.

cost requirements. In the conceptual phase or at the beginning of the embodiment phase, a rough estimate of the cost is first generated, and then as the product is refined, the cost estimate is refined as well. For redesign problems, where changes are not extreme, early cost estimates may be fairly accurate, because the current costs are known.

As the design matures, cost estimations converge on the final cost. This often requires price quotes from vendors and the aid of a cost estimation specialist. Many manufacturing companies have a purchasing or cost-estimating department whose responsibility it is to generate estimates for the cost of manufactured and purchased components. However, the designer shares the responsibility, especially when there are many concepts or variations to consider and when the potential components are too abstract for others to cost estimate. Before we describe cost-estimating methods for use by designers, it is important to understand what control the design engineer has over the manufacturing cost and selling price of the product.

Since cost is usually a driving constraint, many companies use the term Design For Cost, DFC, to emphasize its importance. This means keeping an evolving cost estimate current as the product is refined.

11.2.1 Determining the Cost of a Product

The total cost of a product to the customer (i.e., the list price) and its constituent parts are shown in Fig. 11.1. All costs can be lumped into two broad categories,

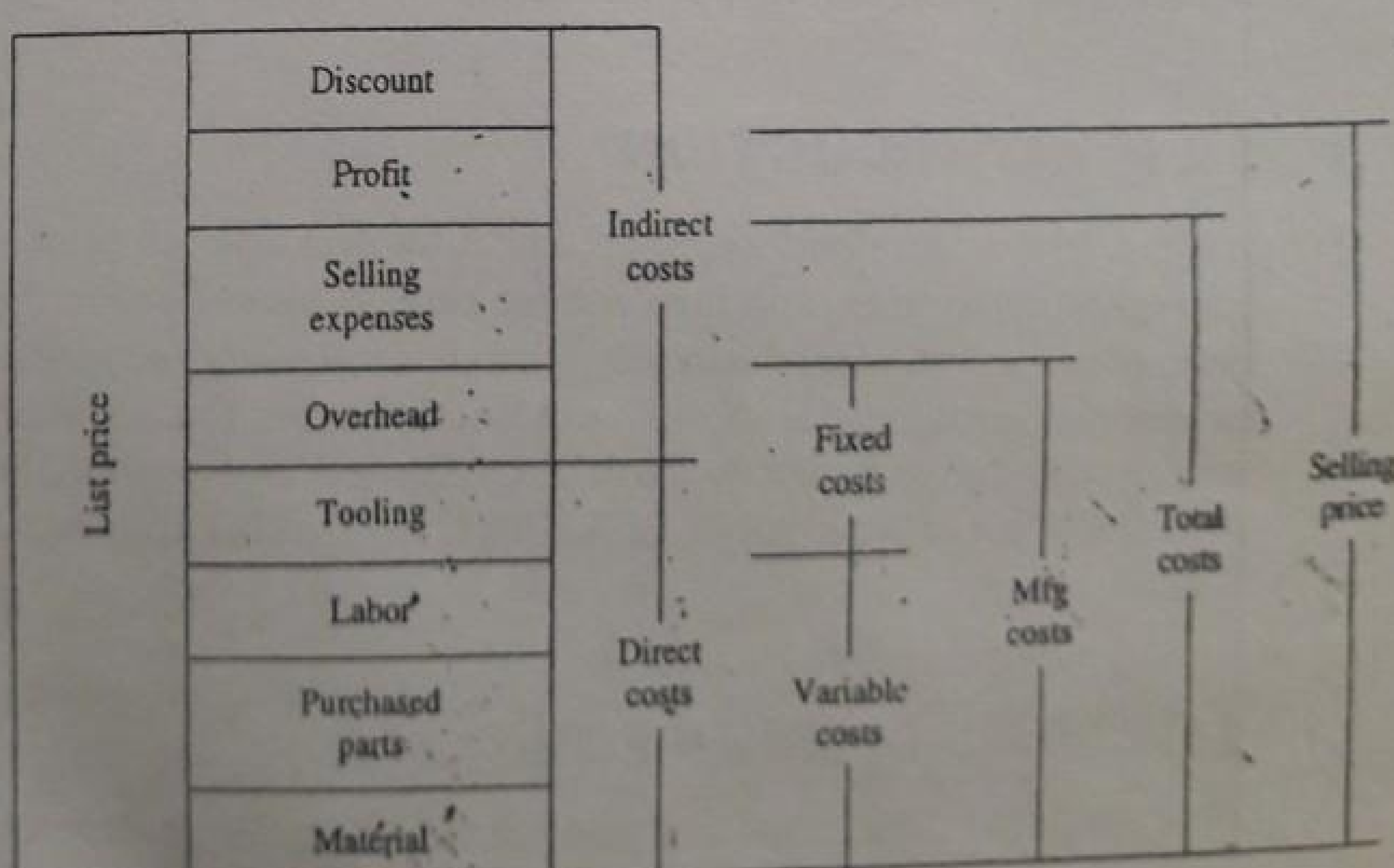


Figure 11.1 Product cost breakdown.

direct costs and indirect costs. *Direct costs* are those that can be traced directly to a specific component, assembly, or product. All other costs are called *indirect costs.* The terminology generally used to describe the costs that contribute to the direct and indirect costs is defined here. Each company has its own method of bookkeeping, so the definitions given here may not match every accounting scheme. However, every company needs to account for all the costs discussed.

A major part of the direct cost is the *material costs.* These include the expenses of all the materials that are purchased for a product, including the expense of the waste caused by scrap and spoilage. Scrap is often an important consideration. For most materials, the scrap can be reclaimed, and the return from the reclamation can be deducted from the material costs. Spoilage includes parts and materials that may not be usable because of manufacturing defects, deterioration, or other damage. Part fallout, those components that cannot be assembled because of poor fit, also contributes to spoilage.

Components that are purchased from vendors and not fabricated in-house are also considered direct costs. At a minimum, this *purchased-parts cost* includes fasteners and the packaging materials used to ship the product. At a maximum, all components may be made outside the company with only the assembly performed in-house. In this case, there are no material costs.

Labor cost is the cost of wages and benefits to the workforce needed to manufacture and assemble the products. This includes the employees' salaries as well as all fringe benefits, including medical insurance, retirement funds, and vacation times. Additionally, some companies include overhead (to be defined shortly) in figuring the direct labor cost. With fringe benefits and overhead included, the labor cost of one worker will be two to three times his or her salary.

The last element of direct costs is the *tooling cost.* This cost includes all jigs, fixtures, molds, and other parts specifically manufactured or purchased for the production of the product. For some products, these costs are minimal; very few items are being made, the components are simple, or the assembly is easy. On the other hand, for products that have injection-molded components, the high cost of manufacturing the mold will be a major portion of the part cost.

Figure 11.1 shows that the sum of the material, labor, purchased parts, and tooling used is the *direct cost.* The *manufacturing cost* is the direct cost plus the *overhead,* which includes all cost for administration, engineering, secretarial work, cleaning, utilities, leases of buildings, and other costs that occur day to day, even if no product rolls out the door. Some companies subdivide the overhead into engineering overhead and administrative overhead, the engineering portion including all expenses associated with research, development, and the design of the product. Many companies subdivide overhead into fixed and variable portions, items such as shop supplies, depreciation on equipment, equipment lease costs, and human resource costs being variable.

The manufacturing cost can be broken down in another important way. The material, labor, and purchased-parts costs are *variable costs,* as they vary directly with the number of units produced. For most high-volume processes, this variation is nearly linear: it costs about twice as much to produce twice as many units.

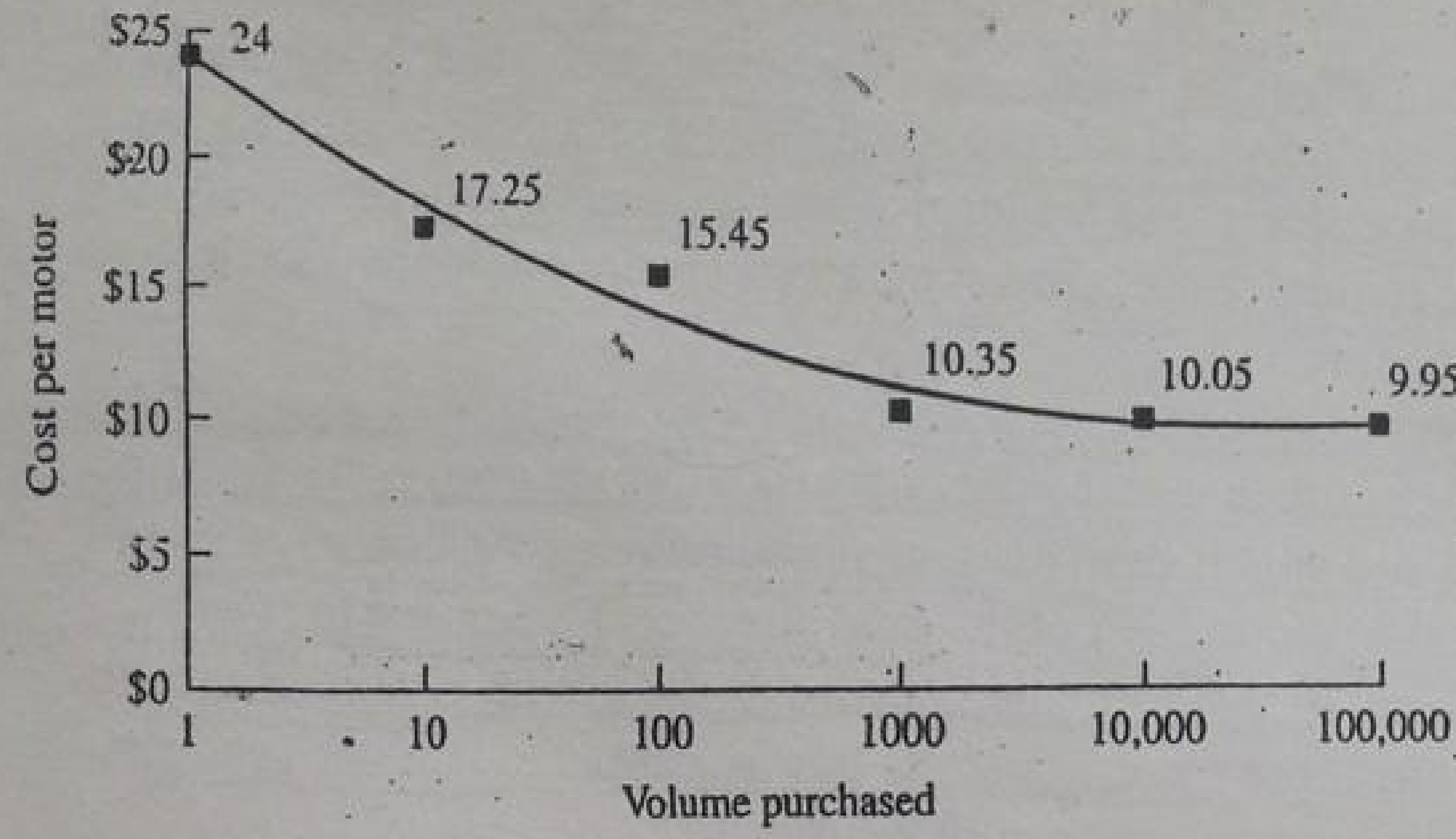


Figure 11.2 Sample of cost per volume purchased for a component.

However, at lower volumes, the costs may change drastically with volume. This is reflected in the price quote made by a vendor for a small electric motor shown in Fig. 11.2.

Other manufacturing costs such as tooling and overhead are *fixed costs,* because they remain the same regardless of the number of units made. Even if production fell to zero, funds spent on tooling and the expenses associated with the facilities and nonproduction labor would remain the same.

In general, the cost of a component, C, can be calculated by:

$$C = C_m + \frac{C_c}{n} + \frac{C_l}{\dot{n}}$$

where C_m is the cost of materials needed for the component (raw materials minus salvage price for scrap), C_c is the capital cost of tooling and a fraction of the cost of the machines and facilities needed, n is the number of components to be made, C_l is the cost of labor per unit time, and $\dot{n}$ is the number of components per unit time. Additionally, if the firm is buying from a vendor, the paperwork and other overhead of selling a small quantity of an item may also appear in C_c. The curve that results from this equation generally looks like that in Fig. 11.2. At low volume, the second and third terms dominate and at high volume the first term, the cost of materials, serves as an asymptote.

The *total cost* of the product is the manufacturing cost plus the selling expenses. It accounts for all the expenses needed to get the product to the point of sale. The actual *selling price* is the total cost plus the *profit.* Finally, if the product has been sold to a distributor or a retail store (anything other than direct sales to the customer), then the actual price to the consumer, the list price, is the selling price plus the *discount.* Thus, the discount is the part of the list price that covers the costs and profits of retail sales. If the design effort is on a manufacturing machine to be used in house, then costs such as discount and selling expenses do not exist. Depending on the bookkeeping practices of the particular company, there may still be profit included in the cost.

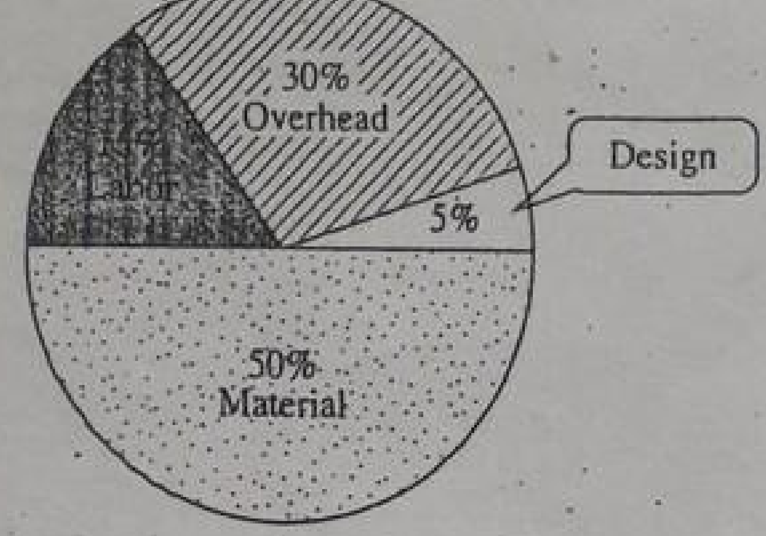


Figure 11.3 Design cost as a fraction of manufacturing cost.

The salaries for the designers, drafters, and engineers and the costs for their equipment and facilities are all part of the overhead. Designers have little control over these fixed expenses, beyond using their time and equipment efficiently. The designer's big impact is on the direct costs: tooling, labor, material, and purchased parts costs. Reconsider Fig. 1.2, reprinted here as Fig. 11.3. These data from Ford show the manufacturing cost, emphasizing the low cost of design activities. If it is assumed that the costs of purchased parts and tooling are included in the material costs, then these account for about 50% of the manufacturing costs. The labor is about 15%, and the overhead, including design expenses, is 35%. As a rule of thumb, for companies whose products are manufactured mainly in house and in high volume, the manufacturing cost is approximately three times the cost of the materials. Also, the selling price is approximately nine times the material cost, or three times the manufacturing cost. This is sometimes called the material-manufacturing-selling 1-3-9 rule. This ratio varies greatly from product to product. The Ford data in Fig. 11.3 show a 1:2 ratio between materials cost and manufacturing cost, less than the rule would predict.

Figure 1.3, reprinted here as Fig. 11.4, shows the influence of design quality on manufacturing cost. As already mentioned, the designer can influence all the direct costs in a product, including the types of materials used, the purchased parts specified, the production methods, and thus the labor hours and the cost of tooling. Management, on the other hand, has much less influence on the manufacturing costs. They can negotiate for lower prices on a material specified by the designer, negotiate lower wages for the workers, or try to trim overhead. With these considerations, it is not surprising that data in Fig. 11.4 show that 50% of the influence on the manufacturing cost is controlled by design.

One final term that should be understood by engineers is *margin*. This is calculated by taking the ratio of profit to selling price. Typically, for product generating companies, a margin of 40–50% will generate a good profit. However, for high-volume production, this may drop to 10%, and for custom production, it may be as high as 60–70%.

To get a feel for these costs, consider a bicycle that has a list price of $750 (Fig. 11.5). As we can see, only half the list price actually goes into manufacturing

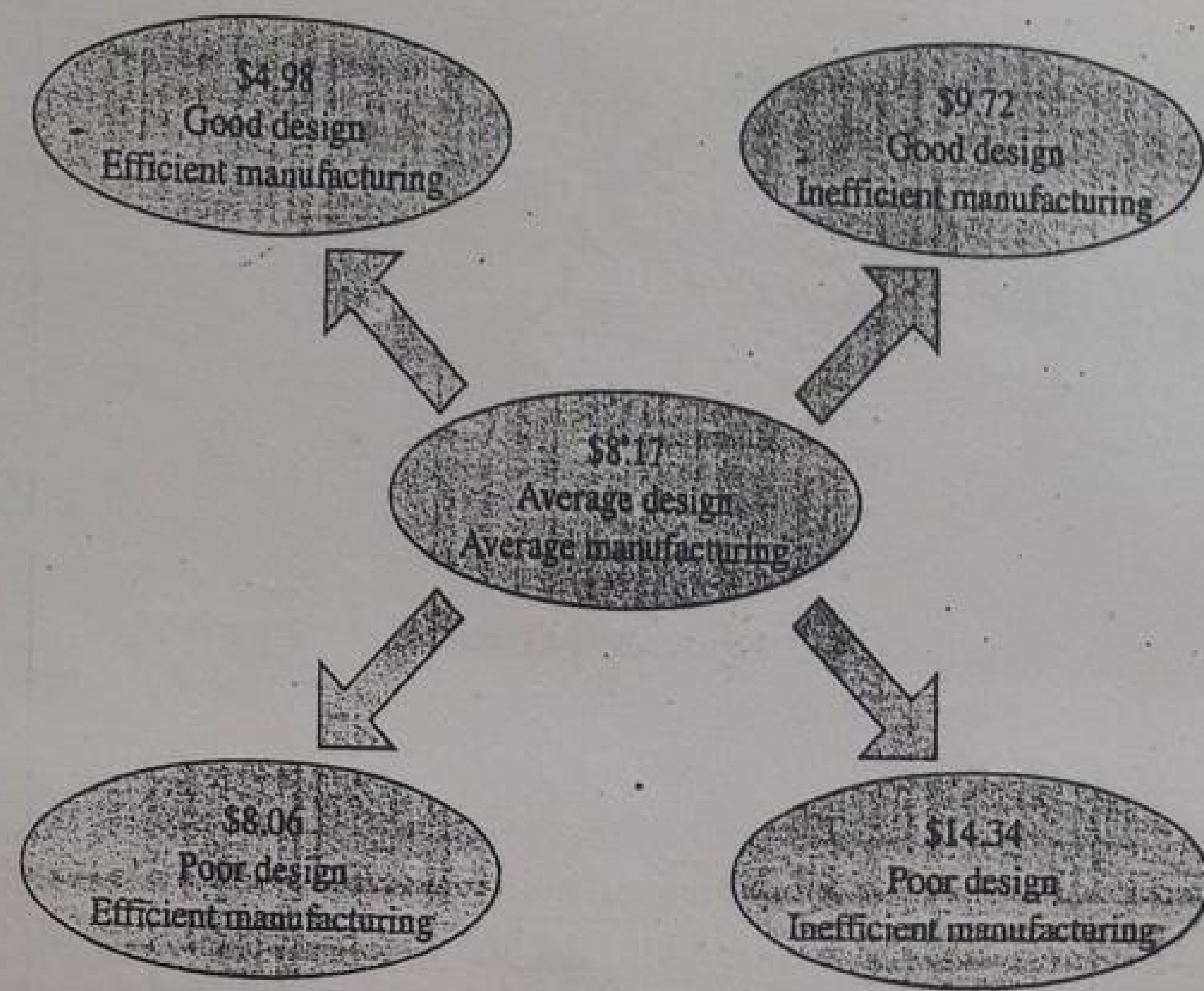


Figure 11.4 The effect of design quality on manufacturing cost.

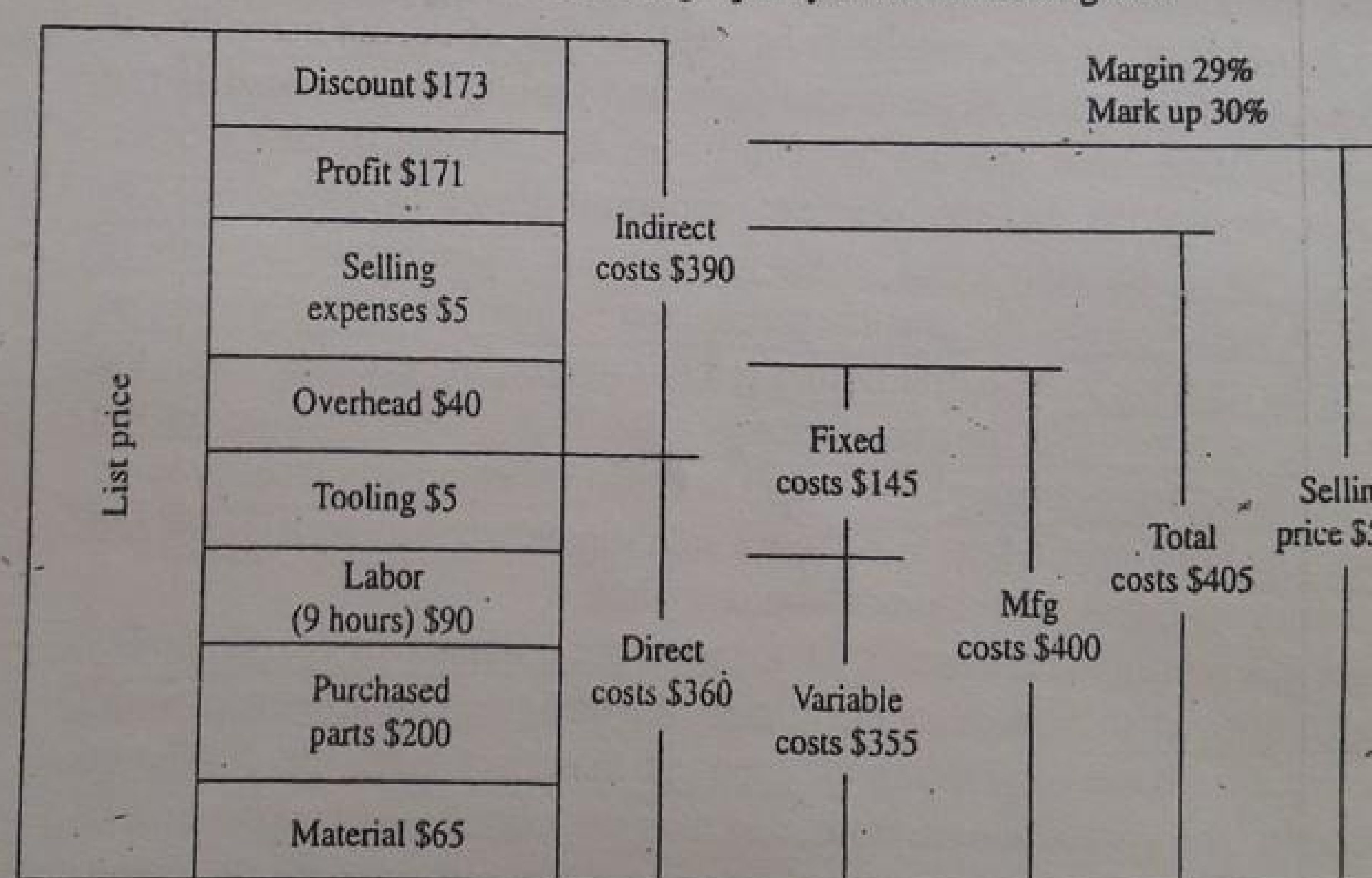


Figure 11.5 Cost breakdown for a $750 bicycle.

the bicycle (direct costs = $360). Also, the manufacturing company only makes $171 profit. Although this seems reasonable, a margin of 29% is just barely high enough to stay in business.

11.2.2 Making a Cost Estimate

It is the responsibility of the engineer to know the manufacturing cost of components designed. The ability to make these estimations comes with experience and with help from experienced team members and vendors. In many companies cost estimating is accomplished by a professional who specializes in determining the cost of a component whether it is made in house or purchased from a vendor. This person must be as accurate as possible in his or her estimates, as major decisions about the product are based on these costs. Cost estimators need fairly detailed information to perform their job. It is unrealistic for the designer to give the cost estimator 20 conceptual designs in the form of rough sketches and expect any cooperation in return. In most small companies, all cost estimations are done by the engineer.

The first estimations should be made early in the product design phase and be precise enough to be of use in making decisions about which designs to eliminate from consideration and which designs to continue refining. At this stage of the process, cost estimates within 30% of the final direct cost are possible. The goal is to have the accuracy of this estimate improve as the design is refined toward the final product. The more experience one has in estimating similar products, the more accurate the early estimates will be.

The cost-estimating procedure depends on the source of the components in the product. There are three possible options for obtaining the components: purchase finished components from a vendor, have a vendor produce components designed in house, or manufacture components in house.

As discussed in Chap. 9, there are strong incentives to buy existing components from vendors. If the quantity to be purchased is large enough, most vendors will work with the product designer and modify existing components to meet the needs of the new product.

If existing components or modified components are not available off the shelf, then they must be produced, in which case a decision must be made as to whether they should be produced by a vendor or made in house. This is the classic "make or buy" decision, a complex decision that is based on the cost of the component involved as well as the capitalization of equipment, the investment in manufacturing personnel, and plans by the company to use similar manufacturing equipment in the future.

Regardless of whether the component is to be made or bought, cost estimates are vital. We look now at cost estimating for two primary manufacturing processes: machining and injection molding.

11.2.3 The Cost of Machined Components

Machined components are manufactured by removing portions of the material not wanted. Thus, the costs for machining are primarily dependent on the cost and shape of the stock material, the amount and shape of the material that needs to be removed, and how accurately it must be removed. These three areas can be further decomposed into seven significant control factors that determine the cost of a machined component:

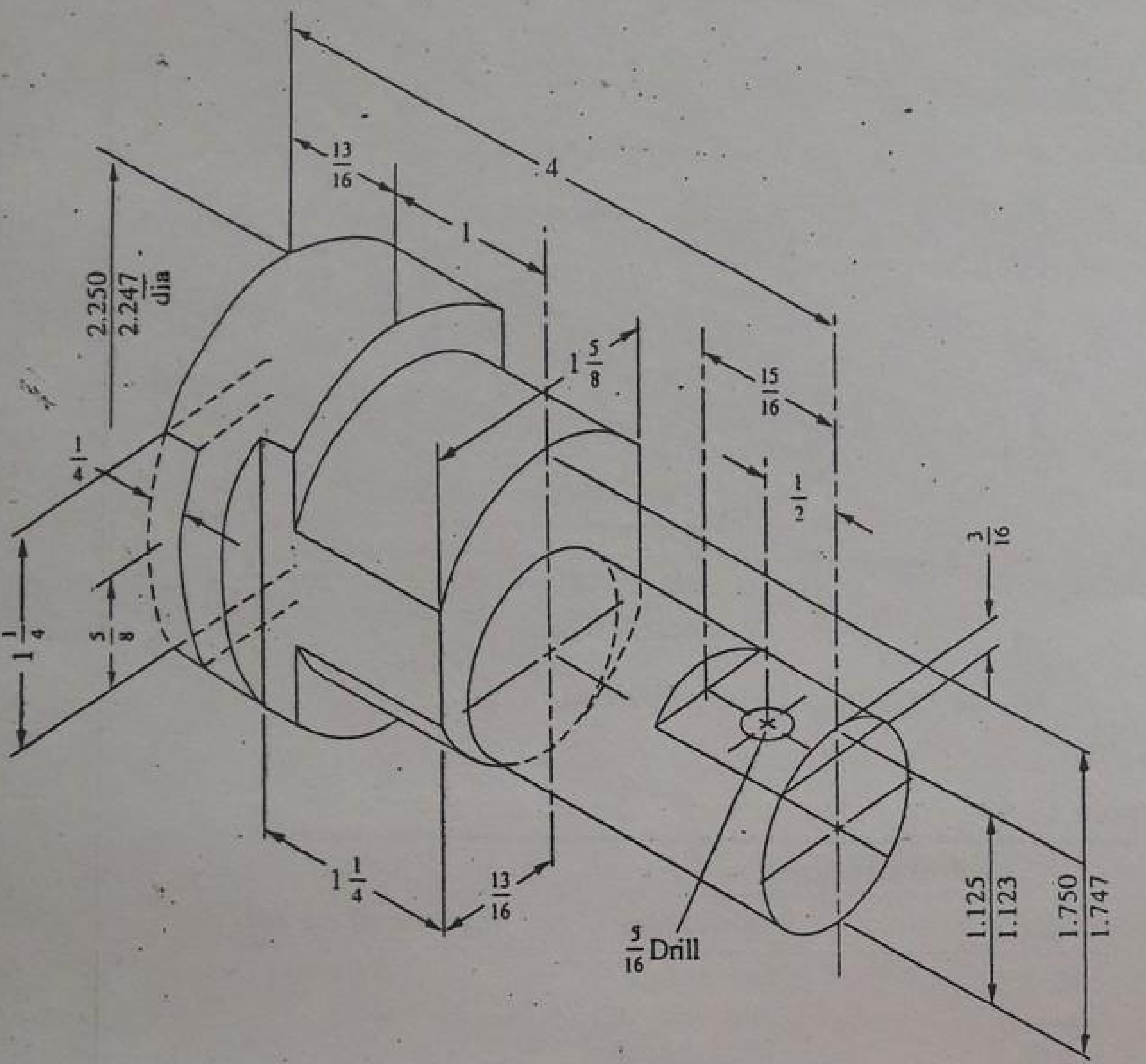
1. **From what material is the component to be machined?** The material affects the cost in three ways: the cost of the raw material, the value of the scrap produced, and the ease with which the material can be machined. The first two are direct material costs, and the last affects the amount of labor, the amount of time, and the choice of machines that are used manufacturing the component.

2. **What type of machine is used to manufacture the component?** The type of machine—lathe, horizontal mill, vertical mill, and so on—used in manufacture affects the cost of the component. For each type, there is not only the cost of the machine time itself but also the cost of the tools and fixtures needed.
3. **What are the major dimensions of the component?** This factor helps determine what size of machines of each type will be required to manufacture the component. Each machine in a manufacturing facility has a different cost for use, depending on the initial cost of the machine and its age.
4. **How many machined surfaces are there, and how much material is to be removed?** Just knowing the number of surfaces and the material removal ratio (the ratio of the final component volume to the initial volume) can aid in giving a good estimate for time required to machine the part. Estimates that are more accurate require knowing exactly what machining operations will be used to make each cut.
5. **How many components are made?** The number of components in a batch has a great effect on the cost. For one piece, fixturing is minimal, though long setup and alignment times are required. For a few pieces, simple fixtures are made. For a high volume, the manufacturing process is automated, with extensive fixturing and numerically controlled machining.
6. **What tolerance and surface finishes are required?** The tighter the tolerance and surface finish requirements, the more time and equipment are needed in manufacture.
7. **What is the labor rate for machinists?**

As an example of how these seven factors affect the cost of machined components, consider the component in Fig. 11.6.[1] For this component the seven significant factors affecting cost are

1. The material is 1020 low-carbon steel.
2. The major manufacturing machine is a lathe. Two additional machines need to be used to mill the flat surfaces and drill the hole.
3. The major dimensions are a 57.15-mm diameter and a 100-mm length. The initial raw material must be larger than these dimensions.
4. There are three turned surfaces and seven other surfaces to be made. The final component is approximately 32% the volume of the original.
5. The number of components to be made is discussed in the next paragraph.
6. The tolerance varies over the different surfaces of the component. On most surfaces, it is nominal, but on the diameters, it is a fit tolerance. The surface finish, .8 μm (32 μin.), is considered intermediate.
7. The labor rate used is $35 per hour; this includes overhead and fringe benefits.

[1] The cost estimates in this section were made by entering values for these factors on a spreadsheet available as a template that can be used to estimate the cost of any machined part.



Tolerances 0.00 – 0.99 → ± 0.004
1.00 – 2.79 → ± 0.006
2.80 – 7.49 → ± 0.009
except as noted
All dimensions in inches

Material: steel 1020
Surface finish 32

Figure 11.6 Sample component for evaluating machining cost.

Figure 11.7 shows the cost of this component for various manufacturing volumes. The values are the total manufacturing cost per component. The cost of materials per component remains fairly constant at $1.48, but the labor hours and thus the cost of labor drop with volume. For machined components, the cost dependence on volume is small in quantities above 10 because of the use of Computer-Aided Manufacturing, CAM.

The dependence of the manufacturing cost on other variables is shown in Table 11.1, in which the tolerance, finish, and material are varied. The first three lines show the change with tolerance. A fine tolerance was used for the data in Fig. 11.7 and is shown in line 1. As the tolerance was relaxed to nominal (2) and then to rough (3), the cost dropped.

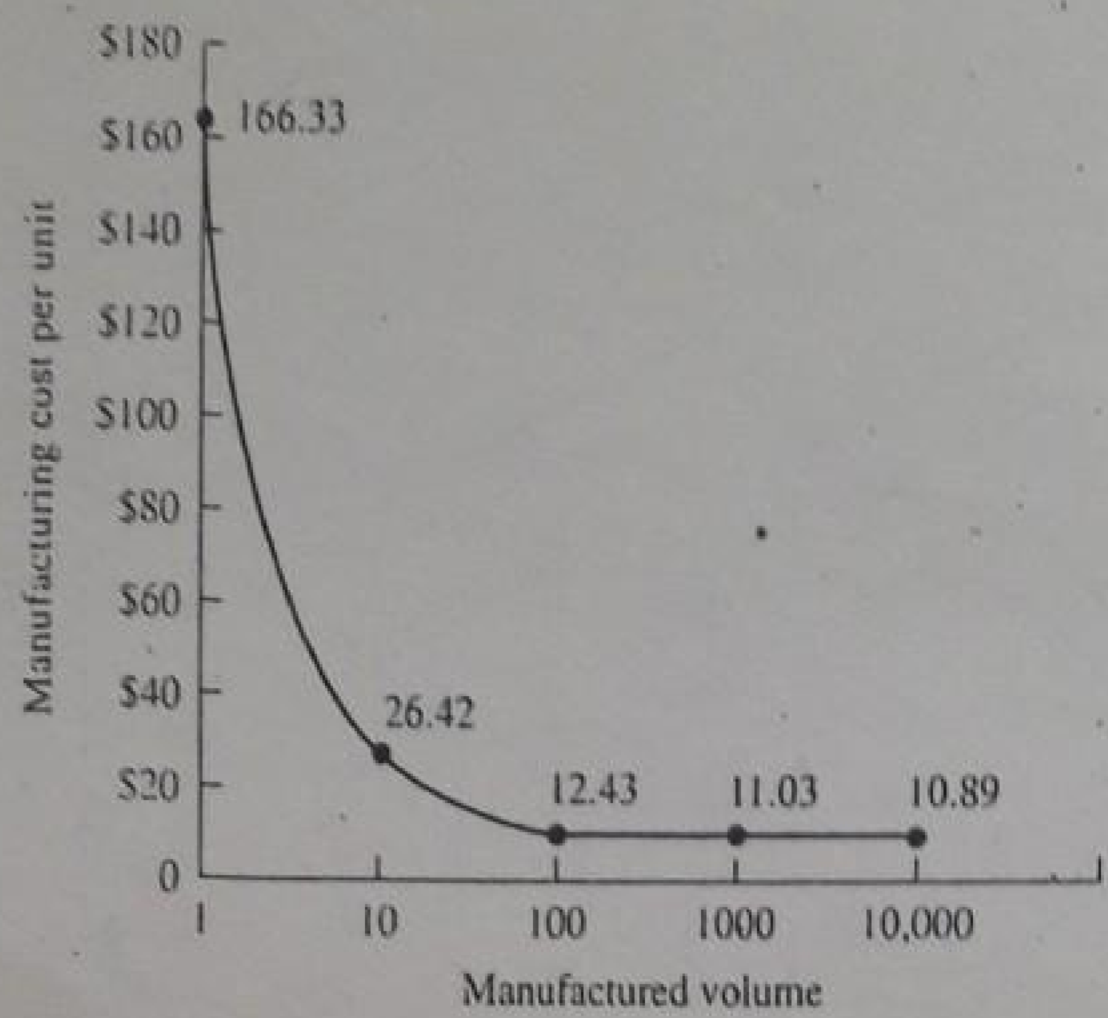


Figure 11.7 Effect of volume on cost.

Table 11.1 Effect of tolerance, finish, and material on cost

Control parameters		
Tolerance	**Surface finish**	**Manufacturing cost**
1. Fine	Intermediate	$11.03
2. Nominal	Intermediate	$8.83
3. Rough	Intermediate	$7.36
4. Fine	Polished	$14.85
5. Fine	As turned	$8.17
6. High-carbon steel		$22.45

Note: For 1000 units.

> Product cost goes down exponentially with increased production volume.

The fourth and fifth lines show the effect of surface finish on the manufacturing cost. The data in Fig. 11.7 were based on an intermediate surface finish, as specified in the drawing. As this was improved (4), the manufacturing cost rose, and as it was reduced to "as turned" (5), the cost dropped dramatically. Also shown in Table 11.1 is the effect of changing the material from low-carbon steel to high carbon steel (6), which doubles the cost when compared to line 1 in part because of an increase in material cost (+$4.00) and an increase in the machining time.

11.2.4 The Cost of Injection-Molded Components

Probably the most popular manufacturing method for high-volume products is plastic injection molding. This method allows for great flexibility in the shape of the components and, for manufacturing volumes over 10,000, is usually cost effective. On a coarse level, all the factors that affect the cost of machined components also affect the cost of injection-molded components. The only differences are that there is only one type of machine, an injection-molding machine, and the questions concerning geometry are modified. Besides the major dimensions of the component, it is important to know the wall thickness and component complexity in order to determine the size of the molding machine needed, the time it will take the components to cool sufficiently for ejection from the machine, the number of cavities in the mold (the number of components molded at one time), and the cost of the mold.

To demonstrate the effect of the factors, we show the cost for a clip, shown in Fig. 11.8.[2] The significant factors affecting cost are

1. The overall dimensions are 9.46 cm (3.72 in.) by 4.52 cm (1.77 in.) in the mold plane and 4.13 cm (1.6 in.) deep.
2. The wall thickness is 3.2 mm (0.125 in.).
3. The number of components to be manufactured is 1 million.
4. The labor hourly rate is $35.
5. The tolerance level is intermediate.
6. The surface finish is not critical.

The cost of manufacturing the component in Fig. 11.8 is shown in Fig. 11.9 for varying production volumes. The capital cost of making a mold is high enough to dominate the cost of the component at low volumes. This is why making just 1000 injection-molded plastic parts would be very expensive. A rule of thumb is that if the manufacturing volume is less than 10,000, plastic injection molding may be cost prohibited.

The manufacturing cost can be affected by the wall thickness. In the drawing, the thickness is 3.2 mm. If this is lowered to 2.5 mm, the part cost will drop about 18%. This is primarily because the time needed in the mold for cooling drops from 18 sec to 13 sec, saving cycle time.

11.3 DFV—DESIGN FOR VALUE

The concept of value engineering (also called value analysis) was developed by General Electric in the 1940s and evolved into the 1980s. Value engineering is a customer-oriented approach to the entire design process. It changes the focus from the cost of a component to its value to the customer. The key point of value

[2]The cost estimates in this section were made by entering values for these factors on a spreadsheet available as a template that can be used to estimate the cost of any machined part.

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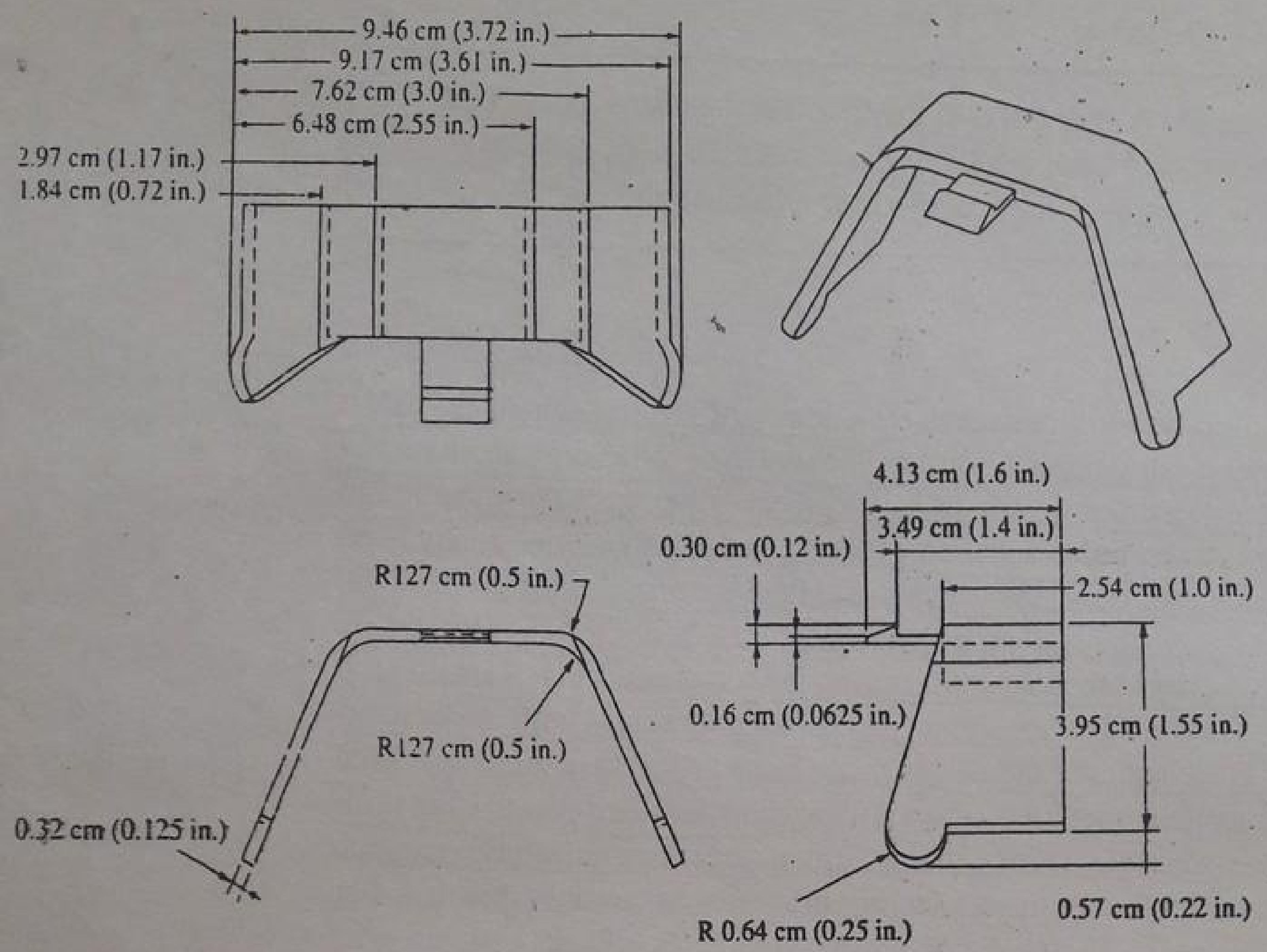

Brad Tittle Oregon State Univ. December 28, 1990	CLIP	Tol: +−0.01 cm Approved: [signature]

Figure 11.8 Component for cost estimation.

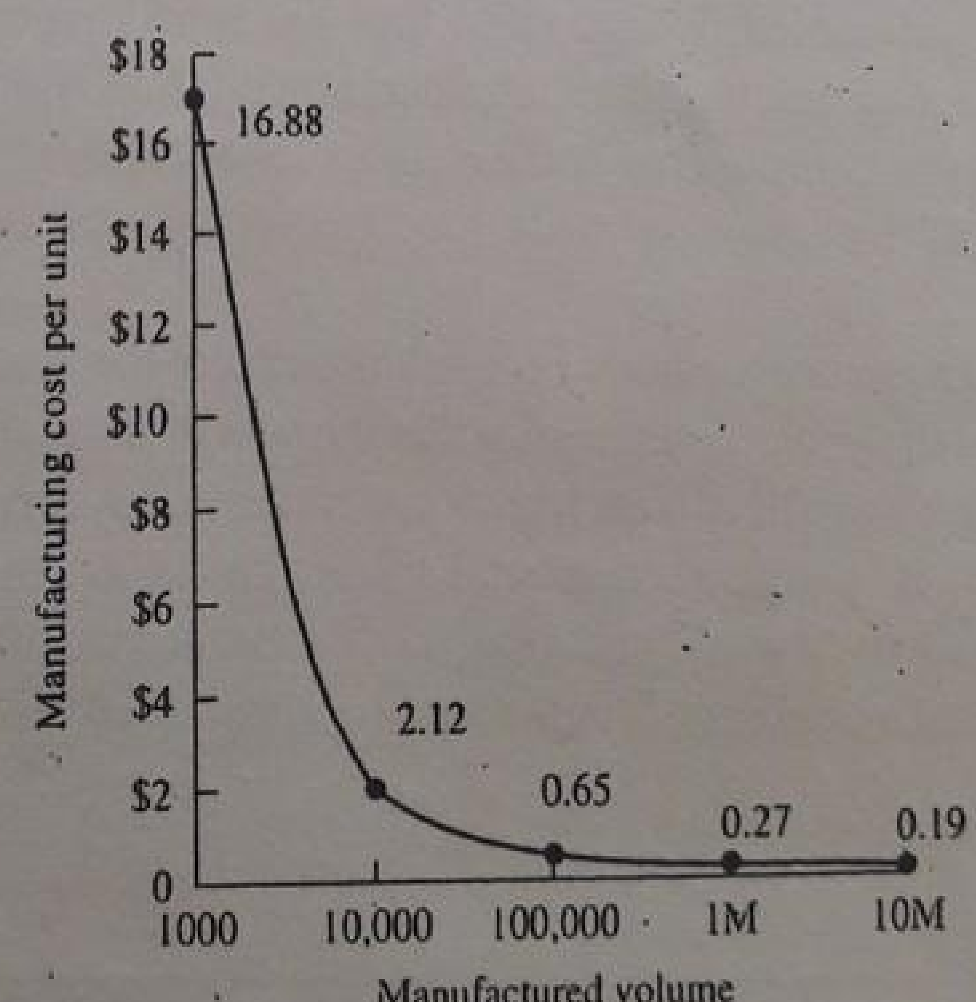

Figure 11.9 The effect of volume on the cost of a plastic part.

engineering is that it is not sufficient to only find cost—it is necessary to find the value of each feature, component, and assembly to be manufactured. Value is defined as

$$\text{Value} = \frac{\text{Worth of a feature, component, or assembly}}{\text{Cost of it}}$$

The worth of a feature of a component, for example, is determined by the functionality it provides to the customer. Thus, a refined definition for value is *function provided per dollar of cost.*

The value formula is used as a theme through the value engineering steps suggested here. These steps are focused on features of components. The method can also be applied to components and assemblies.

Step 1 To ensure that all the functions are known, for each feature of a component ask the question, What does it do? If a feature provides more than one function, this fact must be noted. Features that result from a specific manufacturing operation are at the finest level of granularity that should be considered. For the machined component in Fig. 11.6, each turned diameter and face, each milled surface, and the hole should be considered. For the injection-molded plastic part in Fig. 11.8, the 6.4-mm-radius round feature at the bottom is a good feature to query. This feature provides a number of functions.

Step 2 Identify the life-cycle cost of the feature. This cost should include the manufacturing cost as well as any other downstream costs to the customer. If the feature provides multiple functions, the cost should be divided into cost per function. To do this, consider an equivalent feature that provides only the function in question. Although it is not accurate because of the interdependence of functions, it gives an estimate.

The cost of the round feature ($R = 0.64$ cm) in Fig. 11.8 is not evident. Consultation with tooling and manufacturing engineers revealed that, for a volume of 100,000 components ($0.65 component cost in Fig. 11.9) $0.02 was due to this feature. Their logic was that the feature does not contribute to labor cost because the cycle time would not change if the feature were removed. They estimated that, since the feature was hard to machine in the mold, it contributed about 5% to the mold cost. Amortized over the production volume, this gives $0.017. Finally, the material used for this feature is worth $0.003. So the feature costs $0.02 total. It could be argued that the structure of the body of the component should be included because it contributes to the function of the round feature. A decision has to be made as to where to allocate all the costs in the component, one of the challenges of value engineering.

Step 3 Identify the worth of the function to the customer. In an ideal world, we would be able to ask customers how much each function was worth to them. However, this is not realistic. To obtain at least a qualitative indication of function worth, the information developed in the QFD is used. If no formal method was used to develop the customers' requirements and measures of importance, then the best that can be done is to ask, How important is this feature to the customer?

The feature being used as an example contributes to a number of functions that are very important to the customer. To complicate matters, each of these functions involves other features. The best that can be done is to say that the functions contributed to by the round feature are worth a great deal to the customer. A customer will not pay as much for a product that is hard to attach, so the engineers estimated the worth at $2.00. Keep in mind that this method compares relative values, and not the values themselves.

Step 4 Compare worth to cost to identify features that have low relative value. If one feature costs more than the others and is worth more—provides important function to the product—then its value may be as high as or higher than the others. On the other hand, if its costs outweigh its worth, then it has low value and should be redesigned.

The round feature contributes to a number of important functions for very low cost and thus is considered to be of high value.

The concept of value is further discussed in Section 11.5, Design for Assembly. In that section, features are added to ease assembly. Even though these features cut assembly time and thus cost, they often raise the manufacturing cost. Whether to use these features is best judged by considering their value.

11.4 DFM—DESIGN FOR MANUFACTURE

The term *Design For Manufacture,* or DFM, is widely used but poorly defined. Manufacturing engineers often use this term to include all or some of the best practices discussed in this book. Others limit the definition to include only design changes that facilitate manufacturing but do not alter the concept and functionality of the product. Here we will define DFM as *establishing the shape of components to allow for efficient, high-quality manufacture.* Notice that the subject of the definition is *component.* In fact, DFM could be called DFCM, Design For Component Manufacture, to differentiate it from Design For Assembly, DFA, the assembly of components covered in the next section.

The key concern of DFM is in specifying the best manufacturing process for the component and ensuring that the component form supports the manufacturing process selected. For any component, many manufacturing processes can be used. For each manufacturing process, there are design guidelines that, if followed, result in consistent components and little waste. For example, the best process to manufacture the clip in Fig. 11.8 is injection molding. Thus, the form of the clip will need to follow design guidelines for plastic injection molding if the product is to be free from sink marks, surface finish blemishes, and other problems causing low-quality results.

Matching the component to the manufacturing process includes concern for tooling and fixturing. Components must be held for machining, released from

> If you don't have experience with a manufacturing process you want to use, be sure you consult someone who has—before you commit to using it.

molds, and moved between processes. The design of the component can affect all of these manufacturing issues. Further, the design of the tooling and fixturing should be treated concurrently with the development of the component. The design of tooling and fixturing follows the same process as the design of the component: establish requirements, develop concepts, and then the final product.

In the days of over-the-wall product design processes, design engineers would sometimes release drawings to manufacturing for components that were difficult or impossible to make. The concurrent engineering philosophy, with manufacturing engineers as members of the design team, helps avoid these problems. With thousands of manufacturing methods, it is impossible for a designer to have sufficient knowledge to perform DFM without the assistance of manufacturing experts.

There are far too many manufacturing processes to cover in this text. For details on these, see the *Design for Manufacturability Handbook*.

11.5 DFA—DESIGN-FOR-ASSEMBLY EVALUATION

Design For Assembly, DFA, is the best practice used to measure the ease with which a product can be assembled. Where DFM focuses on making the components, DFA is concerned with putting them together. Since virtually all products are assembled out of many components and assembly takes time (that is, costs money), there is a strong incentive to make products as easy to assemble as possible.

Throughout the 1980s, many methods evolved to measure the assembly efficiency of a design. All of these methods require that the design be a fairly refined product before they can be applied. The technique presented in this section is based on these methods. It is organized around 13 design-for-assembly guidelines, which form the basis for a worksheet (Fig. 11.10). Before we discuss these 13 guidelines, we mention a number of important points about DFA.

> Design For Assembly is important only if assembly is a significant part of the product cost.

(DFA) Design For Assembly

Individual Assembly Evaluation for: Irwin pre 2007 Clamp | **Organization Name:** Example

	OVERALL ASSEMBLY		
1	Overall part count minimized	Very good	6
2	Minimum use of separate fasteners	Outstanding	8
3	Base part with fixturing features (locating surfaces and holes)	Outstanding	8
4	Repositioning required during assembly sequence	> = 2 Positions	4
5	Assembly sequence efficiency	Very good	6
	PART RETRIEVAL		
6	Characteristics that complicate handling (tangling, nesting, flexibility) have been avoided	Most parts	6
7	Parts have been designed for a specific feed approach (bulk, strip, magazine)	Few parts	2
	PART HANDLING		
8	Parts with end-to-end symmetry	Some parts	4
9	Parts with symmetry about the axis of insertion	Some parts	4
10	Where symmetry is not possible, parts are clearly asymmetric	Most parts	6
	PART MATING		
11	Straight-line motions of assembly	Some parts	4
12	Chamfers and features that facilitate insertion and self-alignment	Some parts	4
13	Maximum part accessibility	All parts	8
Note:	Only for comparison of alternate designs of same assembly	TOTAL SCORE	70

Team member: Fred Smith	Team member: Jason Peterson	Prepared by: Fred Smith	
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The Mechanical Design Process — Designed by Professor David G. Ullman

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Figure 11.10 Design for assembly worksheet.

Assembling a product means that a person or a machine must (1) *retrieve* components from storage, (2) *handle* the components to orient them relative to each other, and (3) *mate* them. Thus, the ease of assembly is directly proportional to the number of components that must be retrieved, handled, and mated, and the ease with which they can be moved from their storage to their final, assembled position. Each act of retrieving, handling, and mating a component or repositioning an assembly is called an *assembly operation*.

Retrieval usually starts at some type of component feeder; this can range from a simple bin of loose bulk components to an automatic machine that feeds one component at a time in the proper orientation for a robot to handle.

Component handling is a major consideration in the measure of assembly quality. Handling encompasses maneuvering the retrieved component into position so that it is oriented for assembly. For a bolt to be threaded into a tapped hole, it must first be positioned with its axis aligned with the hole's axis and its threaded end pointed toward the hole. A number of motions may be required in handling the component as it is moved from storage and oriented for mating. If component handling is accomplished by a robot or other machine, each motion must be designed or programmed into the device. If component handling is accomplished by a human, the human factors of the required motions must be considered.

Component mating is the act of bringing components together. Mating may be minimal, like setting one component on the flat surface of another, or it may require threading a fastener into a threaded hole. A term often synonymous with *mating* is *insertion*. During assembly some components are inserted in holes, others are placed on surfaces, and yet others are fitted over pins or shafts. In all these cases, the components are said to be inserted in the assembly, even though nothing may really be inserted, in the traditional sense of the word, but only placed on a surface.

DFA measures a product in terms of the efficiency of its overall assembly and the ease with which components can be retrieved, handled, and mated. A product with high assembly efficiency has a few components that are easy to handle and virtually fall together during assembly. Assembly efficiency can be demonstrated by considering the seat frames designed for a recumbent bicycle (a bicycle ridden in a seated position). Figure 11.11 shows an old frame, which had nine separate components requiring 20 separate operations to put together. These included positioning and welding operations. This frame took 30 min to assemble. In contrast, the new frame (Fig. 11.12) was designed with assembly efficiency as a major engineering requirement. The resulting product has only four components, requiring eight operations and about 8 min to assemble. The savings in labor is obvious. Additionally, there are savings in component inventory, component handling, and dealings with component vendors.

Guidelines similar to those on the worksheet of Fig. 11.10 were used in the design of the new seat frame to make it efficient to assemble. The worksheet is designed to give an assembly efficiency score to each product evaluated. The score ranges from 0 to 104. The higher the score, the better the assembly. This score is

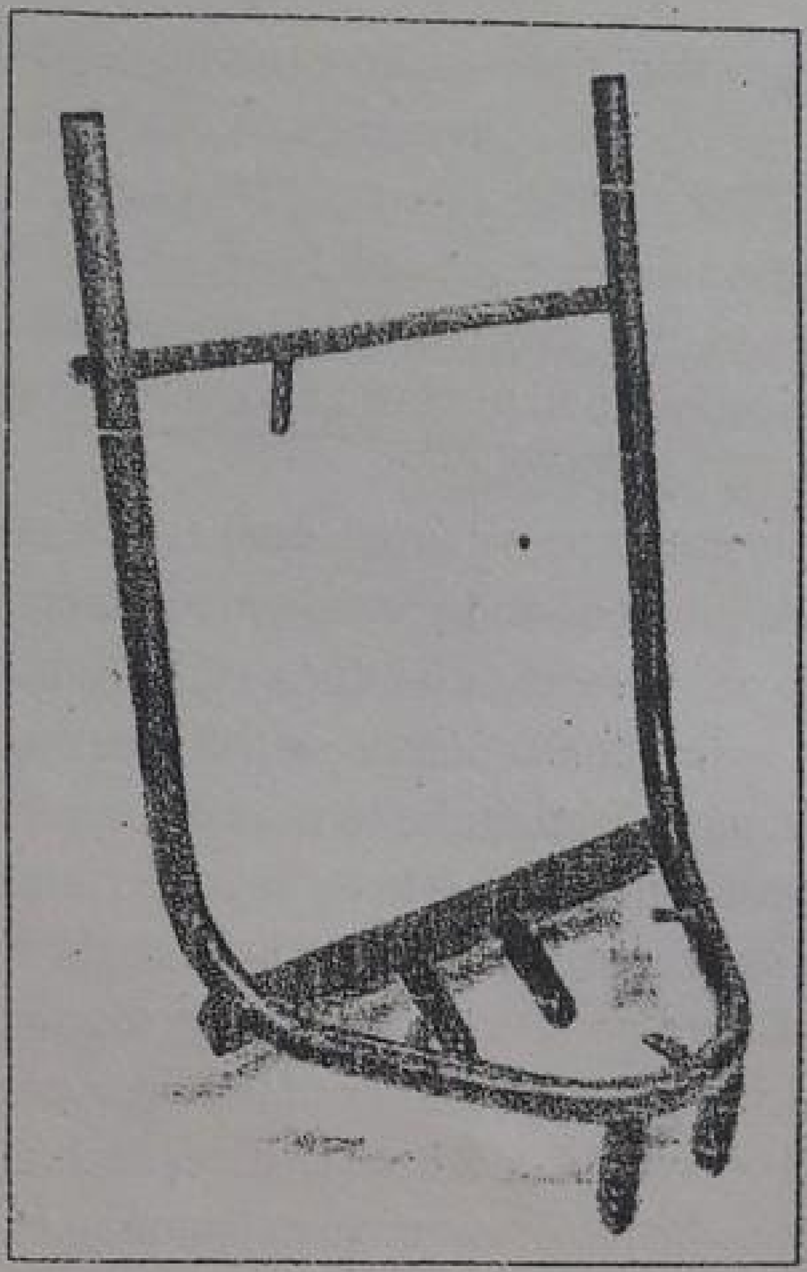


Figure 11.11 Old seat frame.

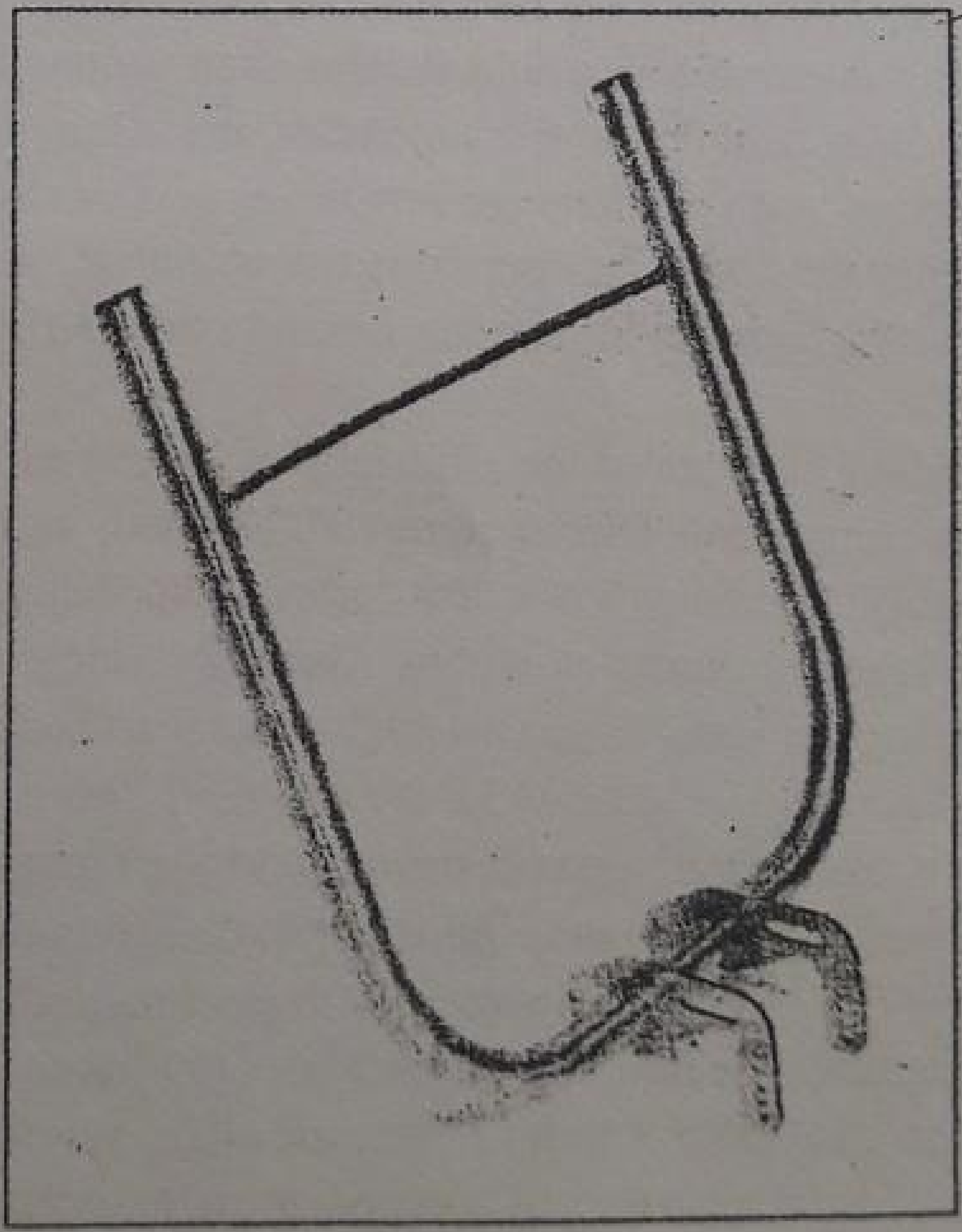


Figure 11.12 Redesigned seat frame.

A single part costs nothing to assemble.
—M. M. Andreassen

used as a relative measure to compare alternative designs of the same product or similar products; the actual value of the score has no meaning. The design can be patched or changed on the basis of suggestions given in the guidelines and then reevaluated. The difference between the score of the original product and that of the redesign gives an indication of the improvement of assembly efficiency.

Although this technique is only applied late in the design process, when the product is so refined that the individual components and the methods of fastening are determined, its value can be appreciated much earlier in the design process. This is true because, after filling out the worksheet a few times, the designer develops the sense of what makes a product easy to assemble—knowledge that will have an effect on all future products.

Using ease of assembly as an indication of design quality makes sense only for mass-produced products, since the design-for-assembly guidelines encourage a few complex components. These types of components usually require expensive tooling, which can only be justified if spread over a large manufacturing volume.

Finally, the relationship between the cost of assembly and the overall cost of the product must be kept in mind when considering how much to modify a design according to these suggestions. In low-volume electromechanical products, the cost of assembly is only 1 to 5% of the total manufacturing cost. Thus, there is little payback for changing a design for easier assembly; the change will require extra design effort and may raise the cost of manufacturing, with little financial return.

Measures for each of the 13 design-for-assembly guidelines will be discussed in Sections 11.5.1 to 11.5.4; Section 11.5.1 gives guidelines, all concerned with the overall assembly efficiency; Sections 11.5.2 to 11.5.4 give design-for-assembly guidelines oriented toward the retrieval, handling, and mating of the individual components.

11.5.1 Evaluation of the Overall Assembly

Guideline 1: Overall Component Count Should Be Minimized. The first measure of assembly efficiency is based on the number of components or subassemblies used in the product. The part count is evaluated by estimating the minimum number of components possible and comparing the design being evaluated to this minimum. The measure for this guideline is estimated in this way:

a. Find the Theoretical Minimum Number of Components. Examine each pair of adjacent components in the design to see if they really should be separate components. Include fastening components such as bolts, nuts, and clips in this accounting. Assuming no production or material limitations: (1) Components must be separate if the design is to operate mechanically. For example, components that must slide or rotate relatively to each other must be separate components. However, if the relative motion is small, then elasticity can be built into the design to meet the need. This is readily accomplished in plastic components by using elastic hinges, thin sections of fatigue-resistant material that act as a one degree-of-freedom joint. (2) Components must be separate if they must be made of different materials, for example, when one component is an electric or thermal insulator and another, adjacent component is a conductor. (3) Components must be separate if assembly or disassembly is impossible. (Note that the last word is "impossible," not "inconvenient.")

Thus, each pair of adjacent components is examined to find if they absolutely need to be separate components. If they do not, then theoretically they can be combined into one component. After reviewing the entire product this way, we develop the theoretical minimum number of components. The seat frame has a minimum of one component. The actual number of components in the redesigned frame (Fig. 11.12) is four.

b. Find the Improvement Potential. To rate any product, we can calculate its improvement potential:

$$\text{Improvement potential} = \frac{\begin{pmatrix}\text{Actual number of}\\ \text{components}\end{pmatrix} - \begin{pmatrix}\text{Theoretical minimum}\\ \text{number of components}\end{pmatrix}}{\text{Actual number of components}}$$

c. Rate the Product on the Worksheet (Fig. 11.10).

- If the improvement potential is less than 10%, the current design is *outstanding.*
- If the improvement potential is 11 to 20%, the current design is *very good.*
- If the improvement potential is 20 to 40%, the current design is *good.*
- If the improvement potential is 40 to 60%, the current design is *fair.*
- If the improvement potential is greater than 60%, the current design is *poor.*

The improvement potential of the seat frame in Figure 11.12 is $(4 - 1)/4 =$ 75%. In this case, design is poor, but the volume is too low to use a method to further reduce the number of components.

As a product is redesigned, keep track of the actual improvement:

$$\text{Actual improvement} = \frac{\begin{pmatrix}\text{Number of components}\\ \text{in initial design}\end{pmatrix} - \begin{pmatrix}\text{Number of components}\\ \text{in redesign}\end{pmatrix}}{\text{Number of components in initial design}}$$

Typical improvement in the number of components in the range of 30 to 60% is realized by redesigning the product in order to reduce the component count.

To put this guideline in perspective, compare it with earlier phases of the design process. In the design philosophy of this text, the functionality of the product is broken down as finely as possible as a basis for the development of concepts (Chap. 7). We then used a morphology for developing ideas for each function. This can lead to poor designs, as can the effort to minimize the number of components. Consider the design of the common nail clipper (Fig. 11.13). If the assumption is made that all the functions are independent and that concepts

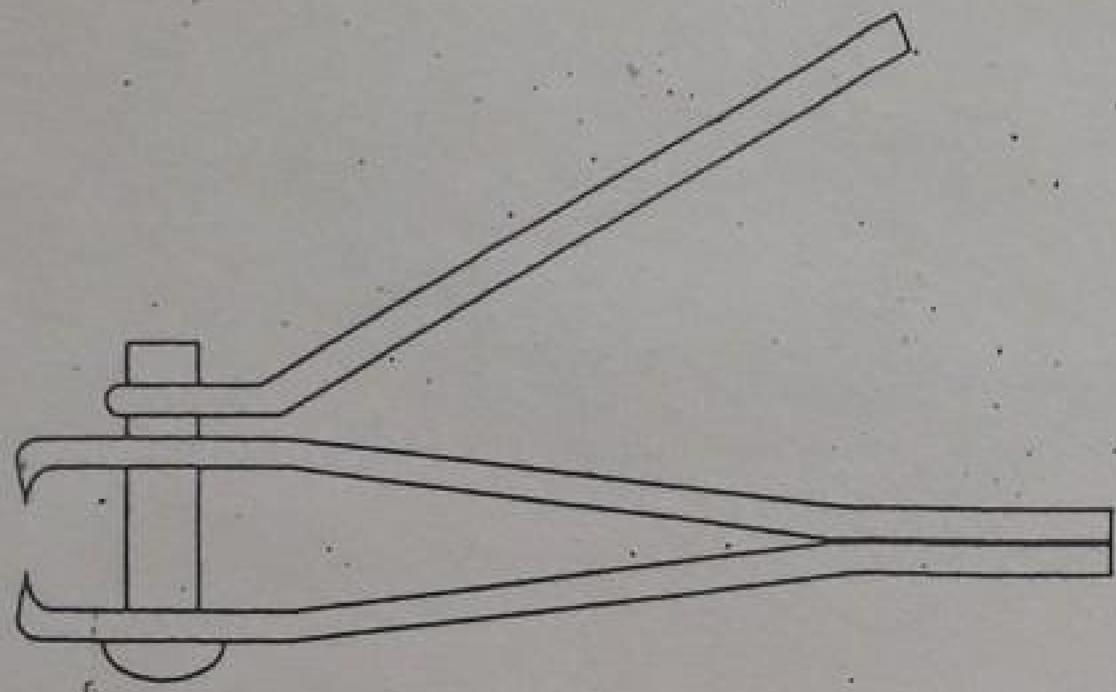


Figure 11.13 Common nail clipper.

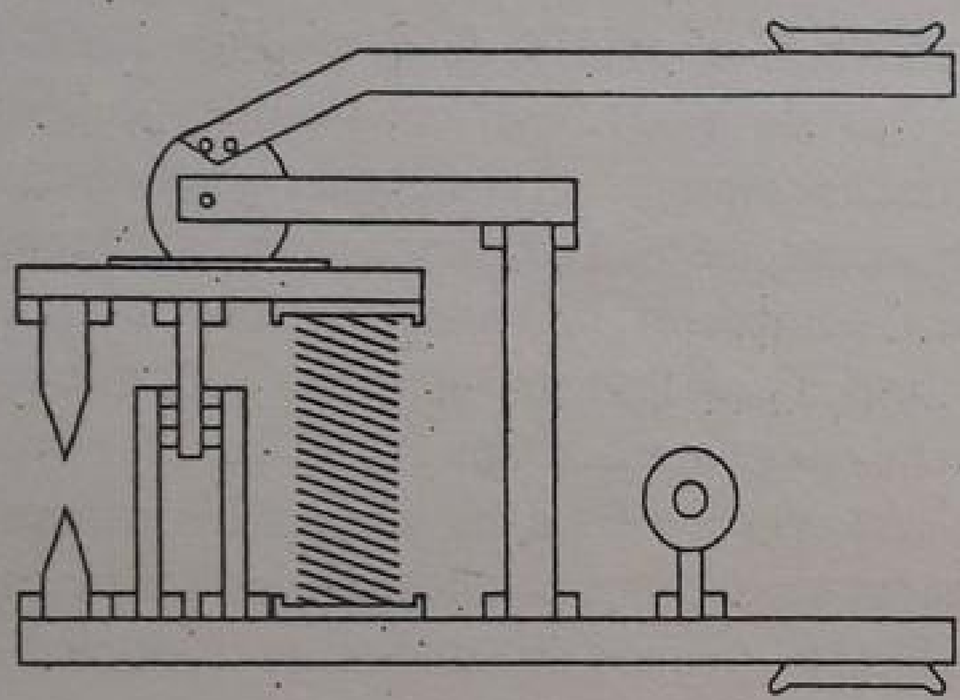


Figure 11.14 Nail clipper with one interface for each function. (Source: Design developed by Karl T. Ulrich, Sloan School of Management, Massachusetts Institute of Technology.)

are generated for each function, then the result, as seen in Fig. 11.14, is a disaster. Note that each function is mapped to one or more interface. At the other extreme, the DFA philosophy leads to the product shown in Fig. 11.15.

Here, in evaluating the product for assembly, this guideline encourages lumping as many functions as possible into each component. This design philosophy, however, also has its problems. The cost of tooling (molds or dies) for the shapes that result from a minimized component count can be high—and that cost is not taken into account here. Additionally, tolerances on complex components may be more critical, and manufacturing variations might affect many functions that are now coupled.

Guideline 2: Make Minimum Use of Separate Fasteners. One way to reduce the component count is to minimize the use of separate fasteners. This is advisable

Every fastener adds costs and reduces strength.

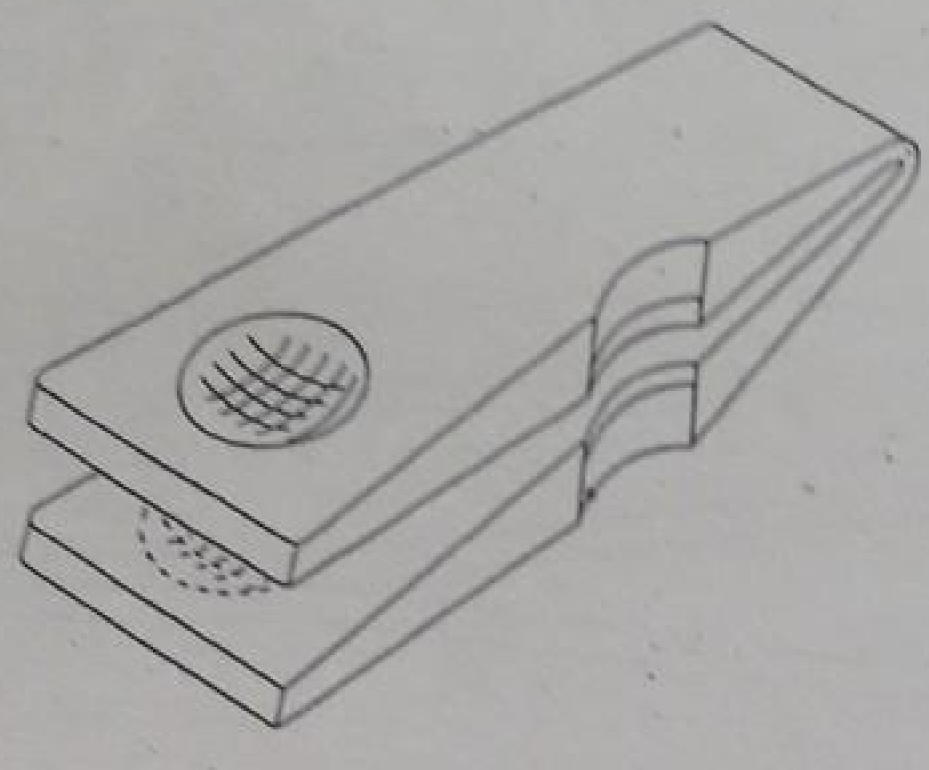


Figure 11.15 A one-piece nail clipper.

for many reasons. First, each fastener used is one more component to handle, and there may be many more than one in the case of a bolt with its accompanying nut, flat washer, and lock washer. Each instance of component handling takes time, typically 10 sec per fastener. Second, the total cost for fasteners is the cost of the components themselves as well as the cost of purchasing, inventorying, accounting for, and quality-controlling them. Third, fasteners are stress concentrators; they are points of potential structural failure in the design. For all these reasons, it is best to eliminate as many fasteners as possible from the design. This is more easily done on high-volume products, for which components can be designed to snap together, than on low-volume products or products utilizing many stock components.

An additional point that should be considered in evaluating a design is how well the use of fasteners has been standardized. A good example of part standardization is the fact that almost everything on the Volkswagen Beetle, a car popular in the 1970s, can be fixed with a set of screwdrivers and a 13-mm wrench.

Finally, if the components fastened together must be taken apart for maintenance, use captured fasteners (fasteners that remain loosely attached to a component even when unfastened). Many varieties of captured fasteners are available, all designed so that they will not be misplaced during assembly or maintenance.

There are no general rules for the quality of a design in terms of the number of separate fasteners. Since the worksheet is just a relative comparison between two designs, an absolute evaluation is not necessary. Obviously, an outstanding design will have few separate fasteners, and those it does have will be standardized and possibly captured. Poor designs, on the other hand, require many different fasteners to assemble. If more than one-third of the components in a product are fasteners, the assembly logic should be questioned.

Figures 11.16 and 11.17 show some ideas for reducing the number of fasteners. In designing with injection-molded plastics, the best way to get rid of fasteners is through the use of snap fits. A typical cantilever snap is shown in Fig. 11.16*a*. Important considerations when designing snaps are the loads during insertion and when seated. During insertion, the snap acts like a cantilever beam flexed by the amount of the insertion displacement. The major stress during insertion is therefore bending at the root of the beam. Thus, it is important to have

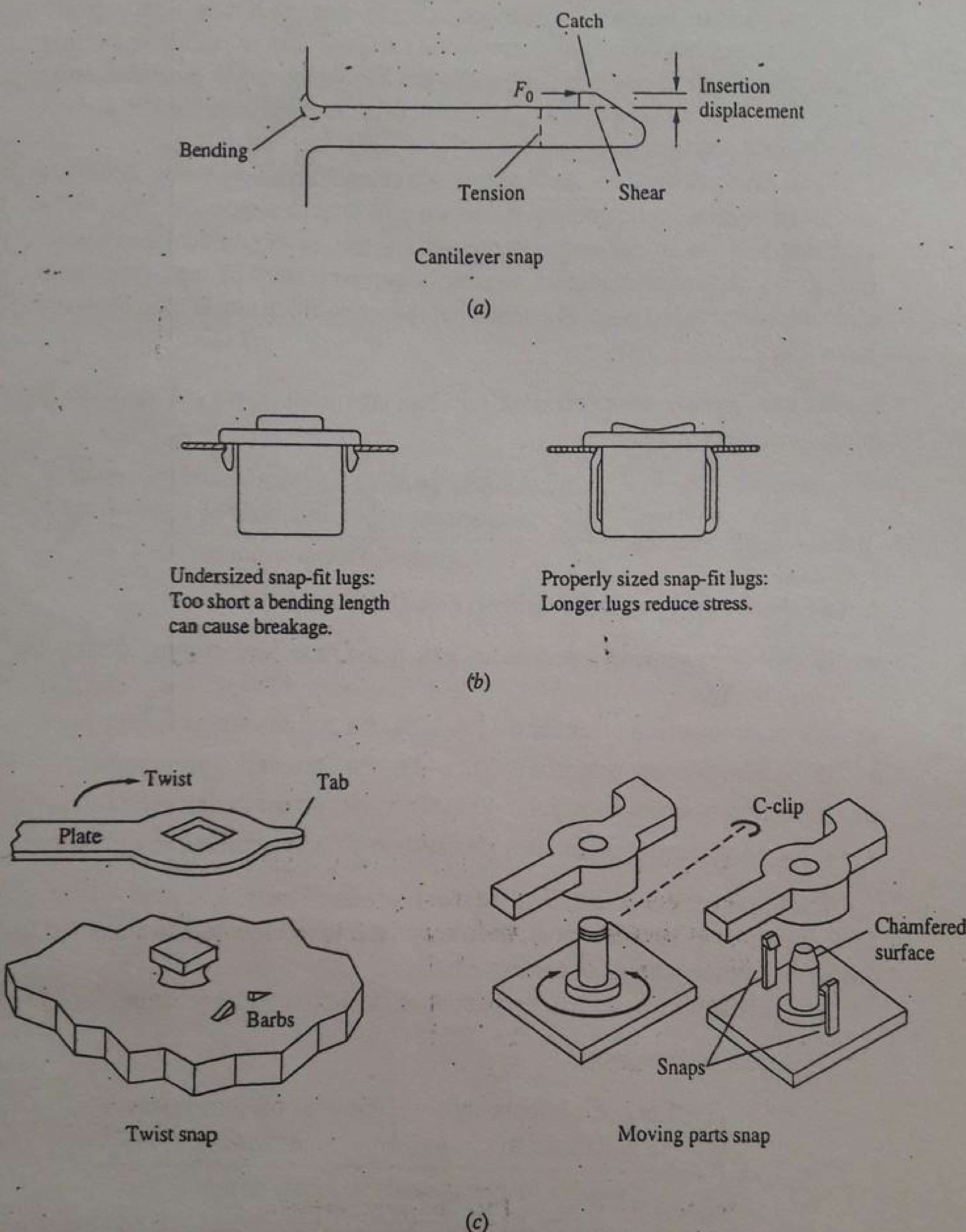


Figure 11.16 Snap-fastener design.

low stress concentrations at that point and to be sure that the snap can flex enough without approaching the elastic limit of the material (Fig. 11.16*b*). When seated, the snap's main load is the force F_0, the force holding the components together. It can cause crushing on the face of the catch, shear failure of the catch, and tensile failure of the snap body. (Think of the force flow here.)

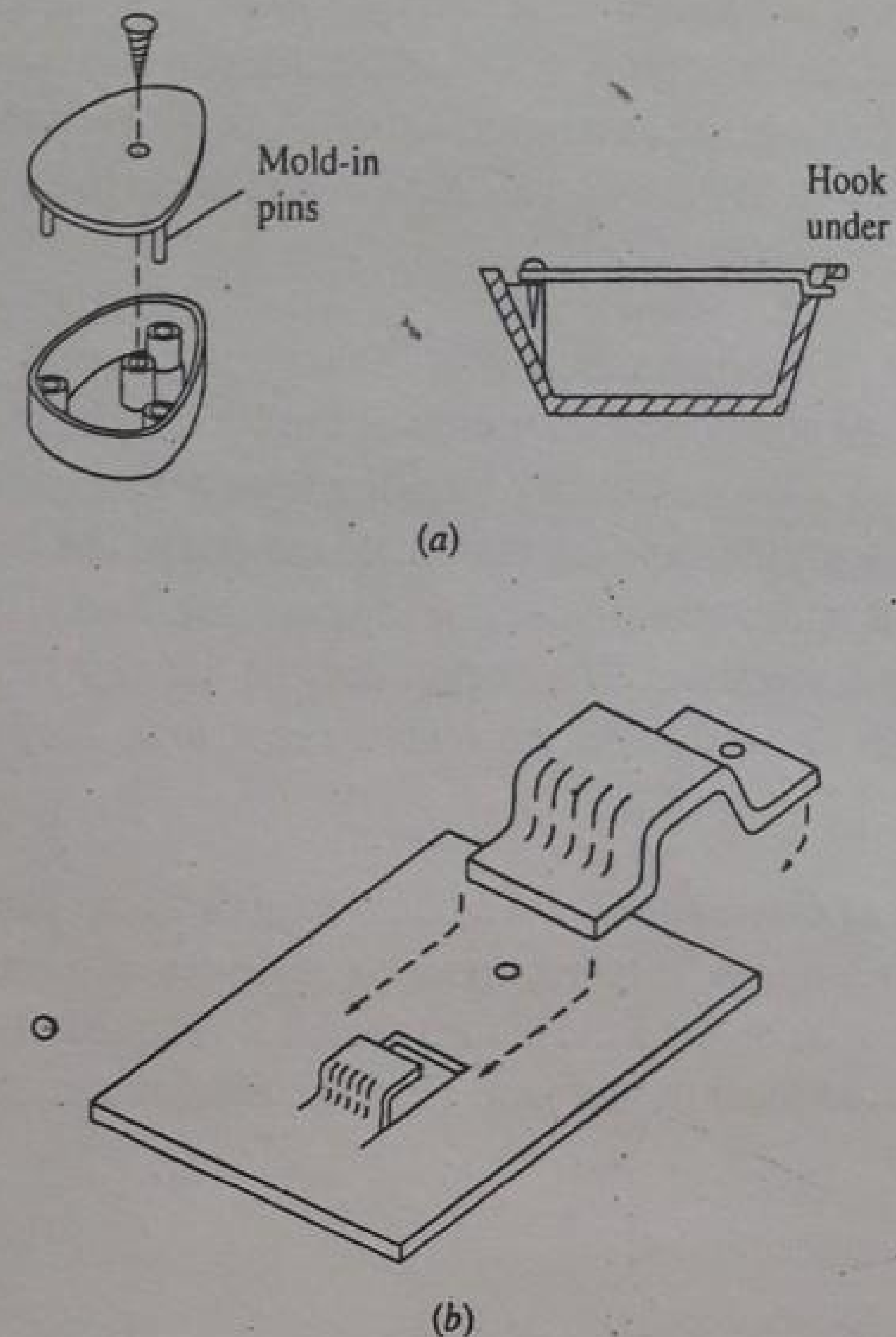


Figure 11.17 Single fastener examples.

Additionally, design consideration must be given to unsnapping. If the device is ever to come apart for maintenance, then consider features that allow a tool or a finger to flex the snap while $F_0 = 0$. Additional snap configurations are shown in Fig. 11.16*c*. Note that each has one feature that flexes during insertion and another that takes the seated load.

Another way to reduce the number of fasteners is to use only one fastener and either pins, hooks, or other interference to help connect the components. The examples in Fig. 11.17 show both plastic and sheet-metal applications of this idea.

Guideline 3: Design the Product with a Base Component for Locating Other Components. This guideline encourages the use of a single base on which all the other components are assembled. The base in Fig. 11.18 provides a foundation for consistent component location, fixturing, transport, orientation, and strength. The ideal design would be built like a layer cake, with each component or subassembly stacking on top of another one. Without this base to build on, assembly may consist of work on many subassemblies, each with its own fixturing and transport needs and final assembly requiring extensive repositioning and fixturing. The use of a single base component has shortened the length of some assembly lines by a factor of 2.

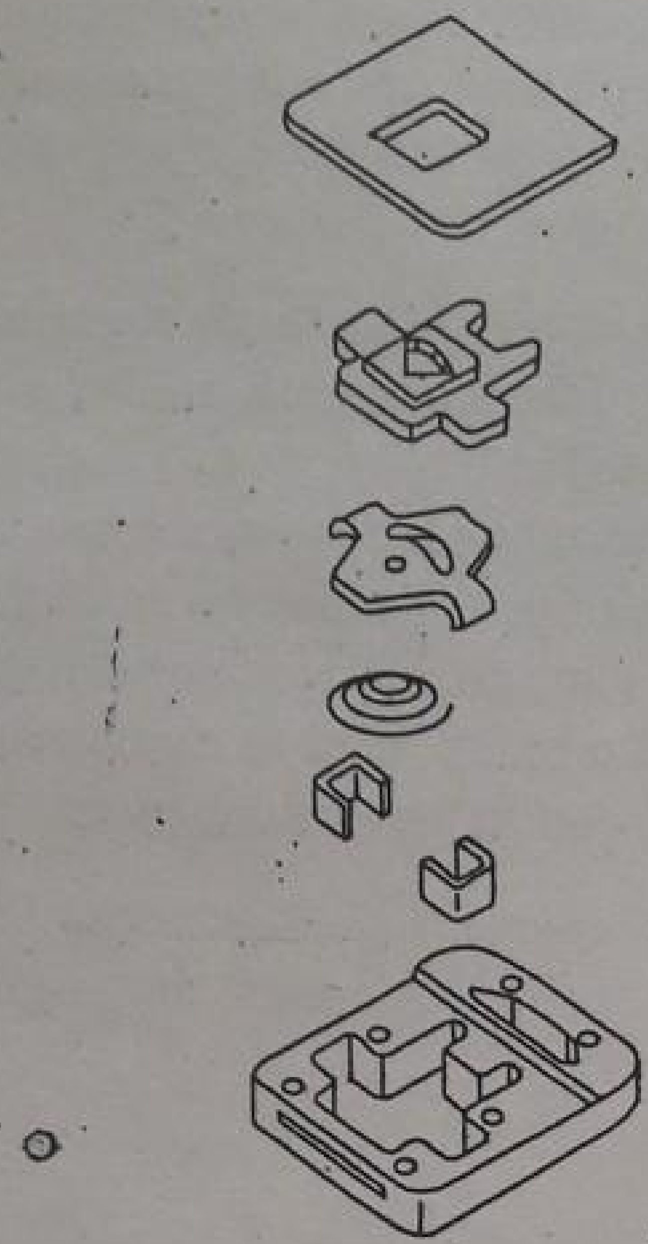


Figure 11.18 Meter assembly.

As with most of these measures, there are no absolute standards for determining an outstanding product and a poor one. Keep in mind that the rating on the worksheet is relative.

Guideline 4: Do Not Require the Base to Be Repositioned During Assembly. If automatic assembly equipment such as robots or specially designed component placement machines are used during assembly, it is important that the base be positioned precisely. On larger products, repositioning may be time-consuming and costly. An outstanding design would require no repositioning of the base. A product requiring more than two repositionings is considered poor.

Guideline 5: Make the Assembly Sequence Efficient. If there are N components to be assembled, there are potentially $N!$ (N factorial) different possible sequences to assemble them. In reality, some components must be assembled prior to others; thus the number of possible assembly sequences is usually much less than $N!$. An efficient assembly sequence is one that

- Affords assembly with the fewest steps.
- Avoids risk of damaging components.
- Avoids awkward, unstable, or conditionally unstable positions for the product and the assembly personnel and machinery during assembly.
- Avoids creating many disconnected subassemblies to be joined later.

Since even a minor design change can alter the available choices in assembly sequence, it is important to consider the efficiency of the sequence during design. The technique described here will be demonstrated through a simple example, the assembly of a ballpoint pen (Fig. 11.19).

Step 1: List All the Components and Processes Involved in the Assembly Process. Begin with a layout or assembly drawing of the product and a bill of materials. All components for the pen assembly are listed in Fig. 11.19. In some products, the components to be assembled include subassemblies and processes—for example, the component called "ink" in the ballpoint pen includes the process of actually putting the ink in the tube. Additionally, some products require testing during the assembly process. These tests should also be included as components. Finally, fasteners should be lumped with the component they hold in place.

Step 2: List the Connections Between Components and Generate a Connections Diagram. The connection diagram for the ballpoint pen is shown in Fig. 11.20.

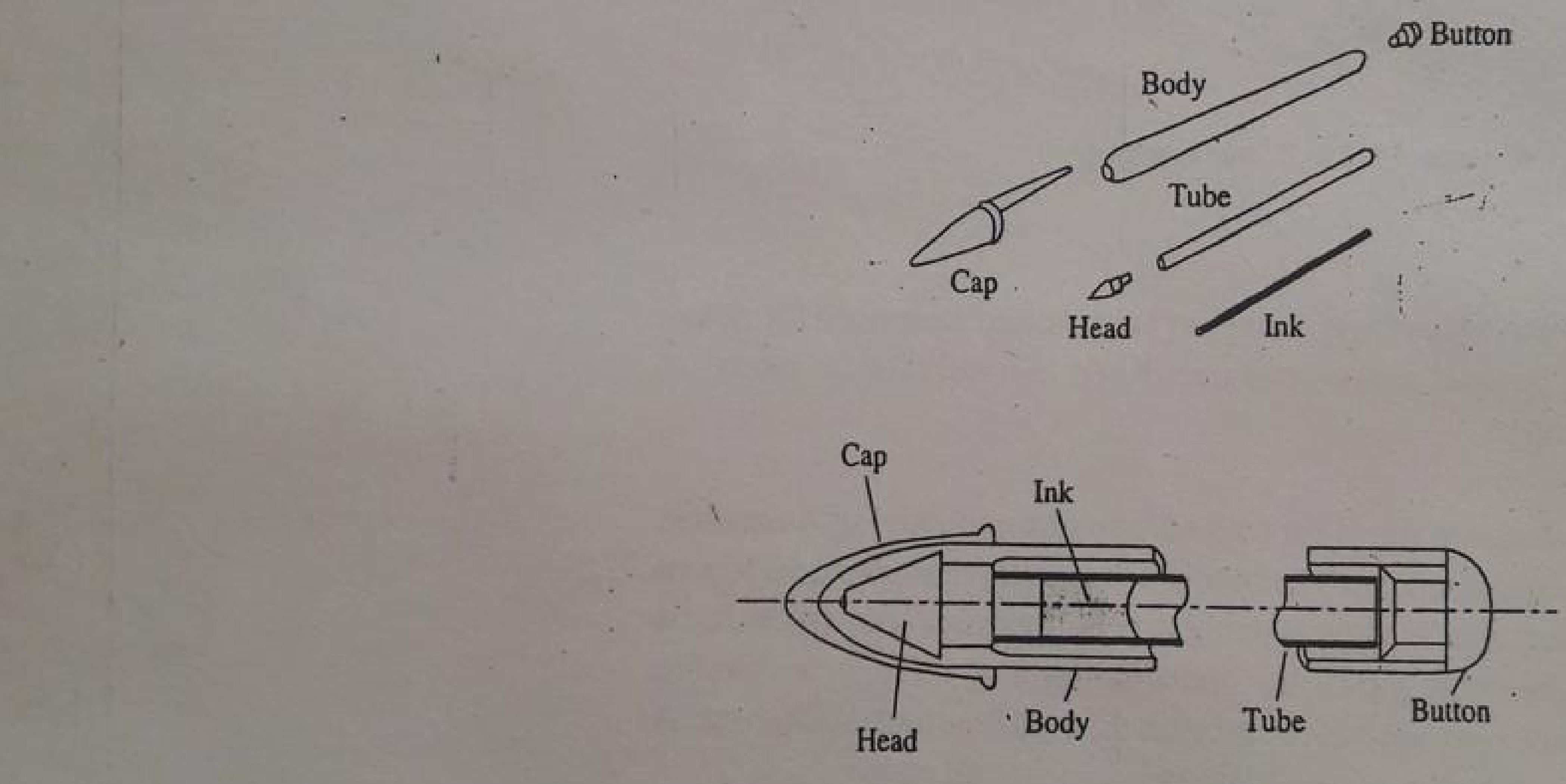


Figure 11.19 Ballpoint pen assembly.

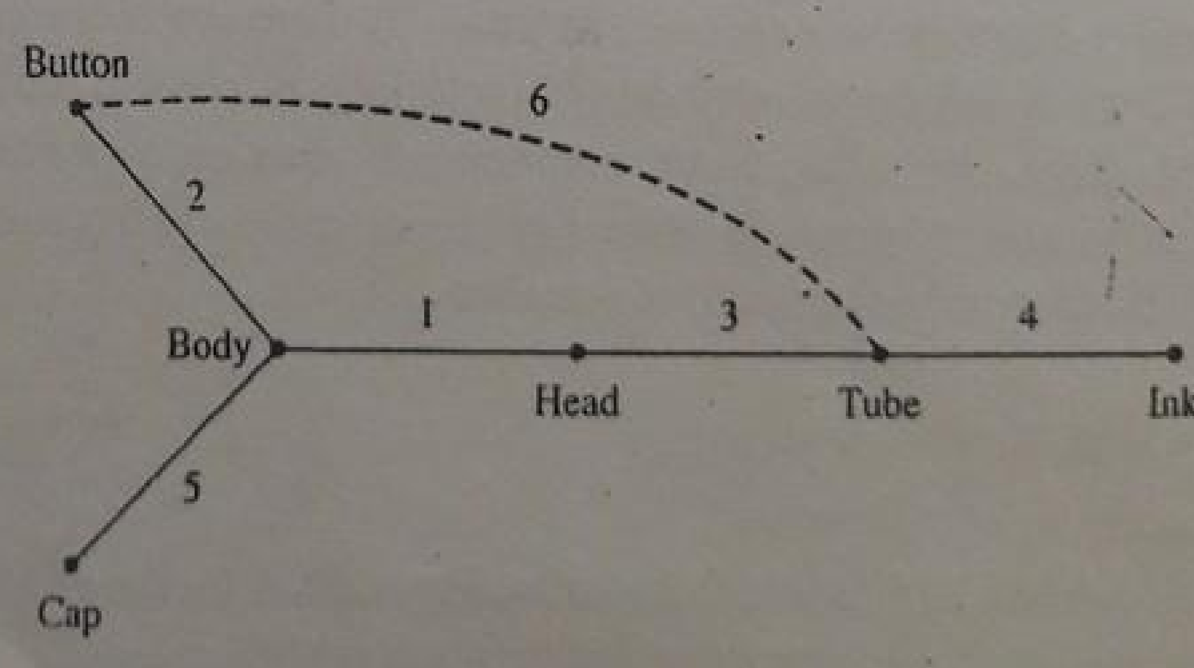


Figure 11.20 Connection diagram for a ballpoint pen.

In this diagram, the nodes represent the components and the links represent the connections. Connection diagrams can have loops. For example, the pen may have the button supporting the end of the tube, creating interface 6, a link between the tube and the button (shown as a dashed line in Fig. 11.20 and assumed not to exist throughout the remainder of this example).

Step 3: Select a Base Component. The base component should be at one end of the connection diagram or be a large component. It should be the component that requires the least subassembly and allows assembly from the fewest directions. For the ballpoint pen, the options are the cap, the button, or the body. The cap requires subassembly of the head in the tube and is thus a poor candidate. The body requires assembly from two directions. The button may be the best base part, but it is hard to hold. Both the body and the button need to be further investigated.

Step 4: Recursively Add the Next Component. Add components to the base using the connection diagram as a guide. It is important to be aware of precedences; for example, the tube must be on the head before the ink is installed. It is useful to list all precedences before starting this step. For the ballpoint pen, the precedences are

Connection 3 must precede connection 4.
Connection 1 must precede connection 5.

Step 5: Identify Subassemblies. Subassemblies can be made of components that have a secure connection with each other, can be reoriented without falling apart, and have a simple connection with the other assembled components. Subassemblies should only be used if they simplify the process. For the pen, the head, tube, and ink form a subassembly that simplifies assembly.

There are many potential assembly sequences for the ballpoint pen. One that is developed using the described procedure is

[2, [3, 4], 1, 5]

or

[button, body, [head, tube, ink], cap]

The first sequence lists the connections, and the second the components, in the order of assembly. The brackets denote subassemblies.

The process given here is very useful in evaluating the assembly sequence and determining the effects of design changes on the sequence. It also measures the efficiency of the assembly sequence. If all connections are made in a logical order, no subassemblies are generated, and no awkward connections made, then the efficiency is rated high; if the connection sequence cannot be accomplished, subassemblies are made, or awkward connections are needed, then the efficiency is low.

11.5.2 Evaluation of Component Retrieval

The measures associated with each guideline for retrieving components range from "all components" to "no components." If all components achieve the guideline, the quality of the design is high as far as component retrieval is concerned. Those components that do not achieve the guidelines should be reconsidered.

Guideline 6: Avoid Component Characteristics That Complicate Retrieval. Three component characteristics make retrieval difficult: tangling, nesting, and flexibility. If components of the type shown in Fig. 11.21 column *a* are stored in a box or tray, they will be nearly impossible to pick up individually because they will become tangled. If the components are designed as shown in Fig. 11.21 column *b*, then they cannot tangle.

A second common problem that complicates retrieval is nesting, in which components jam inside each other (Fig. 11.22). There are two simple solutions for this problem: Either change the angle of the interlocking surfaces or add features that prevent jamming.

Finally, flexible components such as gaskets, tubing, and wiring harnesses are exceptionally hard components to retrieve and handle. When possible, make components as few, as short, and as stiff as possible.

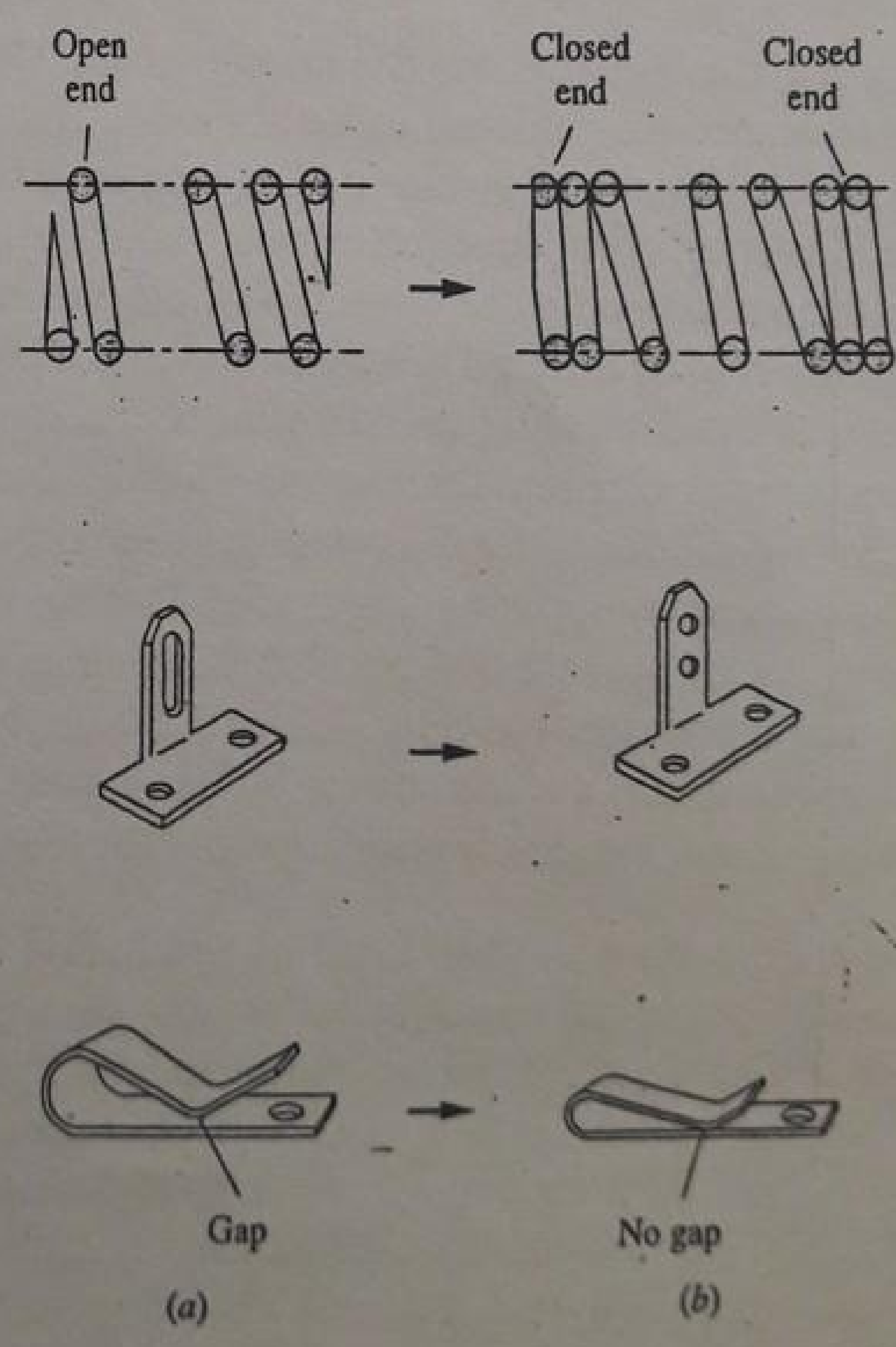


Figure 11.21 Design modifications to avoid component tangling.

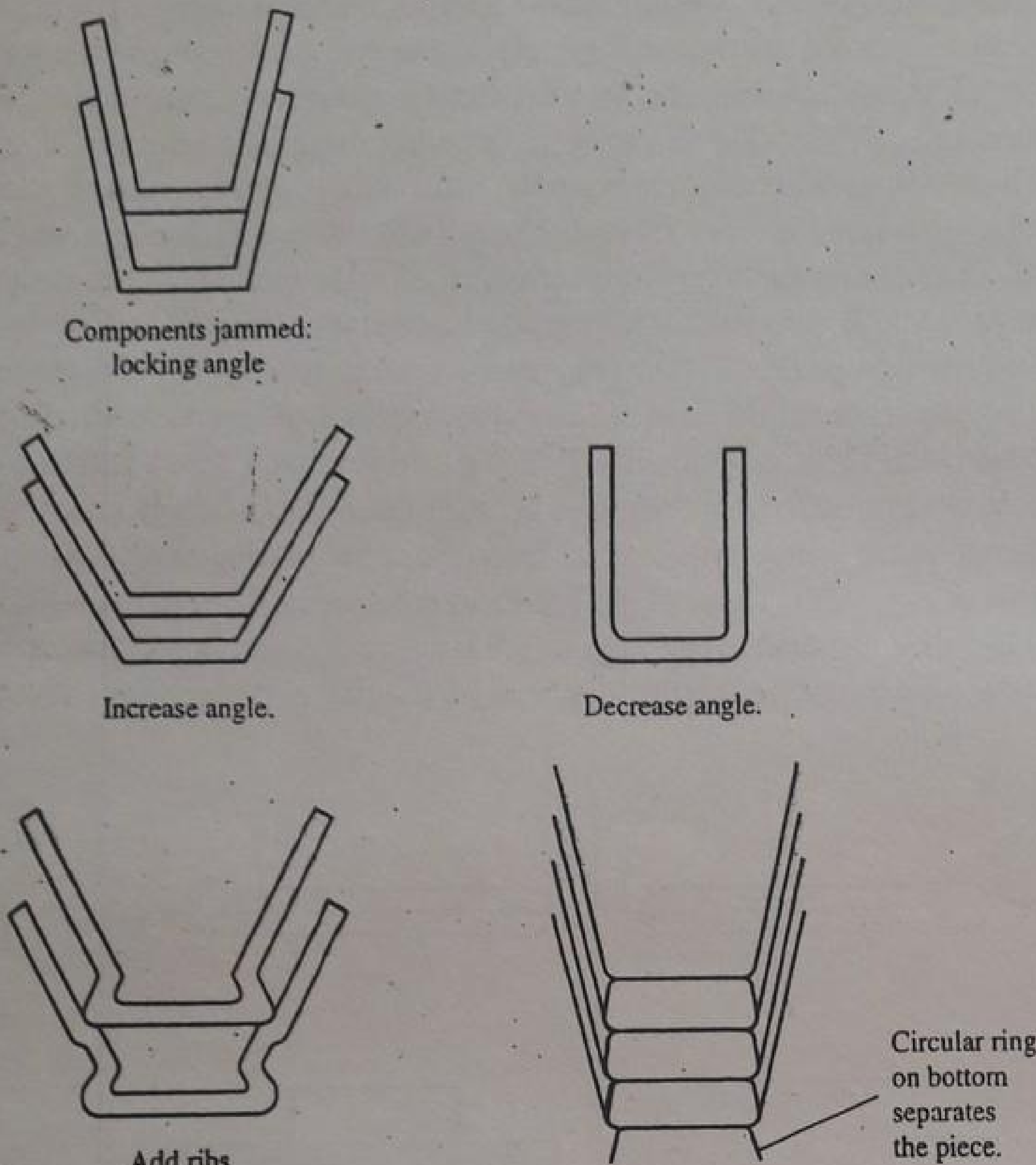


Figure 11.22 Design modifications to avoid jamming.

Guideline 7: Design Components for a Specific Type of Retrieval, Handling, and Mating. Consider the assembly method of each component during design. There are three types of assembly systems: manual assembly, robot assembly, and special-purpose transfer machine assembly. In general, if the volume of the product is less than 250,000 annually, the most economic method of assembly is manual. For products that have a volume of up to 2 million annually, robots are generally best. Special-purpose machines are warranted only if the volume exceeds 2 million. Each of these systems has requirements for component retrieval, handling, and mating. For example, components for manual assembly can be bulk-fed and must have features that make them easy to grasp. Robot grippers, on the other hand, may be fed automatically and can grasp a component externally, like a human; internally, with a suction cup on a flat surface; or with many other end effectors.

11.5.3 Evaluation of Component Handling

The next three design-for-assembly guidelines are all oriented toward the handling of individual components.

Guideline 8: Design All Components for End-to-End Symmetry. If a component can be installed in the assembly only in one way, then it must be oriented and inserted in just that way. The act of orienting and inserting the component takes time and either worker dexterity or assembly machine complexity. If assembly is to be done by a robot, for example, then having only one orientation for insertion may require the robot to be multiaxial. Conversely, if the component is spherical, then its orientation is of no consequence and handling is much easier. Most components in an assembly fall between these two extremes.

There are two measures of symmetry: end-to-end symmetry (symmetry about an axis perpendicular to the axis of insertion) and axis-of-insertion symmetry. (The latter is the focus of guideline 9 and is not discussed here.) End-to-end symmetry means that a component can be inserted in the assembly either end first. Axisymmetric components that are intended to be inserted along their axes are shown in Fig. 11.23. Those in the left-hand column are designed to work in the design only if installed in one way. These same components are shown in the right-hand column modified so that they can be inserted either end first. In each

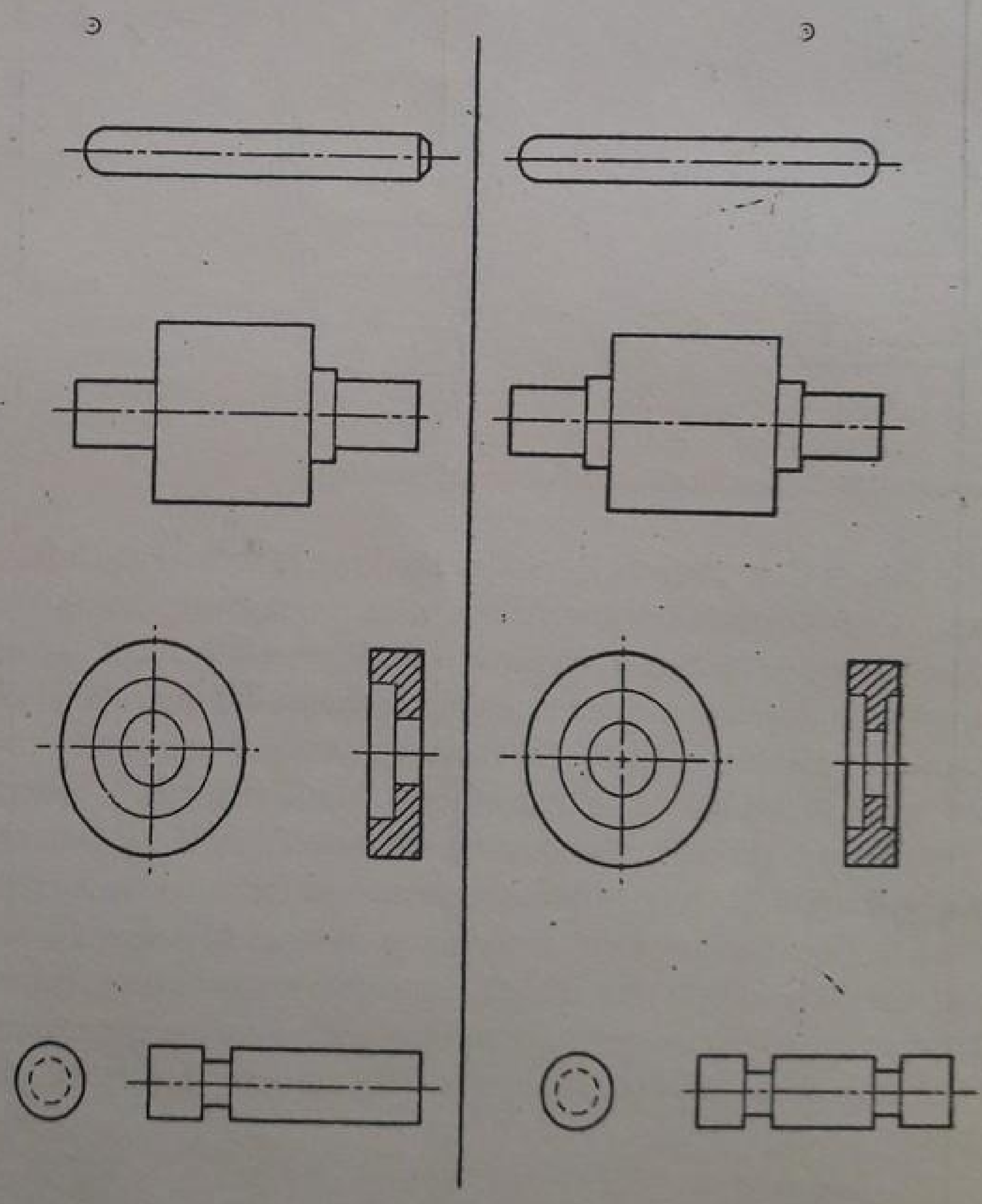


Figure 11.23 Modification of axisymmetric parts for end-to-end symmetry.

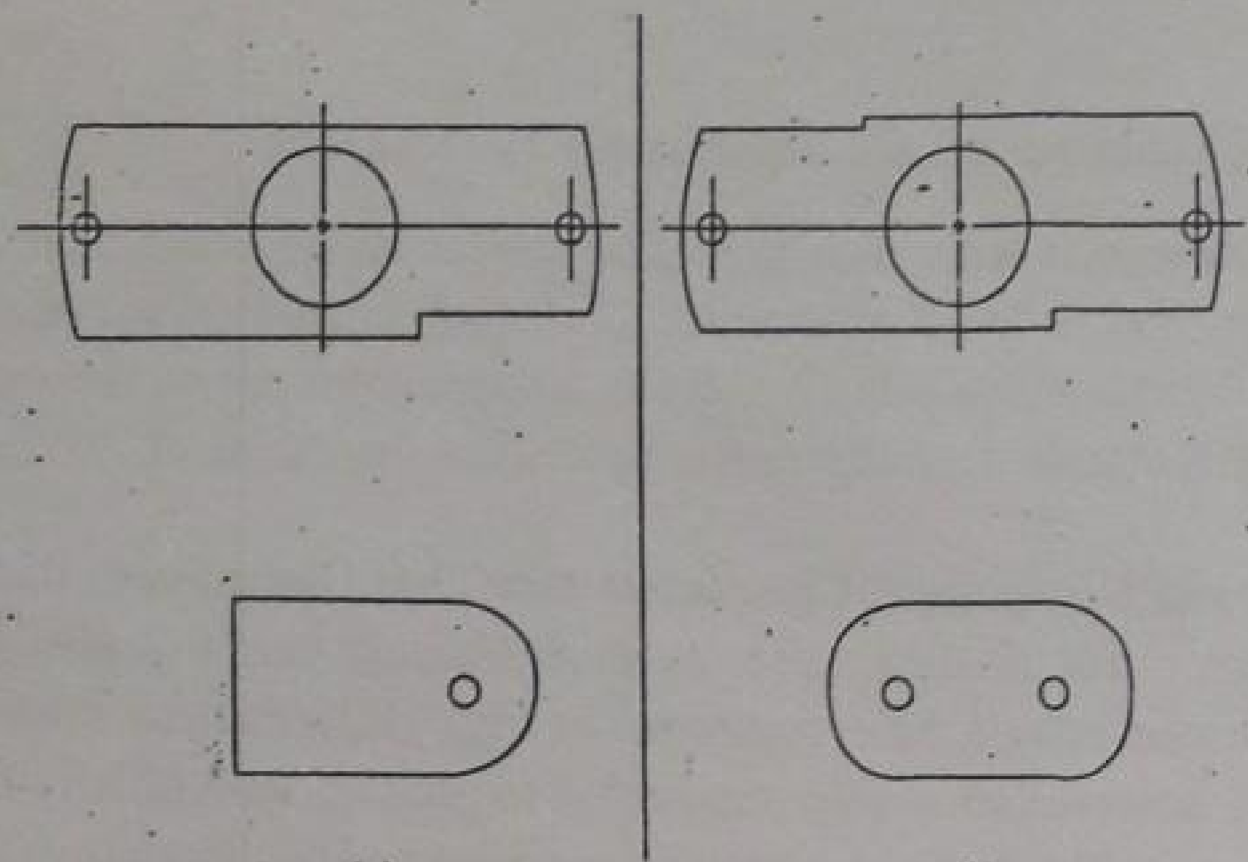


Figure 11.24 Modification of features for symmetry about the axis of insertion.

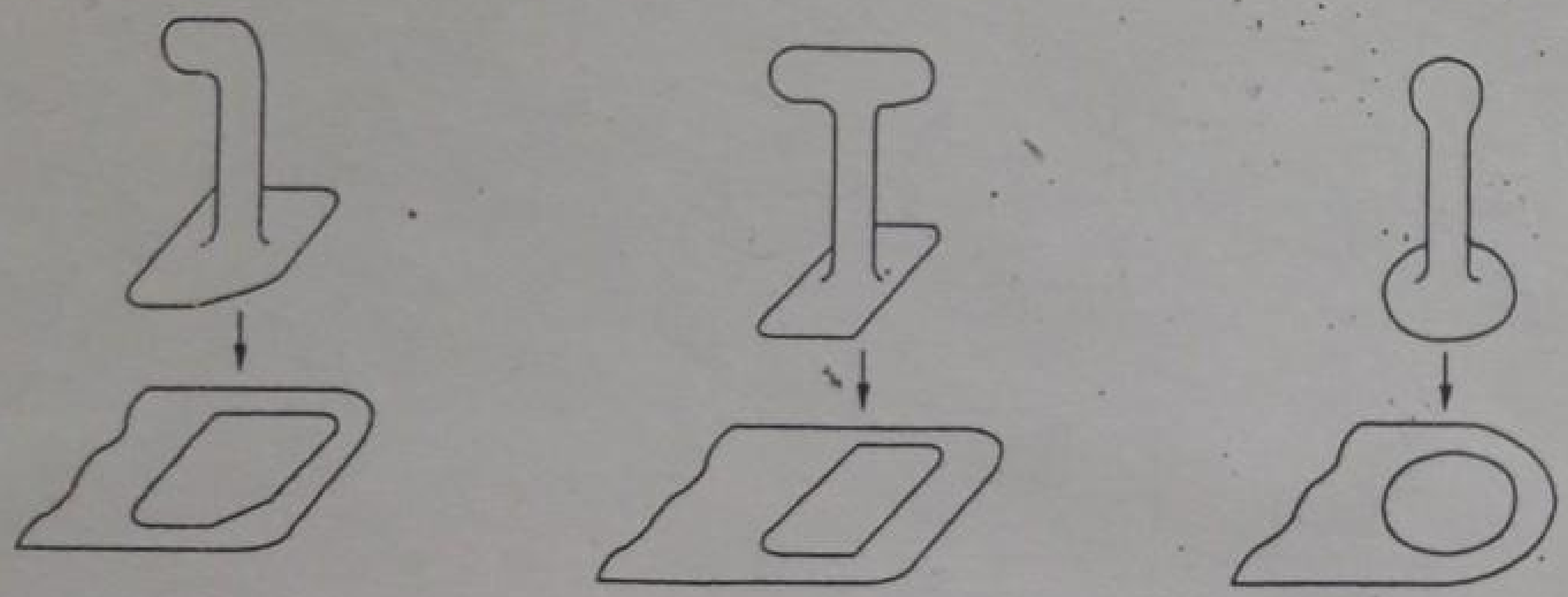
case, the asymmetrical feature has been replicated to make the component end to-end symmetrical for ease of assembly.

Before modifying a component to meet this or similar guidelines, it is important to check the value of the modification. The cost of adding a feature may not improve its functionality for the assembler sufficiently to warrant the modification.

Guideline 9: Design All Components for Symmetry About Their Axes of Insertion. Whereas the previous guideline.called for end-to-end symmetry, a designer should also strive for rotational symmetry. The components in Fig. 11.23 are all axisymmetric if inserted in the direction of their centerline. In Fig. 11.24 the components in column *a* have only one orientation if they are inserted in the plane of the diagram. However, by adding a functionally useless notch (on the top component) or adding a hole and rounding an end (on the bottom component), we can give the components two orientations for insertion—a decided improvement.

In Fig. 11.25*a*, the original design for the component fits only one way into the assembly. The addition of an opposing finger (Fig. 11.25*b*), which is useless functionally, gives the component two possible insertion orientations. Finally, modifying the component functions (Fig. 11.25*c*) can make the component axisymmetric. It is important to ask if the change in functionality is worth the gained ease of assembly. If not, then the asymmetry should be tolerated.

Guideline 10: Design Components That Are Not Symmetric About Their Axes of Insertion to Be Clearly Asymmetric. The component in Fig. 11.25*a* is clearly asymmetric. If it were not asymmetric, the component could be inserted with the finger pointing the wrong way and, as a result, would not function as it was designed to. In Fig. 11.26 the four component designs of the left-hand column have been modified in the right-hand column to afford easy orientation. The goal of this guideline is to make components that can be inserted only in the way intended.



(*a*) The assembly fits together only one way.

(*b*) Two possible directions of insertion.

(*c*) 360° rotational symmetry.

Figure 11.25 Modification of a part for symmetry.

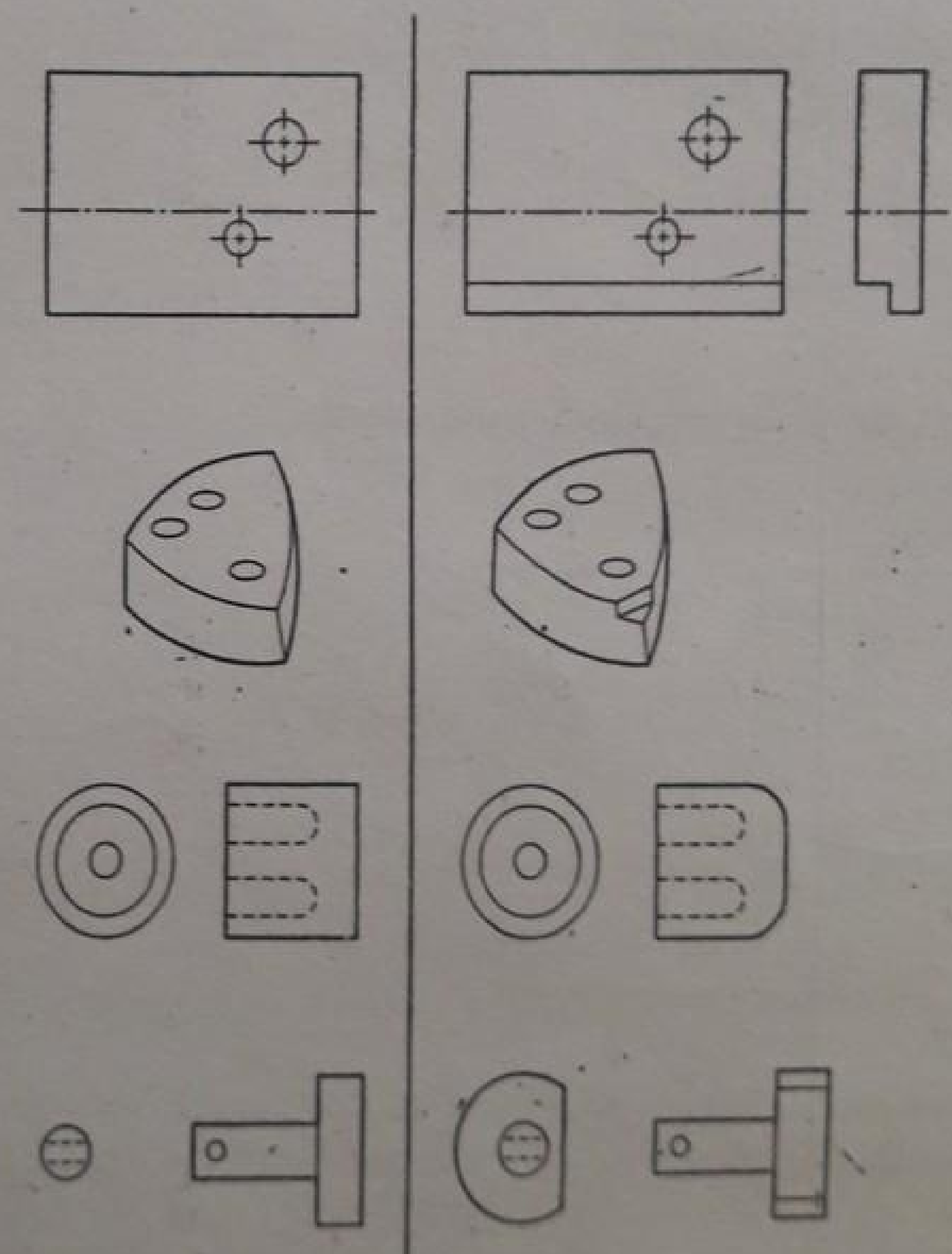


Figure 11.26 Modification of parts to force asymmetry.

11.5.4 Evaluation of Component Mating

Finally, the quality of component mating should be evaluated. Guidelines 11 to 13 offer some design aids for improving assemblability.

Guideline 11: Design Components to Mate Through Straight-Line Assembly, All from the Same Direction. This guideline, intended to minimize the motions of assembly, has two aspects: the components should mate through straight-line motion, and this motion should always be in the same direction. If both of these corollaries are met, the assembly will then fall together from above. Thus, the assembly process will never require reorientation of the base nor any other assembly motion other than straight down. (Down is the preferred single direction, because gravity aids the assembly process.)

The components in Fig. 11.27*a* require three motions for assembly. This number has been reduced in Fig. 11.27*b* by redesigning the interface between the components. Note that the design in Fig. 11.17*b*, although improving the quality in terms of fastener use, has degraded the design in terms of insertion difficulty, again demonstrating that there are always trade-offs to be considered in design.

Guideline 12: Make Use of Chamfers, Leads, and Compliance to Facilitate Insertion and Alignment. To make the actual insertion or mating of a component as easy as possible, each component should guide itself into place. This can be accomplished using three techniques. One common method is to use chamfers, or rounded corners, as shown in Fig. 11.28. Here the four components shown in column *a* are all modified with chamfers in column *b* to ease assembly.

In Fig. 11.29*a* the shaft has chamfers and still the disk is hard to align and press into its final position. This difficulty is alleviated by making part of the shaft a smaller diameter, allowing the disk to mate with the final diameter, as shown in column *b* of the figure. The lead section of the shaft has forced the disk into alignment with the final section. A similar redesign is shown in the lower component, where, in column *b*, by the time the shaft is inserted in the bearing from the right it is aligned properly.

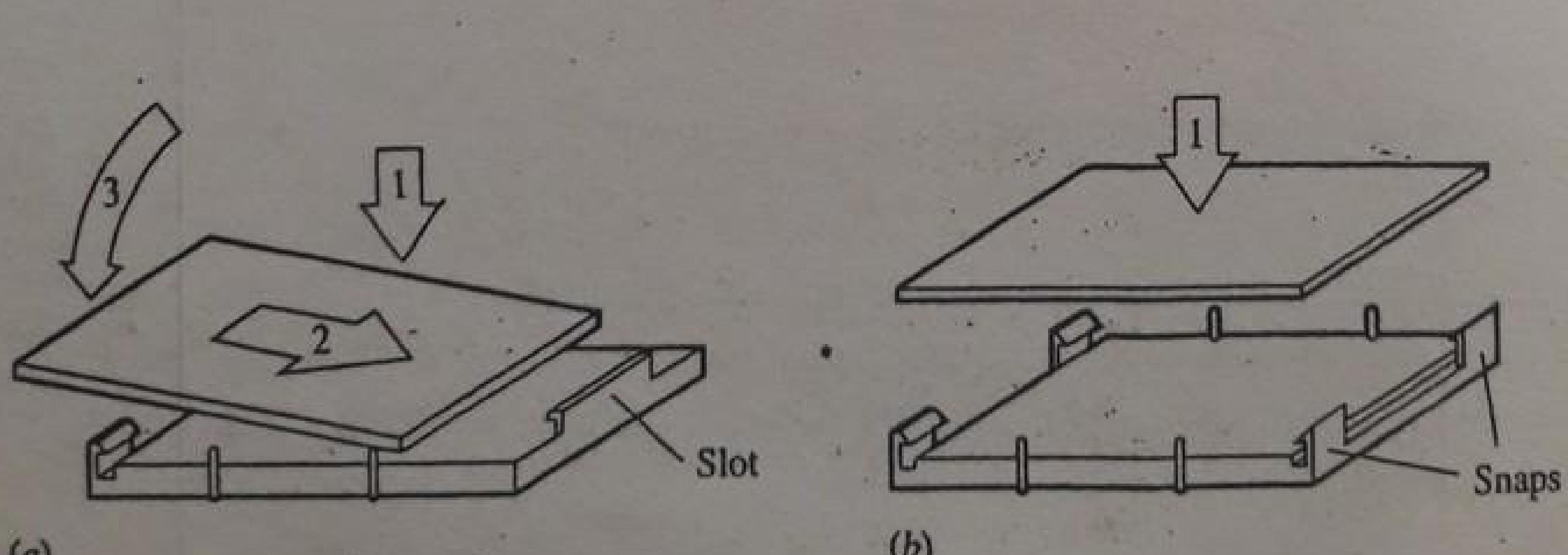


Figure 11.27 Example of one-direction assembly.

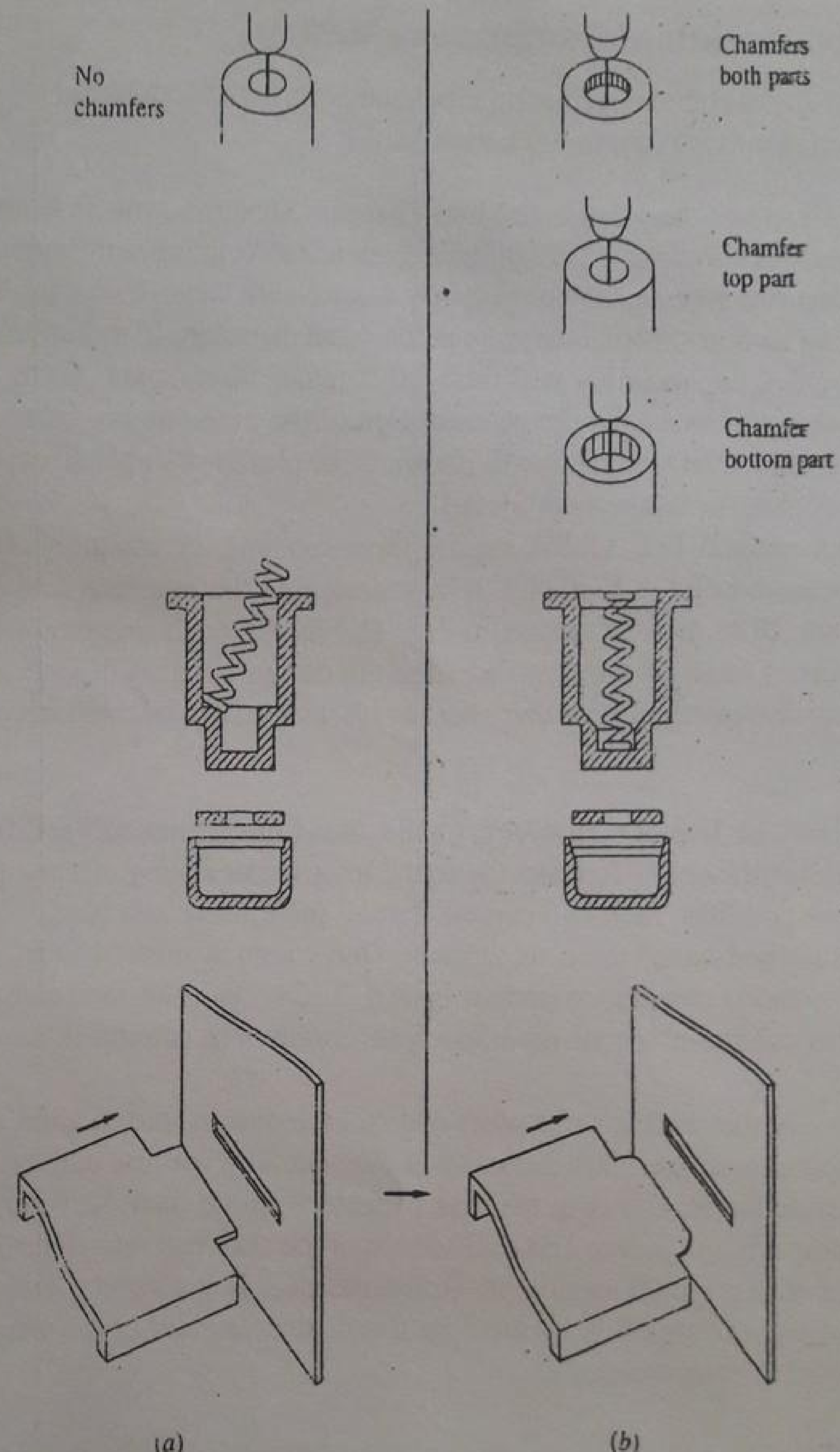


Figure 11.28 Use of chamfers to ease assembly.

Finally, component compliance, or elasticity, is used to ease insertion and also relax tolerances. The component mating scheme in column *b* of Fig. 11.30 need not have high tolerance; even if the post is larger than the hole, the components will snap together.

Guideline 13: Maximize Component Accessibility. Whereas guideline 5 concerned itself with assembly sequence efficiency, this guideline is oriented toward

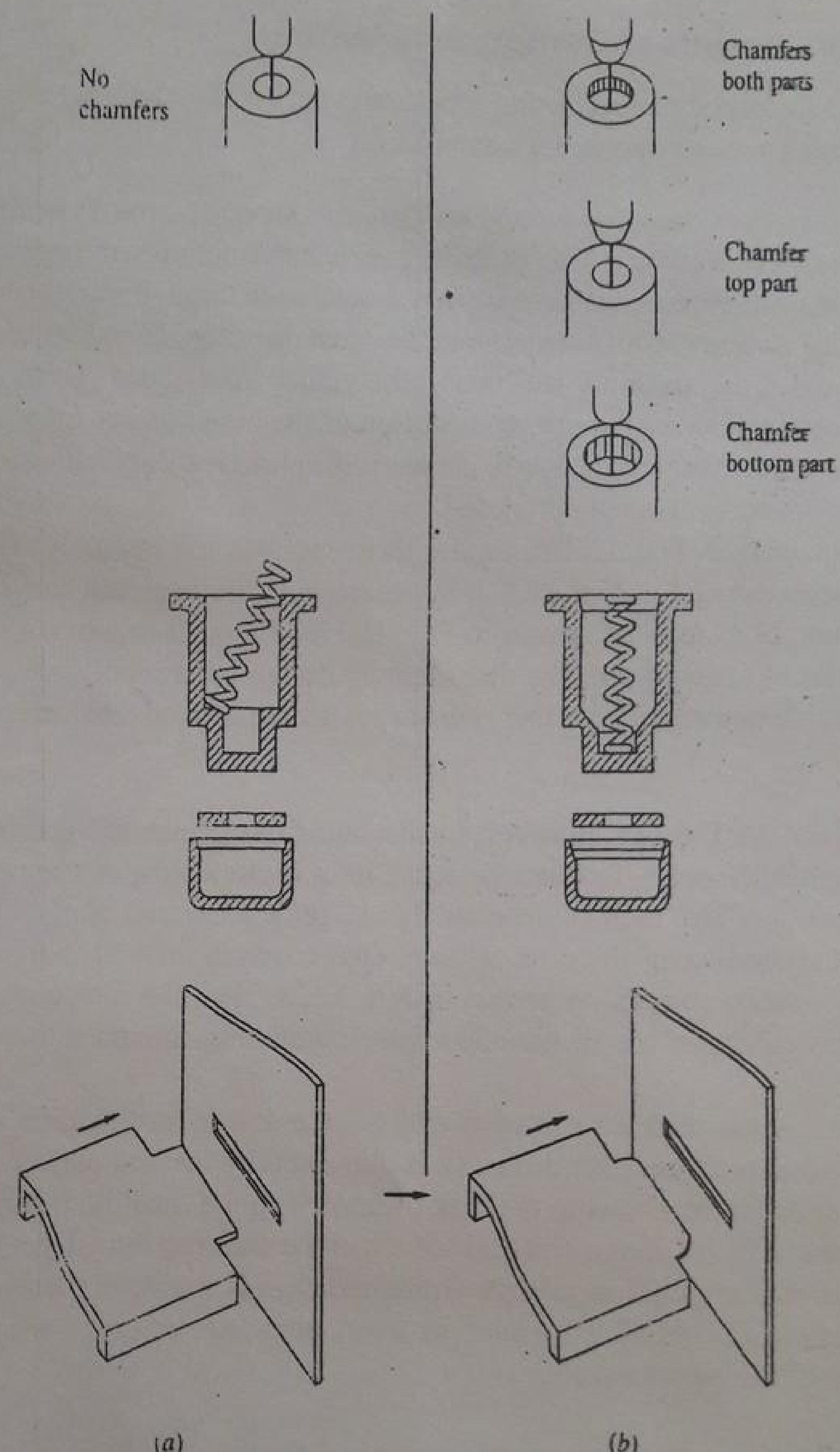


Figure 11.28 Use of chamfers to ease assembly.

Finally, component compliance, or elasticity, is used to ease insertion and also relax tolerances. The component mating scheme in column *b* of Fig. 11.30 need not have high tolerance; even if the post is larger than the hole, the components will snap together.

Guideline 13: Maximize Component Accessibility. Whereas guideline 5 concerned itself with assembly sequence efficiency, this guideline is oriented toward

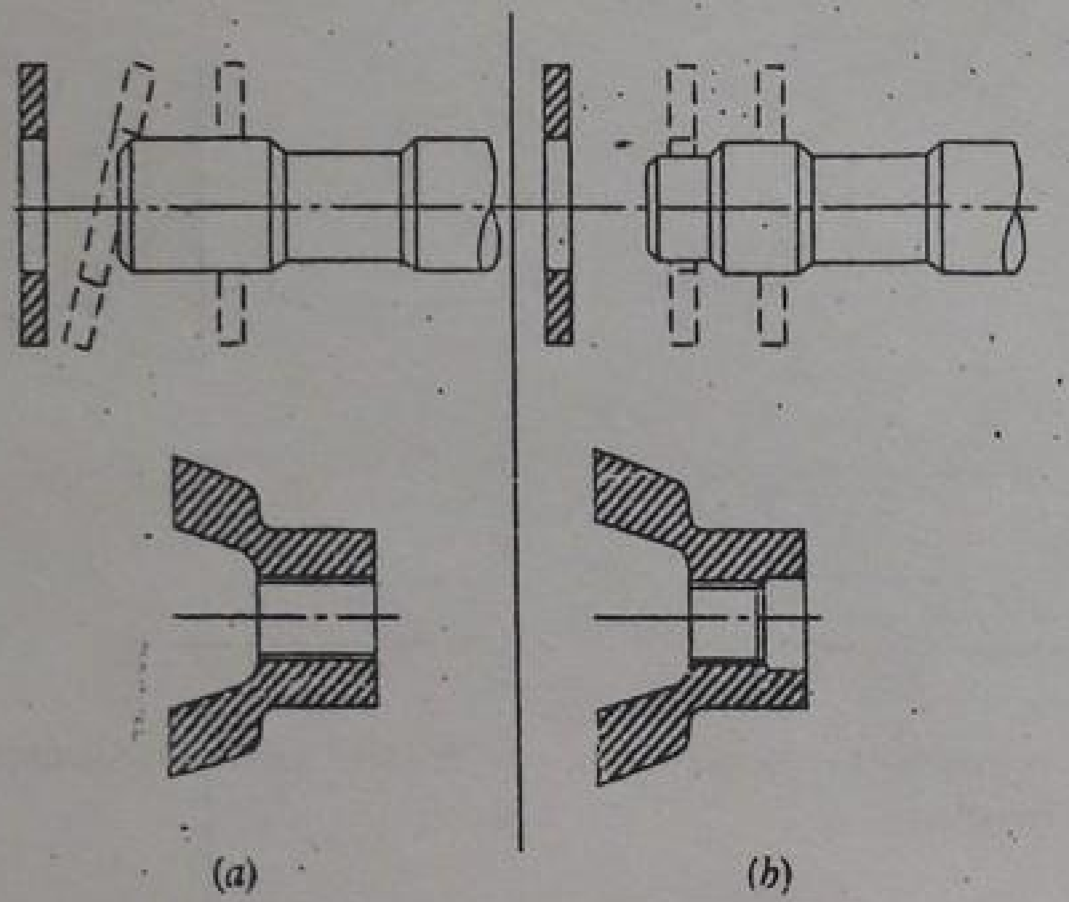


Figure 11.29 Use of leads to ease assembly.

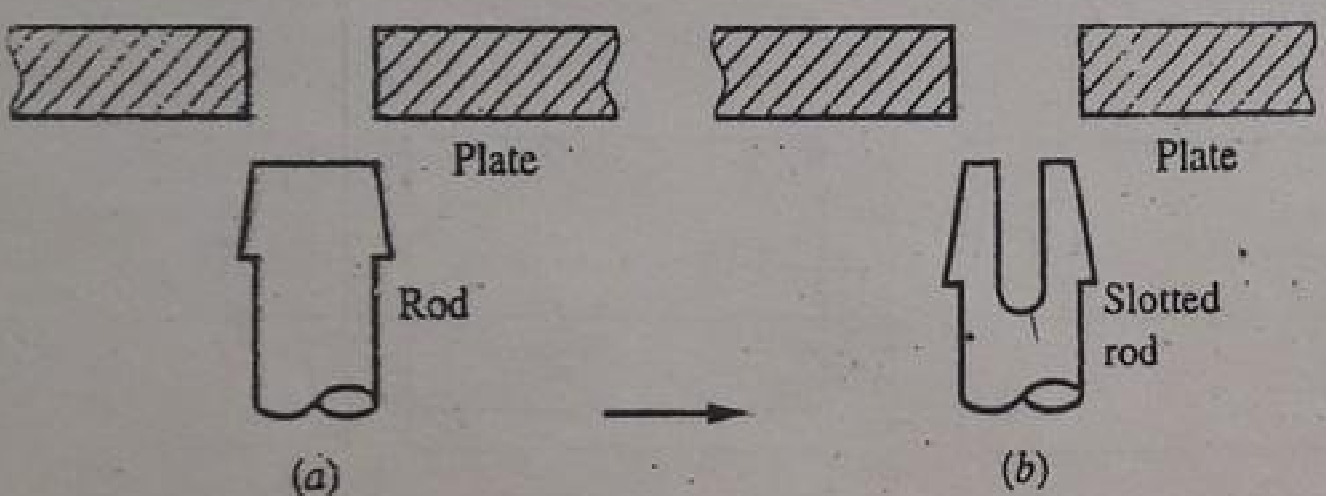


Figure 11.30 Use of compliance to ease assembly.

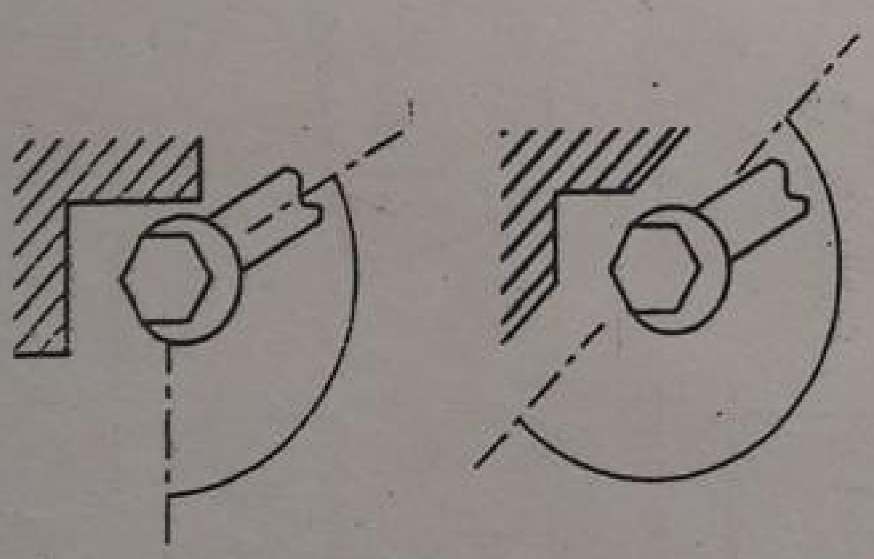


Figure 11.31 Modifications for tool clearance.

sufficient accessibility. Assembly can be difficult if components have no clearance for grasping. Assembly efficiency is also low if a component must be inserted in an awkward spot.

Besides concerns for assembly, there is also maintenance to consider. To replace the fuses in one common computer printer, it is necessary to disassemble the entire machine. In both assembly and maintenance, tools are necessary and room must be allowed for the tools to mate with the components and to be manipulated. As shown in Fig. 11.31, sometimes simple design changes can make tool engagement and motion much easier.

11.6 DFR—DESIGN FOR RELIABILITY

Reliability is a measure of how the quality of a product is maintained over time. Quality here is usually in terms of satisfactory performance under a stated set of operating conditions. Unsatisfactory performance is considered a *failure*, and so in calculating the reliability of a product we use a technique for identifying failure potential called *Failure Modes and Effects Analysis, FMEA*. This best practice is useful as a design evaluation tool and as an aid in hazard assessment, described in Section 8.6.1 (A failure can, but does not necessarily, present a hazard; it presents a hazard only if the consequence of its occurrence is sufficiently severe.) Traditionally, a *mechanical failure* is defined as any change in the size, shape, or material properties of a component, assembly, or system that renders the product incapable of performing its intended function. A failure may be the result of change in the hardware due to aging (for example, wear, material property degradation, or creep) or environmental conditions (for example, overloading, temperature effects, and corrosion). If deterioration or aging noises are taken into account, then the potential for mechanical failure is minimized (see Section 10.7).

To use failure potential as a design aid, it is important to extend the definition of failure to include not only undesirable changes after the product is in service, but also design and manufacturing errors (for example, moving parts interfere, parts do not fit together, or systems do not meet engineering requirements).

Thus, a more general definition is *a mechanical failure is any change or any design or manufacturing error that renders a component, assembly, or system incapable of performing its intended function*. Based on this definition, a failure has two attributes: the function affected and the source of the failure (i.e., the operational change or design or manufacturing error that produced the failure). Typical sources of failure or failure modes are wear, fatigue, yielding, jamming, bonding weakness, property change, buckling, and imbalance.

11.6.1 Failure Modes and Effects Analysis

The Failure Modes and Effects Analysis, FMEA, technique presented here can be used throughout the product development process and refined as the product is refined. The method aids in identifying where redundancy may be needed and in diagnosing failures after they have occurred. FMEA follows these five steps, and can be developed in a simple table, as shown in Figure 11.32:

Step 1: Identify the Function Affected. For each function identified in the evolution of the product, ask, "What if this function fails to occur?" If functional development has paralleled form development, this step is easy; the functions are already identified. However, if detailed functional information is not available, this step can be accomplished by listing all the functions of each component or assembly. For products being redesigned, the functions of a component or assembly are found by examining the connections or component interfaces and identifying the flow of energy, information, or materials through them. Additional considerations come from extending the basic question to read, "What if this

FMEA (Failure Modes and Effects Analysis)

Product: Mars Rover | **Organization Name:** Jet Propulsion Lab

#	Function Affected	Potential Failure Modes	Potential Failure Effects	Potential Causes of Failure	Recommend Actions	Responsible Person	Taken Actions
1	Propel Rover	No torque to wheel	Wheel stops turning	Motor failure	Ensure motors have high reliability—at least 99.9% reliability for 100 hr	Tim Smithson, Electronics Div.	Vendor required to submit failure test results
2			Wheel stops turning	Motor failure	Test ability to propel Rover with 1 or 2 drive wheels inoperative	Barb Rojo	Prototype tested with 2 motors off line
3		Wheel jambs against rock	Wheel stops turning	Inability to sense rocks	Develop ability to sense and avoid rocks or feedback torque increase	B. J. Smith	Work in progress
4			Wheel damages surface	Wheel surface too soft	Specify surface that can with stand abrasion	N. Knovo	Hard test developed

Team member: B. Rojo	Team member:	Prepared by: N. Knovo	
Team member: B. J. Smith	Team member:	Checked by:	Approved by:

The Mechanical Design Process

Designed by Professor David G. Ullman

Form # 22.0

Figure 11.32 FMEA example for MER.

function fails to occur at the right time?" "What if this function fails to occur in the right sequence?" or "What if this function fails to occur completely?"

Step 2: Identify Failure Modes. For each function, there can be many different failures. The failure mode is a description of the way a failure occurs. It is what is observed, what can be detected when the function fails to occur.

Step 3: Identify the Effect of Failure. What are the consequences on other parts of the system of each failure identified in step 1? In other words, if this failure occurs, what else might happen? These effects may be hard to identify in systems in which the functions are not independent. Many catastrophes result when one system's benign failure overloads another system in an unexpected manner, creating an extreme hazard. If functions have been kept independent, the consequences of each failure should be traceable.

dom

Step 4: Identify the Failure Causes or Errors. List the changes or the design or manufacturing errors that can cause the failure. Organize them into three groups: design errors (D), manufacturing errors (M), and operational changes (O).

Step 5: Identify the Corrective Action. Corrective action requires three parts. what action is recommended, who is responsible, and what was actually done. For each design error listed in step 3, note what redesign action should be taken to ensure that the error does not occur. The same is true for each potential manufacturing error. For each operational change, use the information generated to establish a clear way for the failure mode to be detected. This is important, as it is the basis for the diagnosis of problems when they do occur. For operational changes it may also be important to redesign the device so that the failure mode has a reduced effect on the function. This may include the addition of other devices (for example, fuses or filters) to protect the function under consideration; however, the failure potential of these added devices should also be considered. The use of redundant systems is another way to protect against failures. But redundancy might add other failure modes as well as increase costs.

FMEA is best used as a bottom-up tool. This means focusing on a detailed function and dissecting all its potential failure. Fault Tree Analysis (FTA), Section 11.6.2, is better suited for "top-down" analysis. When used as a "bottom-up" tool, FMEA can augment or complement FTA and identify many more causes and failure modes resulting in top-level symptoms. It is not able to discover complex failure modes involving multiple failures within a subsystem, or to report expected failure intervals of particular failure modes up to the upper level subsystem or system.

An example of an FMEA and its tie to FTA is based on the design of the propulsion system for the Mars Exploration Rover, MER. During its development, the Jet Propulsion Laboratory team made extensive use of FMEA and FTA. The examples in this and the following section are loosely based on their work.

The FMEA analysis in Fig. 11.32 is based on a simple template. The function considered is "propel Rover." The total analysis for the system may have many hundreds of failure modes. Only a small part of the analysis is shown in this example. The failure modes identified had to do with one of the six wheels failing to propel the Rover. As can be seen, a failure mode can have multiple effects, causes, or recommended actions.

11.6.2 FTA—Fault Tree Analysis

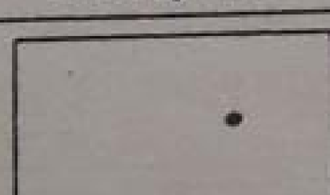
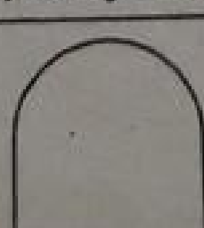
Fault Tree Analysis (FTA) can help in finding failure modes. FTA evolved in the 1960s during the development of the Minuteman Missile System and has gained in use ever since. The goal of this method is to graphically develop a tree of all the faults that could happen to cause a system failure, and the logical relationships among these faults. Further, there are analytical methods to compute probabilities of faults, but we will only give a basic, usable introduction to the method here.

Fault Trees are built from symbols that signify events and logic. The most basic of these are listed in Table 11.2 and used in an example Fault Tree for the MER (Fig 11.33). This Fault Tree is a partial analysis for the event "Loss of Rover Mobility." The full Fault Tree had hundreds of events identified. Fault Trees are built from the top down, beginning with an undesired event (loss of Rover mobility) taken as the root ("top event"). The steps for building a Fault Tree are

Step 1: Identify the top event. There should be only one top event.

Step 2: Identify the events (i.e., faults) that can possibly occur to cause the top event. Ask the question "What can go wrong?" repeatedly until all the events that

Table 11.2 Basic Fault Tree symbols

Event block	FTA symbol	Description
Event		An event, something that happens to something and causes a function to fail.
Basic Event		A basic initiating fault or a failure event.
Undeveloped Event		An event that is not further developed.
Logical operation	**FTA symbol**	**Description**
AND		The output event occurs if all input events occur.
OR		The output event occurs if at least one of the input events occurs.

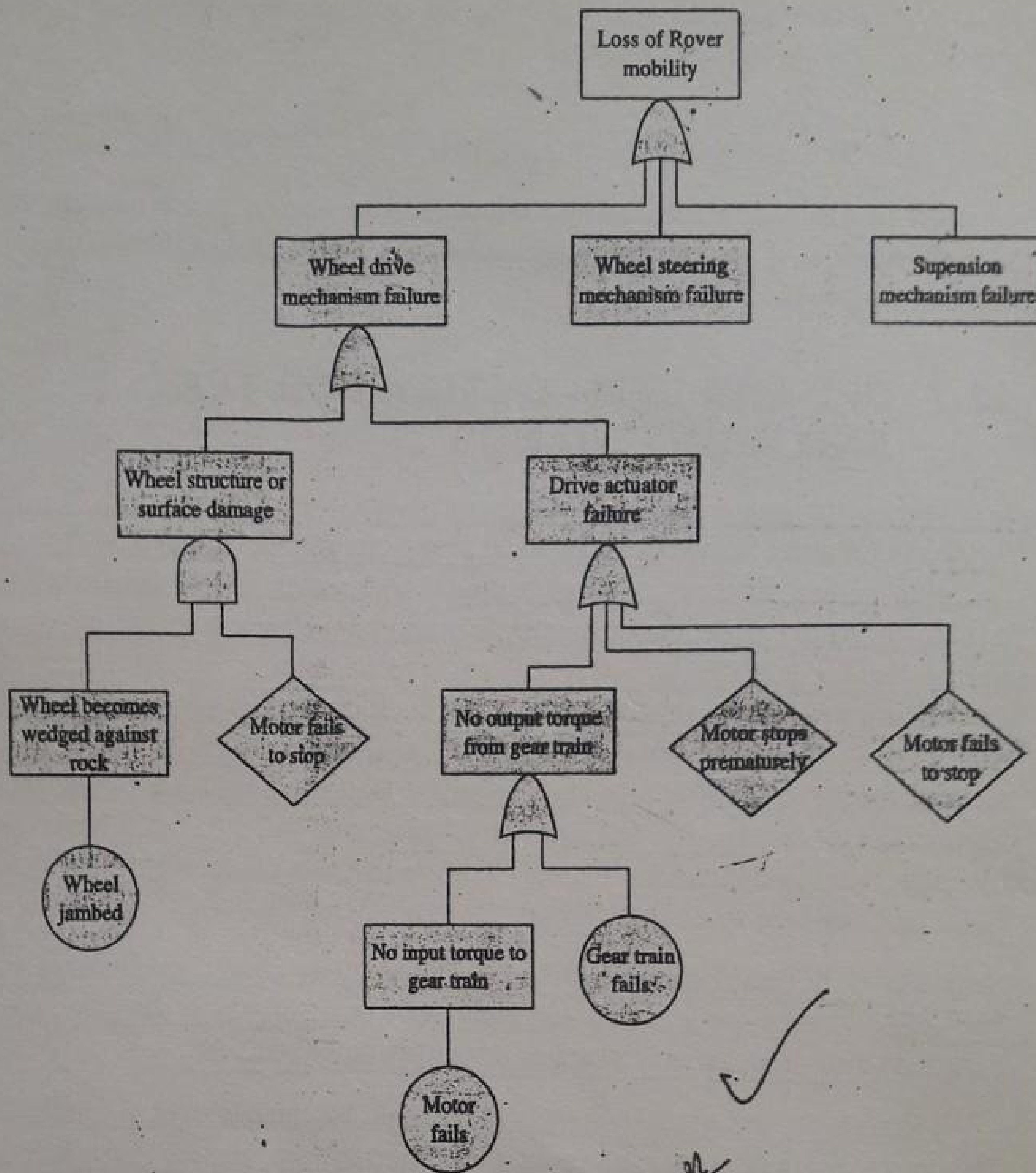


Figure 11.33 Partial Fault Tree for MER Mobility

can occur to cause failure have been identified. Look for hardware and software failures, and human errors. In the MER example, the loss of mobility can be caused by a drive mechanism failure, a steering failure, or a suspension failure.

Step 3: Determine the logical relationship among the events identified in step 2. The goal here is to determine if these newly identified events can happen independently [or], or need to happen together [and]. For example, the loss of rover mobility can be caused by either the drive mechanism failing, or the steering mechanism failing, **or** the suspension failing. Thus, on the Fault Tree an "Or" symbol is used to connect the three events to the top event. Farther down in the tree, in order to cause wheel surface damage, the wheel must both be wedged against a rock **and** the motor has to continue to rotate, damaging the wheel surface.

Step 4: Note which events in the tree will not be further developed. These neither need to be considered in the future, considered by others focused on that specific event, or does not need refinement. For example, "motor fails to stop" can only be caused by a failure of the control system to turn off power to the motor. A separate Fault Tree was developed for the control system by the MER team.

Step 5: Identify the basic events. Each event at the bottom of the tree should end with a basic or initiating event. A basic event is one that cannot be further broken down. In the example Fault Tree "wheel jammed," "motor fails," and "gear train fails" cannot be decomposed any further.

11.6.3 Reliability

Once the different potential failures of the product have been identified, the reliability of the system can be found and expressed in units of reliability called *Mean Time Between Failures* (MTBF), or the average elapsed time between failures. MTBF data are generally accumulated by testing a representative sampling of the product. Often these data are collected by service personnel, who record the part number and type of failure for each component they replace or repair.

These data aid in the design of a new product. For example, a manufacturer of ball bearings collected data for many years. The data showed an MTBF of 77,000 hr for a ball bearing operating under manufacturer-specified conditions. On the average, a ball bearing would last 8.8 years [77,000/(365 × 24)] under normal operating conditions. Of course, a harsh environment or lack of lubrication would greatly reduce this lifetime. Often the MTBF value is expressed as its inverse and called the *failure rate L*, the number of failures per unit time. Failure rates for common machine components are given in Table 11.3, where the failure rate for the ball bearing is 1/77,000, or 13 failures per 1 million hours.

Table 11.3 Failure rates of common components

Mechanical failures, per 10^6 hr		Electrical failures, per 10^6 hr	
Bearing		Meter	26
Ball	13	Battery	
Roller	200	Lead acid	0.5
Sleeve	23	Mercury	0.7
Brake	13	Circuit board	0.3
Clutch	2	Connector	0.1
Compressor	65	Generator	
Differential	15	AC	2
Fan	6	DC	40
Heat exchanger	4	Heater	4
Gear	0.2	Lamp	
Pump	12	Incandescent	10
Shock absorber	3	Neon	0.5
Spring	5	Motor	
Valve	14	Fractional hp	8
		Large	4
		Solenoid	1
		Switch	6

The actual reliability of a component is determined from the failure rate information. Assuming that the failure rate is constant over the life of the component—which is generally true for all but the initial (infant mortality) and the final (wearout) periods—the reliability is defined as

$$R(t) = e^{-Lt}$$

where R, the reliability, is the probability that the component has not failed. For the ball bearing,

$$R(t) = e^{-0.000013t}$$

with t in hours. Thus,

t, hr	R
0	1.000
100	0.999
1000	0.987
8760 (1 year)	0.892
10,000	0.878
43,800 (5 years)	0.566

If 1000 ball bearings are tested, it would be expected that 892 of them would still be operating a year later within specifications.

What if there are four ball bearings in a product and the product will fail if any one bearing fails? The total reliability of that device is the product of the reliabilities of all its components (this is often called *series reliability*):

$$R_{\text{product}} = R_{\text{bearing 1}} \cdot R_{\text{bearing 2}} \cdot R_{\text{bearing 3}} \cdot R_{\text{bearing 4}}$$

Because of the exponential nature of the definition of reliability, the failure rate for that device would be

$$L_{\text{product}} = L_{\text{bearing 1}} + L_{\text{bearing 2}} + L_{\text{bearing 3}} + L_{\text{bearing 4}}$$

For the product with four bearings, $L = 4 \cdot 0.000013 = 0.000052$. Thus, after one year, $R = 0.634$; about one-third of the products will have had a bearing failure.

There are essentially two ways to increase reliability. First, decrease the failure rate. This is accomplished by lowering the bearing's load or by decreasing its rotation rate. A second way to increase reliability is through redundancy, often called *parallel reliability*. For redundant systems, the failure rate is

$$L = \frac{1}{1/L_1 + 1/L_2 + \cdots}$$

Thus, if a ball bearing and a sleeve bearing are designed into the product so that either can carry the applied load, then

$$L = \frac{1}{1/0.000013 + 1/0.000023} = 8.3 \text{ failures}/10^6 \text{ hr}$$

With this technique, reliability evaluations can also be made on complex systems. A model of the failure modes and the MTBF for each of them is needed to accomplish such an evaluation.

11.7 DFT AND DFM—DESIGN FOR TEST AND MAINTENANCE

Testability is the ease with which the performance of critical functions is measured. For instance, in the design of VLSI chips, circuits are included on the chip that allow critical functions to be measured. Measurements can be made during manufacturing to ensure that no errors are built into the chip. Measurements can also be made later in the life of the chip to diagnose failures.

Adding structure in this way, to make testability easier, is often impossible in mechanical products. However, if the technique developed in the previous sections for identifying failures is extended, at least some measure of the testability of the product can be realized. For instance, step 4 of the FMEA technique (Section 11.6.1) required the listing of errors that can cause each failure. An additional step here would address testability:

Step 4A: Is It Possible to Identify the Parameters That Could Cause the Failure? If there are a significant number of cases in which the parameters cannot be measured, there is a lack of testability in the product.

There are no firm guidelines in developing an acceptable level of testability. The designer should ensure, however, that the critical parameters that affect the critical functions can be tested. In this way, the ability to diagnose manufacturing problems and failures when they occur is increased.

The terms *maintainability, serviceability,* and *reparability* are often used interchangeably to describe the ease of diagnosing and repairing a product. Since the 1980s, a dominant philosophy has been to design products that are totally disposable or composed of disposable modules that can be removed and replaced. This is in direct conflict to the Hannover Principles introduced in Chap. 1 and DOE—Design For the Environment, in Section 11.8. These modules often contained still-functioning components along with those that had failed. The structure of the module forced replacement of both good and bad components. This philosophy was characteristic of the "throwaway" attitude of the time, and products designed during this period were often easy to replace and hard to repair. A different philosophy is to design products that are easy to diagnose, disassemble, and repair at any level of function. As discussed, designing diagnosability into a mechanical product is possible, but it takes extra effort and may be of questionable value. This also applies to designing a product that is easy to disassemble and

Make it fail where you want. Design in mechanical fuses.

repair. Since the guidelines given for the design-for-assembly technique do not lead to a product that is easy to disassemble, special care must be taken to ensure that, if desired, the snap fits can be unsnapped and that the disassembly sequence has been considered with as much care as the assembly sequence. Further, the ability to disassemble a product is also important if the product is to be recycled at the end of its useful life. This topic is discussed in Section 11.8.

One important feature of design for maintainability is the concept of a "mechanical fuse." In electrical systems, fuses are used to fail in order to protect the rest of the circuit. The same should be done in mechanical devices. A good use of a mechanical fuse is in high-powered kitchen tabletop mixers. Larger units, those that can mix bread dough, are powerful enough to break fingers and arms. Thus, if something jams these mixers, they stop working. To fix them, you must take a cover off to see that one of the gears has failed. This gear is made of plastic while all the others are of steel. It is designed to break and it is the only gear in the unit that can be purchased at a local appliance repair store.

11.8 DFE—DESIGN FOR THE ENVIRONMENT

Design for the environment is often called green design, environmentally conscious design, life-cycle design, or design for recyclability. Treating environmental concerns as important requirements in the design process began in the 1970s. It was not until the 1990s that it became an important issue in the design community. The major consideration of design for the environment is seen in Fig. 11.34. Here the arrows represent materials that are taken from the Earth or the biosphere and ultimately returned to it. In this figure, all the major green design issues are considered.

When a product's useful life is over, one of three things happens to its components. They are either disposed of, reused, or recycled. For many products there is no thought given beyond disposal. However, in 1995, 94% of all cars and trucks scrapped in the United States were dismantled and shredded, and 75% of the content by weight was recycled. Whereas, in the 1970s and 1980s, there was design emphasis on disposable products, more and more industries are now trying to design in the ability to recycle or reuse parts of retired products.

For example, even though the single-use camera appears to be disposable after use, Kodak has recycled 41 million of its cameras, or 75% of those sold. Likewise, Xerox reuses or recycles 97% of parts and assemblies from the toner cartridges it manufactures.

You are responsible for the resources used in your products.

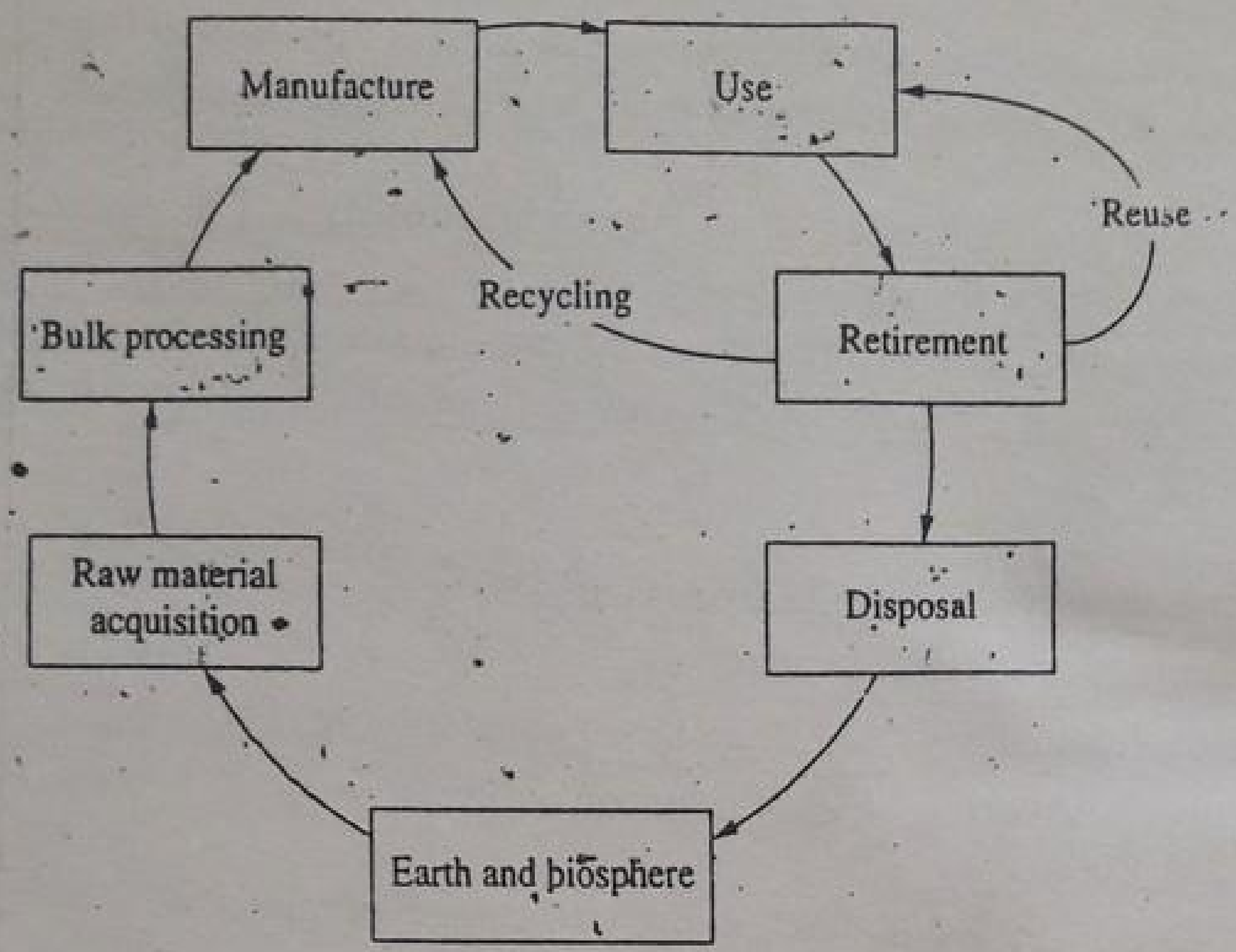


Figure 11.34 Green design life cycle.

This attention to the entire product life cycle is fueled by economics, customer expectation, and government regulation. First, it is becoming less expensive to recycle some materials than it is to pay the expense of processing new raw materials. This is especially true if the product is designed so that it is easily disassembled into components made of a single material. Expense increases if materials are difficult to separate or if one material contaminates another, adversely affecting its material properties. Further, the realization that the resources of raw materials are limited has only recently dawned on many engineers and consumers.

Second, consumers are increasingly more environmentally conscious and aware of the value of recycling. Thus, companies that pollute, generate excessive waste, or produce products that clearly have adverse effects on the environment are looked down on by the public.

Finally, government regulation is forcing attention on the environment. In Germany, manufacturers are responsible for *all* the packaging they create and use. They must collect and recycle it. Further, Mercedes and BMW are designing their new cars so that they, too, can be collected and recycled. European Union laws are forcing this corporate responsibility for the entire life of the product.

In evaluating a product for its "greenness," the guidelines presented next help ensure that environmental design issues have been addressed. These guidelines are an engineering design refinement of the Hannover Principles introduced in Chap. 1. The guidelines serve to compare two designs as do the Design-For-Assembly, DFA, measures in Section 11.5.

Guideline 1: Be Aware of the Environmental Effects of the Materials Used in Products. In Fig. 11.34, every step requires energy, produces waste products, and may deplete resources. Although it is not realistic for the design engineer to know the environmental details of every material used in a product, it is important to know about those materials that may have high environmental impact..

Guideline 2: Design the Product with High Separability. The guidelines for design for disassembly are similar to those for design for assembly. Namely, a product is easy to disassemble if fewer components and fasteners are used, if they come apart easily, and if the components are easy to handle. Other aids for high separability are

- Make fasteners accessible and easy to release.
- Avoid laminating dissimilar materials.
- Use adhesives sparingly and make them water soluble if possible.
- Route electrical wiring for easy removal.

One clear measure of separability is the percentage of material that is easily isolated from other materials.

If some of the components are to be reused, the designer must consider disassembly, cleaning, inspection, sorting, upgrading, renewal, and reassembly.

Guideline 3: Design Components That Can Be Reused to Be Recycled. One design goal is to use only recyclable materials. Automobile manufacturers are striving for this goal. In recycling there are five steps: retrieval, separation, identification, reprocessing, and marketing. Of these five, the design engineer can have the most influence on the separation and identification. Separation was just addressed in guideline 2. Identification means to be able to tell after disassembly exactly what material was used in the manufacture of each component. With few exceptions, it is difficult to identify most materials without laboratory testing. Identification is made easier with the use of standard symbols, such as those used on plastics that identify polymer type.

Guideline 4: Be Aware of the Environmental Effects of the Material Not Reused or Recycled. Currently 18% of the solid waste in landfills is plastic and 14% is metal. All of this material is reusable or recyclable. If a product is not designed to be recycled or reused, it should at least be degradable. The designer should be aware of the percentage of degradable material in a product and the time it takes this material to degrade.

11.9 SUMMARY

- Cost estimation is an important part of the product evaluation process.
- Features should be judged on their value—the cost for a function.
- Design for manufacture focuses on the production of components.
- Design for assembly is a method for evaluating the ease of assembly of a product. It is most useful for high-volume products that have molded components. Thirteen guidelines are given for this evaluation technique.

- Functional development gives insight into potential failure modes. The identification of these modes can lead to the design of more reliable and easier-to-maintain products.
- Design for the environment emphasizes concern for energy, pollution, and resource conservation in processing raw materials for products. It also emphasizes concern for recycling, reuse, or disposal of the product after its useful life is over.

11.10 SOURCES

Boothroyd, G., and P. Dewhurst: *Product Design for Assembly,* Boothroyd and Dewhurst Inc., Wakefield, R.I., 1987. Boothroyd and Dewhurst have popularized the concept of DFA. The range of their tools is much broader than that of those presented here.

Bralla, J. G.: *Design for Manufacturability Handbook,* 2nd edition, McGraw-Hill, New York, 1998. Over 1300 pages of information about over 100 manufacturing processes written by 60+ domain experts. A good starting place to understand manufacturing.

Chow, W. W.-L.: *Cost Reduction in Product Design,* Van Nostrand Reinhold, New York, 1978. An excellent book that gives many cost-effective design hints, written before the term *concurrent design* became popular yet still a good text on the subject. The title is misleading; the contents of the book are a gold mine for the designer engineer.

Lazor, J. D.: "Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis (FTA)," Chap. 6 in *Handbook of Reliability and Management,* 2nd edition, 1995, http://books.google.com/books?id=kWa4ahQUPyAC&pg=PT91&lpg=PT91&dq=fault+tree+analysis+fmea&source=web&ots=3WLMe58qxy&sig=by3Lbbpi3Uxy8KIMEEnEbsyc9qM&hl=en

Life Cycle Design Manual: Environmental Requirements and the Product System, EPA/600/R-92/226, United States Environmental Protection Agency, Jan. 1992. A good source for design for the environment information.

Michaels, J. V., and W. P. Wood: *Design to Cost,* Wiley, New York, 1989. A good text on the management of costs during design.

Nevins, J. L., and D. E. Whitney: *Concurrent Design of Products and Processes,* McGraw-Hill, New York, 1989. This is a good text on concurrent design from the manufacturing viewpoint; a very complete method for evaluating assembly order appears in this text.

Rivero, A., and E. Kroll: "Derivation of Multiple Assembly Sequences from Exploded Views," *Advances in Design Automation,* ASME DE-Vol. 2, American Society of Mechanical Engineers—Design Engineering, Minneapolis, Minn., 1994, pp. 101–106. More guidance on determining the assembly sequence.

Trucks, H. E.: *Designing for Economical Production,* 2nd edition, Society of Manufacturing Engineers, Dearborn, Mich., 1987. This is a very concise book on evaluating manufacturing techniques. It gives good cost-sensitivity information.

11.11 EXERCISES

11.1 For the product developed in response to the design problem begun in Exercise 4.1, estimate material costs, manufacturing costs, and selling price. How accurate are your estimates?

11.2 For the redesign problem begun in Exercise 4.2, estimate the changes in selling price that result from your work.

Exercises 11.3 and 11.4 assume that a cost estimation computer program is available or that a vendor can help with the estimates.

11.3 Estimate the manufacturing cost for a simple machined component:

a. Compare the costs for manufacturing volumes of 1, 10, 100, 1000, and 10,000 pieces with an intermediate tolerance and surface finish. Explain why there is a great change between 1 and 10 and a small change between 1000 and 10,000 pieces.

b. Compare the costs for fit, intermediate, and rough tolerances with a volume of 100 pieces.

c. Compare the costs of manufacturing the component out of various materials.

11.4 Estimate the manufacturing cost for a plastic injection-molded component:

a. Compare the costs for manufacturing volumes of 100, 1000, 10,000, and 100,000. The tolerance level is intermediate, and surface finish is not critical.

b. Compare the cost for a change in tolerance.

c. Why does changing the material have virtually no effect on cost at low plastic injection volume (i.e., 100 pieces)?

11.5 Perform a design-for-assembly evaluation for one of these devices. Based on the results of your evaluation, propose product changes that will improve the product. Be sure that your proposed changes do not affect the function of the device. For each change proposed, estimate its "value."

a. A simple toy (fewer than 10 parts)

b. An electric iron

c. A kitchen mixing machine or food processor

d. An Ipod, cassette, or disk player

e. The product resulting from the design problem (Exercise 4.1) or the redesign problem (Exercise 4.2)

11.6 For the device chosen in Exercise 11.5, perform a failure mode and effects analysis.

11.7 For one of the products in Exercise 11.5, evaluate it for disassembly, reuse, and recycling.

11.12 ON THE WEB

Templates for the following documents are available on the book's website: www.mhhe.com/Ullman4e

- Machined Part Cost Calculator
- Plastics Part Cost Calculator
- DFA
- FMEA