CHAPTER 7

Concept Generation

7.1 INTRODUCTION

In Chap. 6 we went to great lengths to understand the design problem and to develop its specifications and requirements. Now our goal is to use this understanding as a basis for generating concepts that will lead to a quality product. In doing this, we apply a simple philosophy: *Structure,* or *form, follows function.*

A concept is an idea that is sufficiently developed to evaluate the physical principles that govern its behavior. Confirming that the proposed product will operate as anticipated and that, with reasonable further development, it will meet the targets set is a primary goal in concept development. Concepts must also be refined enough to evaluate the technologies needed to realize them, to evaluate the basic architecture (i.e., form) of them, and, to some limited degree, to evaluate their manufacturability. Concepts can be represented in a rough sketch or flow diagram, a proof-of-concept prototype, a set of calculations, or textual notes—an abstraction of what might someday be a product. However a concept is represented, the key point is that enough detail must be developed to model performance so that the functionality of the idea can be ensured.

In some companies, design begins with a concept to be developed into a product. This is a weak philosophy and generally does not lead to quality designs. Further, on the average, industry spends about 15 percent of design time developing concepts. Based on a comparison of the companies in Fig. 1.6, this should be 20–25 percent to minimize changes later.

Some concepts are naturally generated during the engineering requirements development phase, since in order to understand the problem, we have to associate it with things we already know (see Chap. 3). There is a great tendency for designers to take their first idea and start to refine it toward a product. This is a very weak methodology, best expressed by the aphorisms at the top of page 138. This statement and the methods in this chapter support one of the key features of concurrent engineering: generate multiple concepts. The main goal of this chapter, then, is to present techniques for the generation of many concepts.

> If you generate one idea, it is probably a poor one. If you generate twenty ideas, you may have a good one.
> Or, alternatively
> He who spends too much time developing a single concept realizes only that concept.

The flow of conceptual design is shown in Fig. 7.1. Here, as with all problem solving, the generation of concepts is iterative with their evaluation. Also part of the iterative loop, as shown in the figure, is the communication of design information, and the updating of the plans.

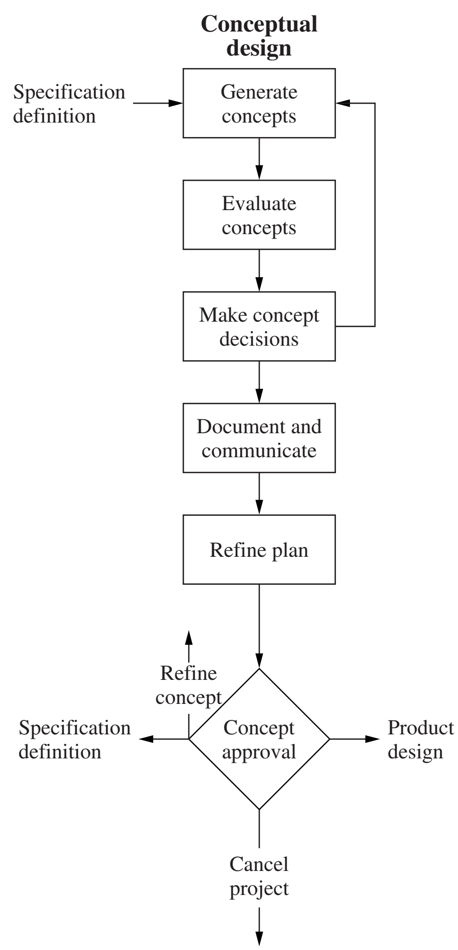


Figure 7.1 The conceptual design phase of the design process.

> To steal ideas from one person is plagiarism,
> to be influenced by many is good design.

In line with our basic philosophy, the techniques we will look at here for generating design concepts encourage the consideration of the function of the device being designed. These techniques aid in decomposing the problem in a way that affords the greatest understanding of it and the greatest opportunity for creative solutions to it.

We will focus on techniques to help with *functional decomposition* and *concept variant generation.* These are based on the fact that important customer requirements are concerned with the functional performance desired in the product. These requirements become the basis for the concept generation techniques. Functional decomposition is designed to further refine the functional requirements; concept variant generation aids in transforming the functions to concepts.

The techniques support a divergent-convergent design philosophy. This philosophy expands a design problem into many solutions before it is narrowed to one final solution. The consideration of multiple configurations is part of the concurrent engineering method described in Chap. 1.

Before continuing, note that the techniques presented here are useful during the development of an entire system and also for each subsystem, component, and feature. This is not to say that the level of detail presented here needs to be undertaken for each flange, rib, or other detail; however, it helps in thinking about all features and it is useful for difficult features.

The suspension problem will be used once again throughout the chapter to demonstrate various steps in the techniques. The results shown for this problem are actual concepts from the design team's notebooks and their final project documentation.

7.2 UNDERSTANDING THE FUNCTION OF EXISTING DEVICES

No matter how new and unique the device being designed is, it is important to understand devices that perform similar functions. There is nothing so new that ideas for it cannot be borrowed from other devices. The benchmarking effort introduced in Section 6.5 continues in this section where we now focus on details of how competitive devices function.

Benchmarking is a good practice because many hundreds of engineering hours have been spent developing the features of existing products, and to ignore this work is foolish. The QFD method, featured in Chap. 6, encourages the study of existing product benchmarks. Studying the ideas of others helps avoid the "NIH complex": since the idea was *N*ot *I*nvented *H*ere, we won't use it.

This section begins with a general discussion of the term "function." It then focuses on how to decompose existing devices to find their function. We then turn our attention to the understanding of the function of proposed devices, those described in patents.

7.2.1 Defining "Function"

In reading this section, it is important to remember that *function* tells *what* the product must do, whereas its *form,* or *structure,* conveys *how* the product will do it. The effort in this chapter is to develop the *what* and then map the *how.* This is similar to the QFD in Chap. 6, where *what* the customer required was mapped into *how* the requirements were to be measured.

Function is the logical flow of energy (including static forces), material, or information between objects or the change of state of an object caused by one or more of the flows. For example, in order to attach any component to another, a person must *grasp* the component, *position* it, and *attach* it in place. These functions must be completed in a logical order: grasp, position, and then attach. In undertaking these actions, the human provides information and energy in controlling the movement of the component and in applying force to it. The three flows—energy, material, and information—are rarely independent of each other. For instance, the control and the energy supplied by the human cannot be separated. However, it is important to note that both are occurring and that both are supplied by the human to the component.

The functions associated with the flow of energy can be classified both by the type of energy and by its action in the system. The types of energy normally identified with electromechanical systems are mechanical, electrical, fluid, and thermal. As these types of energies flow through the system, they are *transformed, stored, transferred (conducted), supplied, and dissipated*. These are the "actions" of the components or assemblies in the system. Thus, all terms used to describe the flow of energy are action words; this is characteristic of all descriptions of function. Also considered as part of the flow of energy is the flow of forces even when they do not result in motion. This concern for force flows is further developed in Section 10.2.

The functions associated with the flow of materials can be divided into three main types. *Through-flow,* or material-conserving processes is the first. Material is manipulated to change its position or shape. Some terms normally associated with through-flow are *position, lift, hold, support, move, translate, rotate,* and *guide.* The second type is *diverging flow,* or dividing the material into two or more bodies. Terms that describe diverging flow are *disassemble* and *separate. Converging flow,* or assembling or joining materials, is the third. Terms that describe converging flow are *mix, attach,* and *position relative to.*

The functions associated with information flow can be in the form of mechanical signals, electrical signals, or software. Generally the information is used as part of an automatic control system or to interface with a human operator. For example, if you install a component with screws, after you tighten the screws you wiggle the component to see if it is really attached. Effectively you ask the question, Is the component attached? and the simple test confirms that it is. This is

> Function happens primarily at interfaces between components.

a common type of information flow. Software is used to modify information that flows through an electronic circuit—a computer chip—designed to be controlled by the code. Thus electrical signals transport information to and from the chip and the software transforms the information.

Function can also relate the change of state of an object. If I say that a spring stores energy, then the internal state of stress in the spring is changed from its initial state. The energy that is stored was transferred to (i.e., flowed into) the spring from some other object. Typically, state changes that are important in mechanical design describe transformations of potential or kinetic energy, material properties, form (e.g., shape, configuration, or relative position), or information content.

With this basic understanding of function, we can describe a useful method for benchmarking an existing product.

7.2.2 Using Product Decomposition to Understand the Function of Existing Devices

Product decomposition is a method to understand how a product works. When we see a new device we often look closely at it to understand how it works. Sometimes the operation is obvious and sometimes it is very obscure. The methodology described next is designed to help understand an existing piece of hardware. The primary goal is to find out how the device works. What is its function? Additionally, we want to be aware of how the parts of the device were made, the materials they were made out of, and the manufacturing processes used. These will be valuable pieces of information when we refine our concepts into product, as discussed in Chap. 10.

To make sure that the function of a device is understood these steps are suggested.

Step 1: For the Whole Device, Examine Interfaces with Other Objects. Since the function of a device is defined by its effect on the flow of energy, information, and material, a starting place is to examine these flows into and out of the device being examined. Consider a desktop stapler (Fig. 7.2). Before reading on, identify the energy, information, and material that flow through the stapler.

In this paragraph all the "other objects," the world in which the stapler operates, are underlined. The energy into the stapler is from the user's hand pushing on the top and, for equilibrium, the desk pushing back on the bottom. The information flow is back to the user to tell her when to stop pushing. In other words the question is asked, Is the staple fully into the paper? The increase in force needed to press the stapler plus the change in sound answer that question. Finally, when considering materials, staples and paper flow into the device and stapled paper flows out.

Figure 7.2 A stapler to be decomposed.

Step 2: Remove a Component for More Detailed Study. Remove a single component or an assembly from the device. Note carefully how it was fastened to the rest of the device. Also, note any relationships it has to other parts that it may not contact. For example, it may have to have a clearance with some other parts in order to function. It may have to shield other assemblies from view, light or radiation. It may have to guide some fluid. In fact, the part removed from the assembly may be a fluid, for example, consider the water flowing through a valve in order to study the function of the valve on the water.

For the stapler, remove the top assembly (Fig. 7.3), the part that the hand pushes on. This requires just unsnapping the top at the pivot and disconnecting a spring.

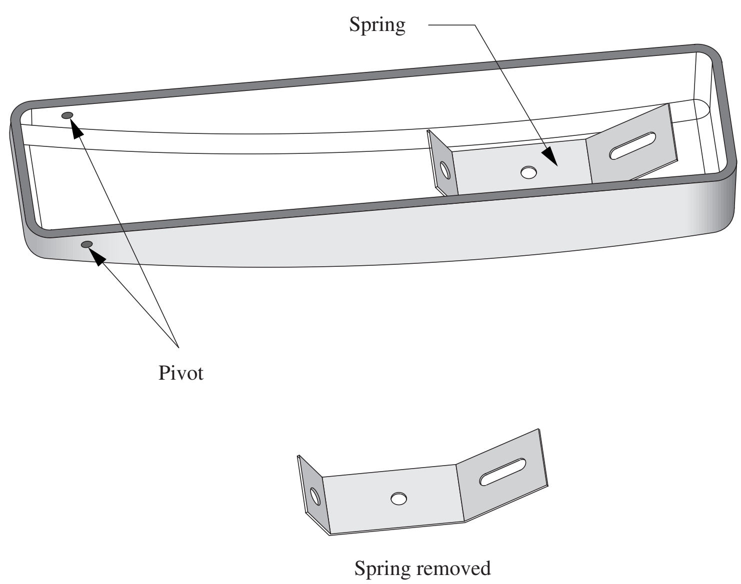


Figure 7.3 The top assembly of the stapler.

This assembly has two parts, the plastic top piece and a spring that snaps into guides molded into the plastic top.

Step 3: Examine Each Interface of the Component to Find the Flow of Energy, Information, or Materials. The goals here are to really understand how the functions identified in step 1 are transformed by the component. Additionally, we want to understand how the parts are fastened together, how forces are transformed and flow from one component to another, and the purpose for each feature of component.

In looking at each connection remember that forces may be transferred between components in three directions (x, y, z) and moments transferred about three axes. Further, there should be features of each interface that either give a degree of freedom to the force or moment or restrains it.

For the stapler top assembly there are five interfaces with other components and the outside world (Fig. 7.4):

1. The interface between the user's hand and the top of the stapler. Energy flows here as described in step 1.
2. The interface to the shaft at the pivot point. This limits the top assembly motion to one degree of freedom—rotation about the shaft. Energy flows here to keep the top assembly aligned with the rest of the stapler.
3. The interface to the staple at the end of the spring. Energy flows between the spring and the staple to push the staple into the paper.
4. The interface with the guide channel on the sides of the spring. The structure that guides the staple also supports the spring so it cannot buckle when pushing on the staple. Very little energy flows here—besides friction, only enough force to keep the spring from buckling.
5. The interface with the base structure. The same spring material that pushes the staple also pushes the top assembly to its original position. Energy flows from base to top through the spring.

The free body diagram in Fig. 7.4 shows all possible forces. Notice that the force between the hand and the stapler is shown as three forces and three moments

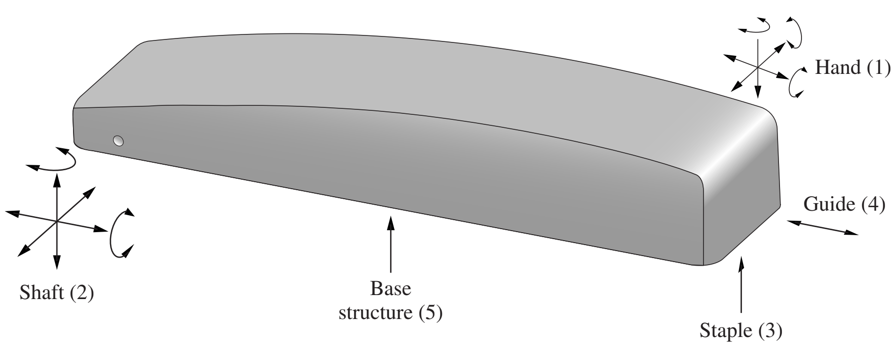


Figure 7.4 Forces on the top assembly.

to the top assembly, not just the single force downward to perform the stapling action. This is done because, in reality, the hand will not push just straight down.

The primary flow of information is by the increase in force transmitted from the staple, through interfaces 1 and 3, to the hand.

7.2.3 Patents as a Source of Ideas

Patent literature is a good source of ideas. It is relatively easy to find patents on just about any subject imaginable and many that are not. Problems in using patents are that it is hard to find exactly what you want in the literature; it is easy to find other, interesting, distracting things not related to the problem at hand; and patents are not very easy to read.

There are two main types of patents: *utility patents* and *design patents.* The term *utility* is effectively synonymous with *function,* so the claims in a utility patent are about how an idea operates or is used. Almost all patent numbers you see on products are for utility patents. Design patents cover only the look or form of the idea, so here the term *design* is used in the visual sense. Design patents are not very strong, as a slight change in the form of a device that makes it look different is considered a different product. All design patent numbers begin with the letter "D." Utility patents are very powerful, because they cover how the device works, not how it looks.

There are over 6 million utility patents, each with many diagrams and each having diverse claims. To cull these to a reasonable number, a *patent search* must be performed. That is, all the patents that relate to a certain utility must be found. Any individual can do this, but it is best accomplished by a professional familiar with the literature.

Patent searching changed dramatically in the mid 1990s. Prior to this time it was necessary to dig through difficult indices and then actually go to one of 50 patent depositories in the United States to see the full text and diagrams. It is now possible to search for patents easily on the web. Two good websites are listed in the Section 7.10.

Before detailing how to best do a patent search, the anatomy of a patent is described. Figure 7.5 is the first page of an early BikeE patent. The heading states that this is a U.S. patent, gives the patent number (Since there is not a "D" in front of this number, it is a utility patent), the name of the first inventor, and the date. Important information in the first column is the filing (i.e., application) date, its class, and other references cited.

The length of time between the filing date and date of the patent is about one year in this case. The patent process may take longer depending on revisions (see Section 13.5) and the specific area (e.g., software patents can take three years or longer due to backlog at the patent office).

All patents are organized by their class and subclass numbers. For the example in Fig. 7.5, the primary class is 280 and subclass is 281.1. Looking in the *Manual of U.S. Patent Classification,* which can be found in most libraries or at one of

United States Patent [19]

Ullman et al.

[11] **Patent Number: 5,509,678**

[45] **Date of Patent: Apr. 23, 1996**

[54] **RECUMBENT BICYCLE**

[76] Inventors: **David G. Ullman**, 1655 NW. Hillcrest Dr.; **Paul A. Atwood**, 2315 SE. Crystal Lake Dr., both of Corvallis, Oreg. 97330

[21] Appl. No.: **406,647**

[22] Filed: **Mar. 20, 1995**

Related U.S. Application Data

[63] Continuation of Ser. No. 188,036, Jan. 28, 1994, abandoned.

[51] **Int. Cl.**[6] **B62K 3/02**

[52] **U.S. Cl.** **280/281.1**; 280/287; 280/288.1

[58] **Field of Search** 280/263, 270, 280/271, 272, 273, 274, 287.1, 284, 287, 288.1, 288.3, 220, 278; 297/215.14; 248/424, 298

[56] **References Cited**

U.S. PATENT DOCUMENTS

582,279	5/1897	Gold	280/272
583,130	5/1897	Smith	280/272
600,046	3/1898	Sparks	280/271
3,588,144	6/1971	Padial	280/276 X
3,807,762	4/1974	Ogisu	280/287
3,811,705	5/1974	D'Ambra	280/276 X
4,129,317	12/1978	Bell	280/274
4,283,070	8/1981	Forrestall et al.	280/274
4,527,811	7/1985	DeMoss	297/215.14 X
4,548,421	10/1985	Wiener	280/288.1
4,659,098	4/1987	Jacobson	280/288.1
4,786,070	11/1988	Adee	280/288.1
4,789,173	12/1988	Lofgren et al.	280/282 X
4,824,130	4/1989	Chiu	280/287
4,925,203	5/1990	Buckler	280/288.1
5,201,538	4/1993	Mayn	280/282 X
5,364,160	11/1994	Fritschen et al.	280/283 X

FOREIGN PATENT DOCUMENTS

3540976	5/1987	Germany	280/282

OTHER PUBLICATIONS

Popular Science, Jan. 1994, "What's New", p. 18.

Primary Examiner—Margaret A. Focarino
Assistant Examiner—Victor E. Johnson
Attorney, Agent, or Firm—J. Preston Oxenham

[57] **ABSTRACT**

A recumbent bicycle has a tubular frame member with a longitudinal axis running from front to rear. A rear support module includes a saddle for nestingly embracing a rear portion of the frame member. Cantilever support members extend downward from the saddle to free ends which are attached to an axle for a rear wheel. A head tube and bearing attached to the front of the frame member support a head shaft and a fork with a bifurcated lower portion suitable for mounting a front wheel. The fork lies generally in a plane and is supported, set forward of the head shaft, by extension plates such that the head shaft axis intercepts the fork plane. A drive sprocket assembly is at the front of the frame member. A seat assembly has opposing track slides engaging a track at the top of the frame member. The slides can be drawn together to clamp the track and fix the seat. The fork and rear support member are of such relative lengths that the front of the frame member is closer to a supporting surface than the rear of the member and, when the seat is moved along the track toward the sprocket assembly, it also moves toward the steering stem and the supporting surface.

15 Claims, 8 Drawing Sheets

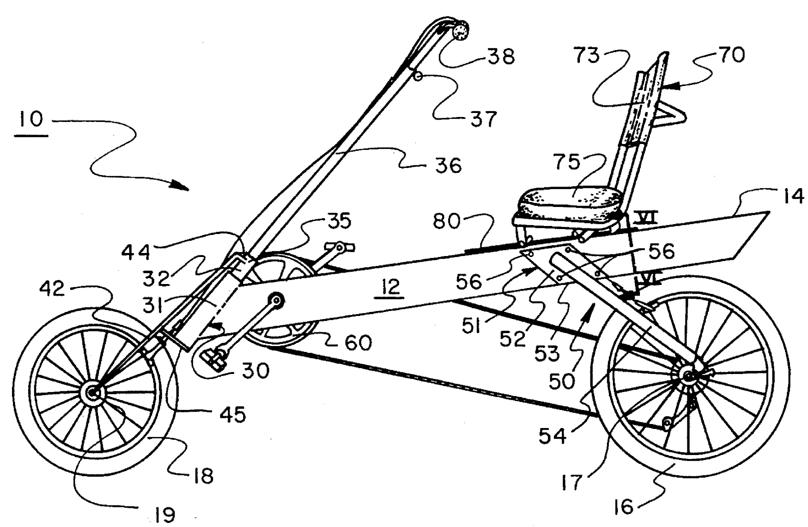


Figure 7.5 Early BikeE patent.

the websites, Class 280 is titled "Land Vehicles." The subclasses are written as in an outline. For subclass 281.1, the outline looks like:

	Wheeled
200	Occupant Propelled Type
281.1	Frames and Running Gear

Thus, this patent has been classified as one relating to the frames or running gear of occupant propelled wheeled land vehicles or, in other words, bicycle frames. The patent is also listed under other classes and, as can be seen in Fig. 7.5, other classes were searched before the patent was granted. What is important about the class/subclass is that this is a starting point for finding other useful patents as will be discussed later.

Also in the first column of Fig. 7.5 is "references cited." These are other, earlier patents that are relevant to this patent. Note that in this case, the earliest patent cited is 1897. Referencing a patent this old is often the case because all new ideas are based on much older work.

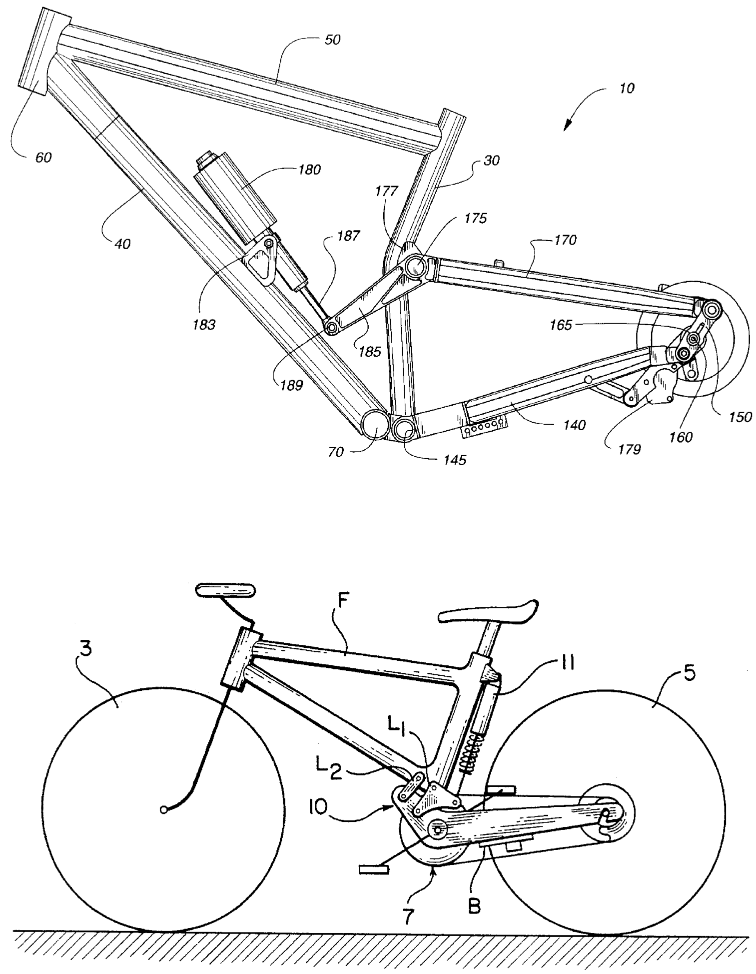
In the second column, after the rest of the references, is the abstract. The abstract is often the first claim of the patent or a paraphrase of it. Often patents have 20 or more claims. Claims are statements about the unique utility (i.e., function) of the device. In patents, subsequent claims are generally built on the first one.

Finally, on the patent front page is a patent drawing. This is usually the first drawing in the patent. As seen in Fig. 7.5, a patent drawing is a stylized line drawing of the device complete with numbers that describe the various parts. The remainder of the patent contains a description of the patent, a description of the drawings, the claims, and the drawings.

To use patents as an aid to understanding existing devices, the patent literature can be searched by classification or keyword. If a patent number is known, then use its main class/subclass to search for other similar devices. In the current example, searching under 280/281.1 yields over 250 recent patents. One problem with patent searches is that usually more information is uncovered than can be reviewed. Looking at the titles of the patents to help reduce the number, the configurations shown in Fig. 7.6 were found. With each of these patents, the methods in the previous section can be used to understand their functionality.

If it is not clear how to start, then use keywords to search. Prior to the introduction of the Web, keyword searching was not readily possible. Using "bicycle and suspension" to search resulted in 236 patents. Reviewing these showed that many were for concepts that did not fit the problem being solved. However, many with class/subclass 280/276 seemed to have potential, thus searching this class/subclass may yield more results.

Note that even though much can be learned about the utility or function of a concept from a patent, finding patents for this purpose is difficult as they are really



(*b*)

Figure 7.6 (a) A figure from Schwinn patent 5,957,473 and (b) a figure from Rockshox patent 5,452,910.

indexed by form. The terms "bicycle" and "suspension" do not really address how the suspension works. This can only be inferred from reading a patent, a time-consuming task. This limitation has led to a method that was developed to streamline the effort (see Section 7.7.1).

This section has only covered using the patent literature to understand how others have solved similar problems. The process of actually applying for a patent is covered in Section 13.5.

7.3 A TECHNIQUE FOR DESIGNING WITH FUNCTION

The goal of functional modeling is to decompose the problem in terms of the flow of energy, material, and information. This forces a detailed understanding, at the beginning of the design project, of *what* the product-to-be is to do. The functional decomposition technique is very useful in the development of new products.

There are four basic steps in applying the technique and several guidelines for successful decomposition. These steps are used iteratively and can be reordered as needed. This technique can be used iteratively with QFD to help understand the problem. In this discussion the usefulness of the technique will be demonstrated with the BikeE suspension system to show its use with an original design problem and with the space shuttle aft field joint to show its use with a more complex redesign problem.

7.3.1 Step 1: Find the Overall Function That Needs to Be Accomplished

This is a good first step toward understanding the function. The goal here is to generate a single statement of the overall function on the basis of the customer requirements. All design problems have one or two "most important" functions. These must be reduced to a simple clause and put in a *black box.* The inputs to this box are all the energy, material, and information that flow into the boundary of the system. The outputs are what flows out of the system.

Guideline: Energy Must Be Conserved. Whatever energy goes into the system must come out or be stored in the system.

Guideline: Material Must Be Conserved. Materials that pass through the system boundary must, like energy, be conserved.

Guideline: All Interfacing Objects and Known, Fixed Parts of the System Must Be Identified. It is important to list all the objects that interact, or interface, with the system. Objects include all features, components, assemblies, humans, or elements of nature that exchange energy, material, or information with the system being designed. These objects may also constrain the system's size, shape, weight, color, etc. Further, there are some objects that are part of the system being designed that cannot be changed or modified. These too must be listed at the beginning of the design process.

Guideline: Ask the Question, How Will the Customer Know if the System Is Performing? Answers to this question will help identify information flows that are important.

Guideline: Use Action Verbs to Convey Flow. Action verbs such as those in Table 7.1 can be used to describe function. Obviously, there are many other verbs beyond those listed that tell about the intended action.

Table 7.1 Typical mechanical design functions

Absorb/remove	Dissipate	Release
Actuate	Drive	Rectify
Amplify	Hold or fasten	Rotate
Assemble/disassemble	Increase/decrease	Secure
Change	Interrupt	Shield
Channel or guide	Join/separate	Start/stop
Clear or avoid	Lift	Steer
Collect	Limit	Store
Conduct	Locate	Supply
Control	Move	Support
Convert	Orient	Transform
Couple/interrupt	Position	Translate
Direct	Protect	Verify

Finding the Overall Function: The BikeE Suspension Example

For the suspension system, the "most important" function can be worded in a couple of different ways. It may be "transform the forces transmitted between the wheel and chain, and the frame of the bike." Or, the function may be to "transfer forces between wheel, chain, and frame and absorb peak loads between wheel and frame," which is really two overall functions—transfer and absorb. Either of these statements will do. They are brief and they tell that the goal is to alter the energy flow; that the boundaries of the system are the wheel, the chain, and the frame of the bike, as shown in Fig. 7.7; and that the primary type of flow is energy.

Finding the Overall Function: The Space Shuttle* Challenger *Aft Field Joint Example

Here the problem is to redesign the joint between the aft mid segment and aft segment (see Fig. 4.4). It will be shown through this example that for the most part, *function occurs at the interfaces between components.* The main function of the joint is to "seal the segments together." It is the subfunction decomposition of this main function that adds to an understanding of the joint.

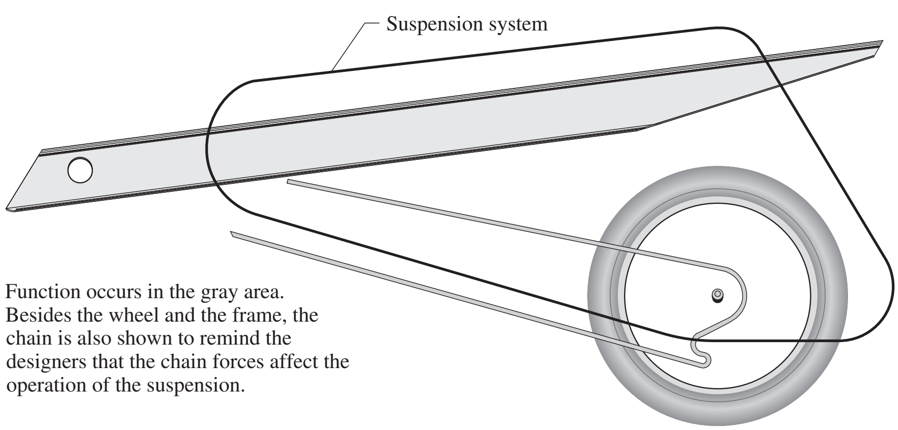


Figure 7.7 The boundary of the suspension design problem.

7.3.2 Step 2: Create Subfunction Descriptions

The goal of this step and step 3 are to decompose the overall function. This step focuses on identifying the subfunctions needed, and the next step concerns their organization. Both steps will be applied to the examples at the end of step 3.

There are three reasons for decomposing the overall function: First, the resulting decomposition controls the search for solutions to the design problem. Since concepts follow function and products follow concepts, we must fully understand the function before wasting time generating products that solve the wrong problem.

Second, the division into finer functional detail leads to a better understanding of the design problem. Although all this detail work sounds counter to creativity, most good ideas come from fully understanding the functional needs of the design problem. Since it improves understanding, it is useful to begin this process before the QFD process in Chap. 6 is complete and use the functional development to help determine the engineering specifications.

Finally, breaking down the functions of the design may lead to the realization that there are some already existing components that can provide some of the functionality required.

Each subfunction developed will show either:

- An object whose state has changed

or

- An object that has energy, material, or information transferred to it from another object.

The following guidelines are important in accomplishing the decomposition. It will take several iterations to finalize all this information. However, time spent here will save time later when it is realized that the product has intended functions that could have been found and dealt with much earlier. The examples at the end of step 3 will demonstrate the use of the guidelines.

Guideline: Consider *What,* Not *How*. It is imperative that only *what* needs to happen—the function—be considered. Detailed, structure-oriented *how* considerations must be suppressed as they add detail too soon. Even though we remember functions by their physical embodiments, it is important that we try to abstract this information. If, in a specific problem solution, it is not possible to proceed without some basic assumptions about the form or structure of the device, then document the assumptions.

Guideline: Use Only Objects Described in the Problem Specification or Overall Function. A way to ensure that new components do not creep into the product unknowingly is to use only nouns previously used (e.g., in the QFD or in step 1) to describe the material flow or interfacing objects. If any other nouns are used during this step, either something is missing in the first step (go back to step 1 and reformulate the overall function), the specifications are incomplete, or a design decision to add another object to the system has been made (consider very carefully, as in the suspension example presented shortly).

Guideline: Break the Function Down as Finely as Possible. This is best done by starting with the overall function of the design and breaking it into the separate functions. Let each function represent a change or transformation in the flow of material, energy, or information. Action verbs often used in this activity are given in Table 7.1.

Guideline: Consider All Operational Sequences. A product may have more than one operating sequence while in use (see Fig. 1.8). The functions of the device may be different during each of these. Additionally, prior to the actual *use* there may be some *preparation* that must be modeled, and similarly, after use there may be some *conclusion.* It is often effective to think of each function in terms of its preparation, use, and conclusion.

Guideline: Use Standard Notation When Possible. For some types of systems there are well-established methods for building functional block diagrams. Common notation schemes exist for electrical circuits and piping systems, and block diagrams are used to represent transfer functions in systems dynamics and control. Use these notations if possible. However, there is no standard notation for general mechanical product design.

7.3.3 Step 3: Order the Subfunctions

The goal is to add order to the functions generated in the previous step. For many redesign problems this occurs simultaneously with their identification in step 2, but for some processing systems this is a major step. The goal here is to order the functions found in step 2 to accomplish the overall function in step 1. The guidelines and examples presented next should help with this step.

Guideline: The Flows Must Be in Logical or Temporal Order. The operation of the system being designed must happen in a logical manner or in a time sequence. This sequence can be determined by rearranging the subfunctions. First arrange them in independent groups (preparation, uses, and conclusion). Then arrange them within each group so that the output of one function is the input of another. This helps complete the understanding of the flows and helps find missing functions.

Guideline: Redundant Functions Must Be Identified and Combined. Often there are many ways to state the same function. If each member of the design team has written his or her subfunctions on self-stick removable notepaper, all the pieces can be put on the wall and grouped by similarity. Those that are similar need to be combined into one subfunction.

Guideline: Functions Not Within the System Boundary Must Be Eliminated. This step helps the team come to mutual agreement on the exact system boundaries; it is often not as simple as it sounds.

Guideline: Energy and Material Must Be Conserved as They Flow Through the System. Match inputs and outputs to the functional decomposition. Inputs to each function must match the outputs of the previous function. The inputs and outputs represent energy, material, or information. Thus the flow between functions conveys the energy, material, or information without change or transformation.

Creating a Subfunction Description: The BikeE Suspension System Example To help understand the function of the system, the design team drew a simple freebody diagram (Fig. 7.8) based on Fig. 7.7. With the gray area representing the to-be-designed suspension system, the arrows in Fig. 7.8 represent the forces due to the chain tension, the wheel pushing up, and the frame loading on the suspension system to balance out the other two forces. This problem is essentially a two-dimensional problem as side loads are small on a bicycle. Note that during the design of the first BikeE model, the one with no suspension, the force due to chain tension was not considered. It was later learned that the highest stress in the rear stay (i.e., the part that connects the frame to the wheel in Fig. 4.12) was due to chain forces and not the vertical forces due the rider's weight and resulting vertical wheel force.

Based on this understanding, the team decomposed the main functions into subfunctions, as shown in Fig. 7.9. Keep in mind when studying this figure that there is no one right way to do a functional decomposition and that the main reason for doing it is to ensure that the function of the device to be developed is understood.

The team decomposed the force from the wheel into as many functions as they could think of. Note that they focused on interfaces, how the energy gets

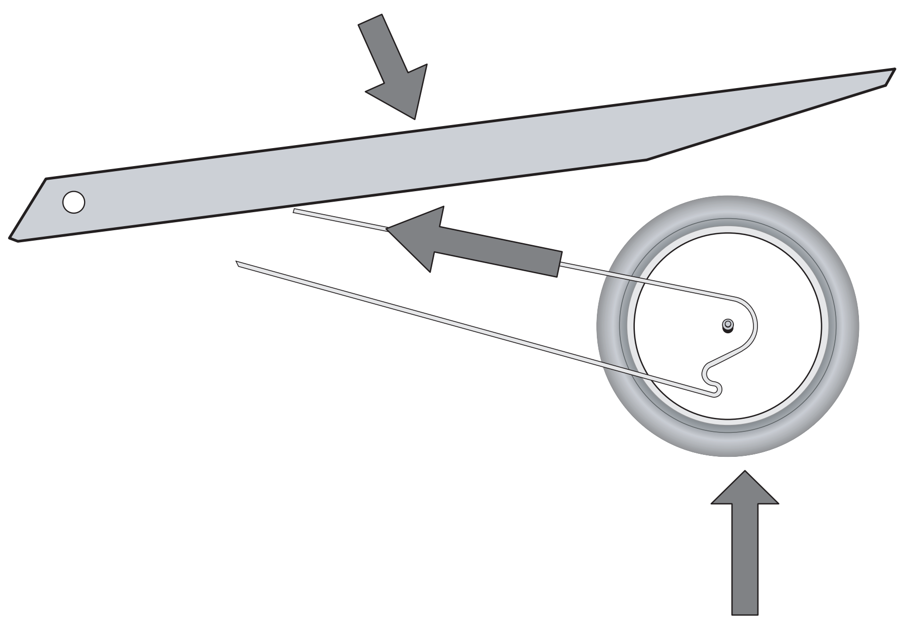


Figure 7.8 The forces on the suspension system.

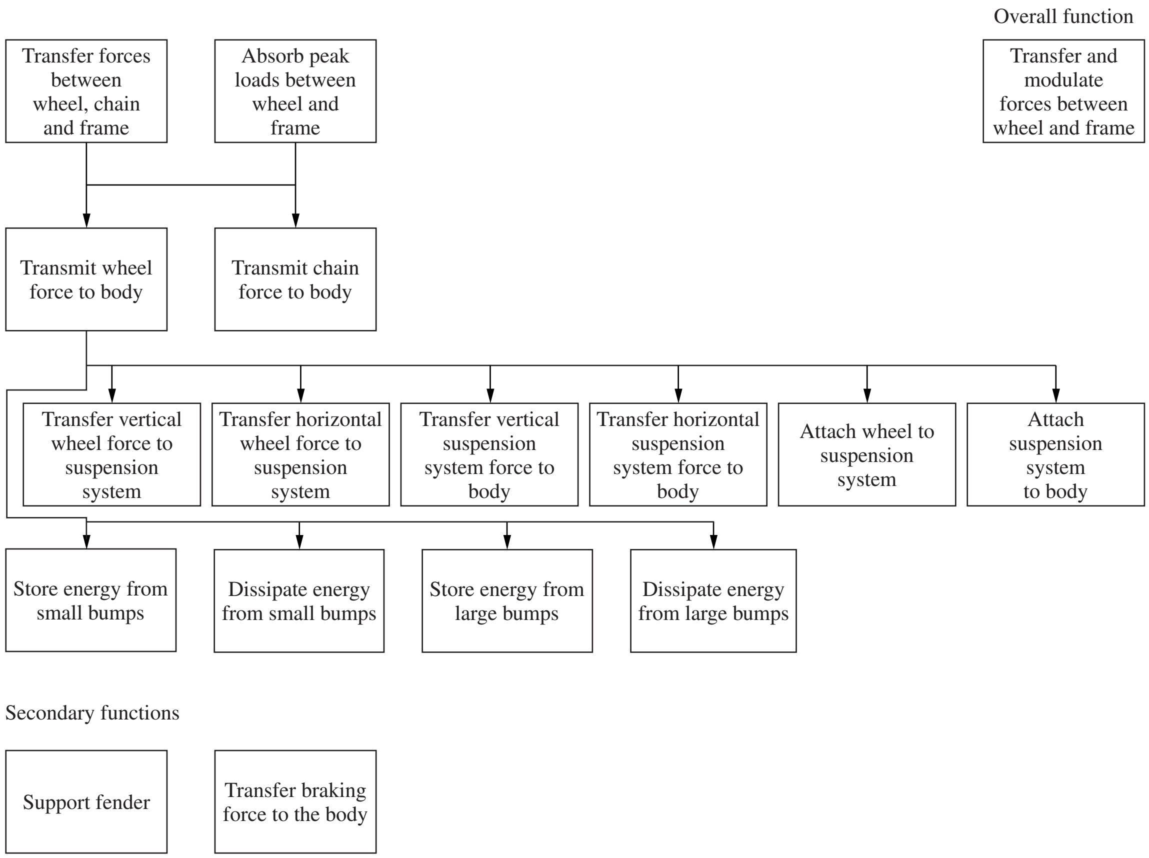


Figure 7.9 Functional decomposition for the suspension system.

in and out of the systems, and what has to happen internally to the energy. They divided the transfer of energy into concern for large bumps and small bumps based on their experience that it is difficult to get a smooth ride over little bumps and still have a system that can take the large hits. Think of a Cadillac versus a Baja buggy. They also divided the energy storage from the energy dissipation, the spring from the damper.

While developing the subfunctions they also remembered that the system to be designed would probably have to carry a fender and the brakes. They noted these as secondary functions.

Creating Subfunction Description: The Space Shuttle* Challenger *Aft Field Joint Example.
In this example the decomposition of the function of the joint greatly aids in its understanding. Here it is easiest to decompose the function in a tree-like structure. Part of the resulting tree for the aft field joint is shown in Fig. 7.10. Note that the goal is to decompose the function of the joint as finely as possible using action verbs to relate interactions among the objects.

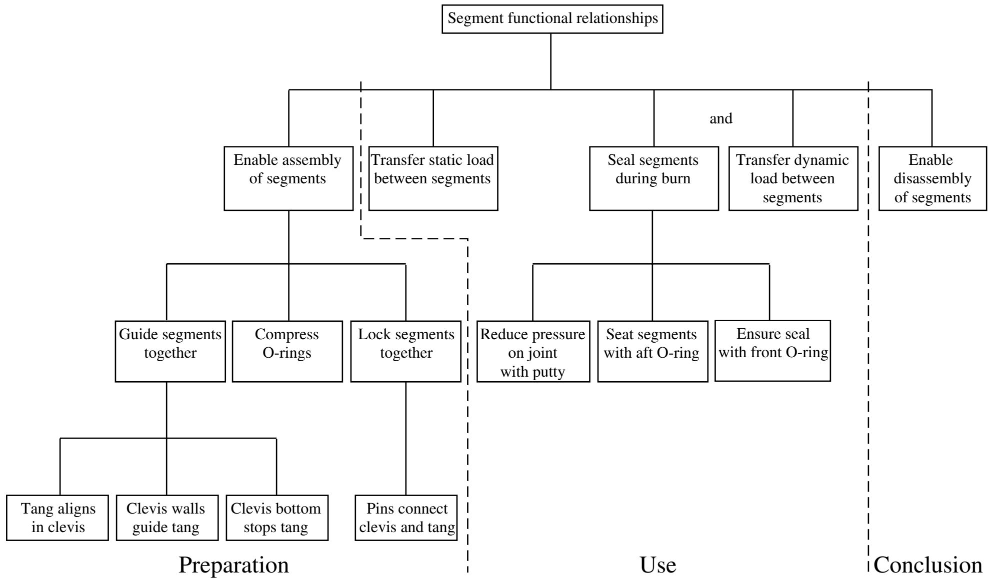


Figure 7.10 The space shuttle aft field joint functional decomposition.

The first level of decomposition takes into account the preparation, use, and conclusion of the function of the joint. For preparation the verb *enable* has been used. This is not a strong action verb, nor is *allow,* as neither of them can be related to transfer or modification of energy, material, or information. It would have been better to just say, "Assemble the segments."

After the segments are assembled, the joint must support the static load (effectively a transfer of energy). By thinking of the sequence of events in the life of the joint, we can identify nonobvious, important functions.

When the rocket is fired, the joint must seal and transfer dynamic loads. Note that the parallel nature of these two functions is shown in the diagram.

These first-level functions can be further decomposed, as shown in the figure and discussed in step 4.

7.3.4 Step 4: Refine Subfunctions

The goal is to decompose the subfunction structure as finely as possible. This means examining each subfunction to see if it can be further divided into sub-subfunctions. This decomposition is continued until one of two things happens: "atomic" functions are developed or new objects are needed for further refinement. The term atomic implies that the function can be fulfilled by existing objects. However, if new objects are needed, then you want to stop refining because new objects require commitment to how the function will be achieved, not refinement of what the function is to be. Each noun used represents an object or a feature of an object.

> Try to not reinvent the wheel.

Further Refining the Subfunctions: The Space Shuttle **Challenger** ***Aft Field Joint Example.***
As shown in Fig. 7.10, two of the functions are further refined. An approach to decomposition is to ask, What has to happen to "enable assembly of segments?" Continuing to ask, What has to happen? until new objects are needed to answer the question will help functional decomposition. This is the same philosophy as asking Why? in developing the customers' requirements.

As shown in the figure, at least two levels of decomposition are easily realizable, as can be seen by considering the functions of the features of the clevis and tang that help "align," "guide," and "stop" the segments. After the decomposition is finished, it could be used as a basis for developing ideas to replace the clevis and tang (see Section 7.5). The function of transferring the loads between segments is further refined in Section 10.2.

It must be realized that the function decomposition cannot be generated in one pass and that it is a struggle to develop the suggested diagrams. However, it is a fact that the design can be only as good as the understanding of the functions required by the problem. This exercise is both the first step in developing ideas for solutions and another step in understanding the problem. The functional decomposition diagrams are intended to be updated and refined as the design progresses.

Further Refining the Subfunctions: The BikeE Suspension System
Some of the subfunctions shown in Fig. 7.9 are atomic, but others can be further refined. For example, steel springs, air cylinders, or other pieces of existing hardware can fulfill the "store energy" functions. However, the function "attach wheel to suspension system" can be decomposed. In order to be attached, the wheel must be positioned, guided, and stopped. Going to these details may seem silly, but thinking about them can make it easier to assemble and use the resulting product.

7.4 CONCEPT GENERATION METHODS

Dreaming up new ideas is an enjoyable experience. In generating a new idea, an engineer can take great pride in his or her creativity. Often, however, the idea is not original after all; the wheel has been invented again.

It is impossible to know about all previous concepts. For example, in the 1920s, while designing a gyroscope for an automatic pilot, the Sperry Gyroscope Company needed a bearing that would hold the end of the gyro shaft in position with both axial and lateral accuracy, would support the gyroscope, and would have very low friction. The designers came up with what they thought was a clever design, a shaft with a conical end riding on three balls in a cup. This one clever idea achieved all the design functions; it was subsequently patented and put into

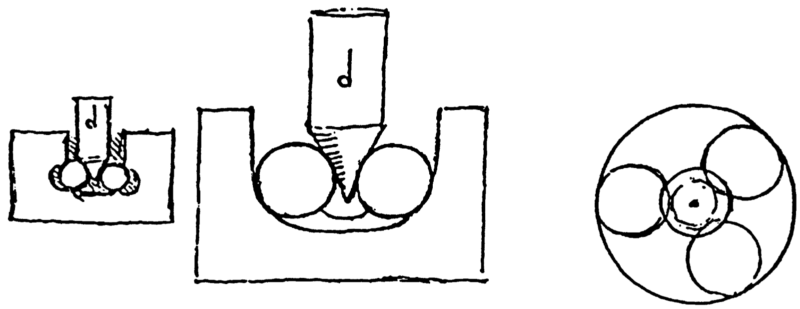


Figure 7.11 A low-friction bearing from da Vinci's notebooks. (© EMB-Service, CH-Lucerne, from book: *Unknown Leonardo* by Ladislao Reti, 1974. Reprinted by permission.)

service with great success. In 1965 a previously unknown notebook of Leonardo da Vinci's, dating from about 1500, was discovered in Madrid. Sketches from this notebook (Fig. 7.11) show a design identical to that later developed at Sperry. Of course, the Sperry designers had no way of knowing that the idea had been developed in the sixteenth century. In fact, there is a good chance that it may have been developed many times over between the sixteenth and twentieth centuries and not recorded in any fashion. The point is that every effort must be made to find design ideas that have been previously developed; the problem is that most previous ideas are not recorded by function and indexed in any way.

What follows in this section is a list of useful sources of design information that might keep a designer from reinventing the bearing. A majority of these sources refer to products that are already embodied and can therefore influence the concepts being generated. Unfortunately, there is no good way to adequately represent design concepts other than graphically, by their form. A good designer will abstract the function of a design from the form, utilize the important aspects, and discard the rest.

Once the function is understood, there are many methods to help generate concepts to satisfy them. *Concepts are the means for providing function.* Concepts can be represented as verbal or textual descriptions, sketches, paper or clay models, block diagrams, or any other form that gives an indication of how the function can be achieved. Note that in the last sentence the terms, "form" and "how" were used. Where the first half of this chapter focused on the function, what needs to be accomplished; we now begin to worry about form, how the customer's requirements can be accomplished. In this section, many methods will be introduced. No single method is best. A good designer is familiar with these methods and uses them, or a combination of them, as needed. The methods to be discussed are organized in Fig. 7.12 with their section numbers identified.

As shown in the diagram, there are a number of *basic methods* that can help with concept development. These are detailed in Section 7.5. A more controlled method, one that relies heavily on the *basic methods,* is developed in Section 7.6.

> Follow the kiss rule: *k*eep *i*t *s*imple *s*tupid.

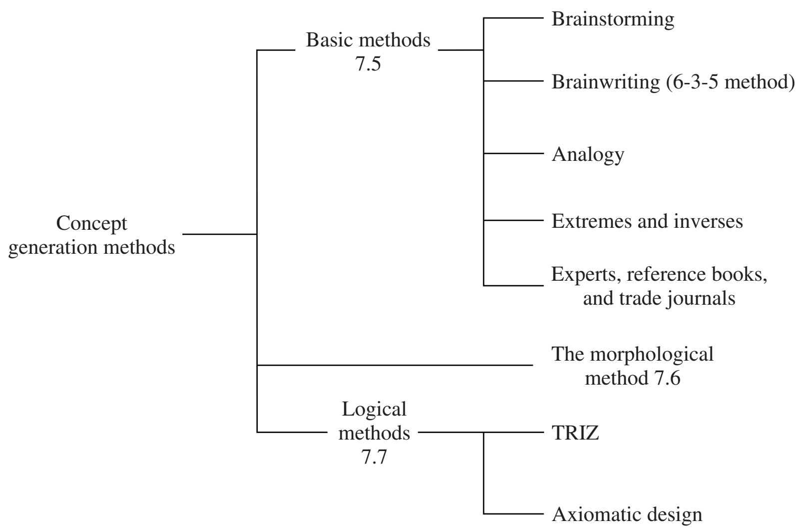


Figure 7.12 Concept generation methods. ("Concept generation methods" based on a diagram originated by Professor Jami Shah, Arizona State University. Reprinted by permission of Professor Jami Shah.)

Recently, two methods have evolved that give real structure to concept generation. These *logical methods* are fairly complex and so they are only introduced in Section 7.7.

7.5 BASIC METHODS OF GENERATING CONCEPTS

The methods in this section are commonly used to develop concepts. As will be seen they are based on knowledge of the functions. The methods are presented in no particular order and can be used together. An experienced designer will jump from one to another to solve a specific problem.

7.5.1 Brainstorming as a Source of Ideas

Brainstorming, initially developed as a group-oriented technique, can also be used by an individual designer. What makes brainstorming especially good for group efforts is that each member of the group contributes ideas from his or her own viewpoint. The rules for brainstorming are quite simple:

1. Record all the ideas generated. Appoint someone as secretary at the beginning; this person should also be a contributor.
2. Generate as many ideas as possible, and then verbalize these ideas.

3. Think wild. Silly, impossible ideas sometimes lead to useful ideas.
4. Do not allow evaluation of the ideas; just the generation of them. This is very important. Ignore any evaluation, judgment, or other comments on the value of an idea and chastise the source.

In using this method, there is usually an initial rush of obvious ideas, followed by a period when ideas will come more slowly with periodic rushes. In groups, one member's idea will trigger ideas from the other team members. A brainstorming session should be focused on one specific function and allowed to run through at least three periods during which no ideas are being generated. It is important to encourage humor during brainstorming sessions as even wild, funny ideas can spark useful concepts. This is a proven technique that is useful when new ideas are needed.

7.5.2 Using the 6-3-5 Method as a Source of Ideas

A drawback to brainstorming is that it can be dominated by one or a few team members (see Section 3.5.3). The 6-3-5 method forces equal participation by all. This method is effectively brainstorming on paper and is called *brainwriting* by some. The method is similar to that shown in Fig. 7.13.

To perform the 6-3-5 method, arrange the team members around a table. The optimal number of participants is the "6" in the method's name. In practice, there can be as few as 3 participants or as many as 8. Each takes a clean sheet of paper and divides it into three columns by drawing lines down its length. Next, each team member writes 3 ideas for how to fulfill a specific agreed-upon function, one at the top of each column. The number of ideas is the "3" in the method's name. These ideas can be sketched or written as text. They must be clear enough that others can understand the important aspects of the concept.

After 5 minutes of work on the concepts, the sheets of paper are passed to the right. The time is the "5" in the method's name. The team members now have another 5 minutes to add 3 more ideas to the sheet. This should only be done after studying the previous ideas. They can be built on or ignored as seen fit. As the papers are passed in 5-minute intervals, each team member gets to see the input of each of the other members, and the ideas that develop are some amalgam of the best. After the papers have circulated to all the participants, the team can discuss the results to find the best possibilities.

There should be no verbal communication in this technique until the end. This rule forces interpretation of the previous ideas solely from what is on the paper, possibly leading to new insight and also eliminating evaluation.

7.5.3 The Use of Analogies in Design

Using analogies can be a powerful aid to generating concepts. The best way to think of analogies is to consider a needed function and then ask, What else provides this function? An object that provides similar function may trigger ideas

"It's our new assembly line. When the person at the end of the line has an idea, he puts it on the conveyor belt, and as it passes each of us, we mull it over and try to add to it."

Figure 7.13 Automated brainwriting. (© 2002 by Sidney Harris.)

for concepts. For example, ideas for how the BikeE suspension may look and function can be drawn from motorcycles, cars, crickets, tree limbs, or anything else that provides some or all of the needed function.

Analogies can also lead to poor ideas. For centuries, people watched birds fly by flapping their wings. By analogy, flapping wings lift birds, so flapping wings should lift people. It wasn't until people began to experiment with fixed wings that the real potential of manned flight became a reality. In fact, what occurred is that by the time of the Wright Brothers in the early 1900s, the problem of manned flight had been divided into four main functions, each solved with some independence of the others: lift, stability, control, and propulsion. The Wright Brothers actually approached each of these in the order listed to achieve controlled, sustained flight.

7.5.4 The Use of Extremes and Inverses

This method is helpful in refining and understanding concepts. It is introduced here and referred to again during product development in Section 10.2. This method is informal and is simply: *transform current concepts into others by taking them to extremes or considering inverses.* Specific suggestions for how to do this are listed here and, later in Section 7.6, these will be applied to the BikeE suspension system design problem.

- Make one dimension very short or very long. Think about what will happen if it goes to zero or infinity. Try this with multiple dimensions.
- Take the current order of things and switch them around. Put what is on top, on the bottom; or what is first, last.
- Try taking what is the inside of something and making it the outside or vice versa.
- Make something that is rigid, flexible or something that is flexible, rigid.
- A motion that is linear can be nearly accomplished by a very large arc or a linkage (see Fig. 7.14), so explore what would happen with almost-linear motion.
- Make something that is first thought of as straight, curved. Think of it as cooked spaghetti that can be in any form it wants to be and then hardened in that position. Do this with planar objects or surfaces.

7.5.5 Finding Ideas in Reference Books and Trade Journals

Most reference books give analytical techniques that are not very useful in the early stages of a design project. In some you will find a few abstract ideas that are useful at this stage—usually in design areas that are quite mature and with ideas so decomposed that their form has specific function. A prime example is the area of linkage design. Even though a linkage is mostly geometric in nature, most linkages can be classified by function. For example, there are many geometries that can be classified by their function of generating a straight line along part of their cycle. (The function is to move in a straight line.) These straight-line mechanisms can be grouped by function. Two such mechanisms are shown in Fig. 7.14.

Many good ideas are published in trade journals that are oriented toward a specific discipline. Some, however, are targeted at designers and thus contain information from many fields. A listing of design-oriented trade journals is given in Sources at the end of this chapter (Section 7.10).

7.5.6 Using Experts to Help Generate Concepts

If designing in a new domain, one in which we are not experienced, we have two choices to gain the knowledge sufficient to generate concepts. We either find someone with expertise in that domain or spend time gaining experience on our own. It is not always easy to find an expert; the domain may even be one that has no experts. With the suspension, for example, there were no experts

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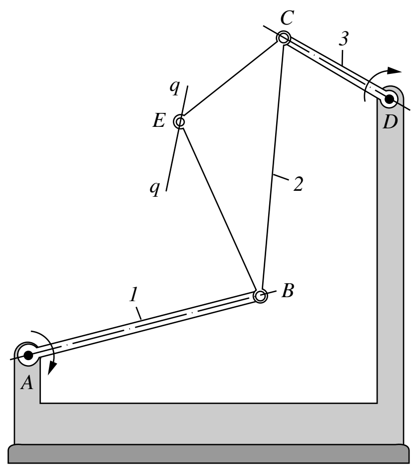
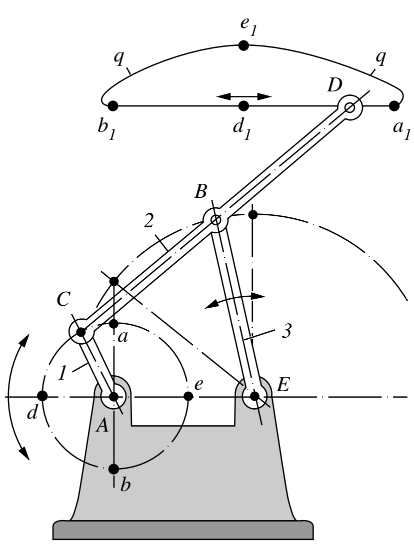
650	WATT FOUR-BAR APPROXIMATE STRAIGHT-LINE MECHANISM	LW GI



The lengths of the links of four-bar linkage *ABCD* comply with the conditions: $AD = 1.84AB$, $BE = 0.76AB$, $BC = 1.03AB$, $EC = 0.55AB$, and $DC = 0.52AB$. When link *1* turns about fixed axis *A*, point *E* of link *2* describes a path of which portion *q*-*q* is approximately a straight line.

651	CHEBYSHEV FOUR-BAR APPROXIMATE STRAIGHT-LINE MECHANISM	LW GI



The lengths of the links of four-bar linkage *ABCD* comply with the conditions: $CB = BE = BD = 2.5AC$ and $AE = 2AC$. When link *1* rotates about fixed axis *A*, point *D* of link *2* describes path *q*-*q*. Upon motion of point *C* along arc *a*-*d*-*b*, point *D* travels along approximately straight line a_1-d_1-b_1.

Figure 7.14 Straight-line mechanisms. (From I. I. Artobolevsky, *Mechanisms in Modern Engineering Design,* MIR Publishers, Moscow, 1975.)

> Complexity grows faster than your ability to understand it.

knowledgeable in suspensions on recumbent bicycles as one had not been previously commercialized.

How do you become an expert in an area that is new or unique? How do you become expert when you cannot find or afford the existing experts? Evidence of expertise can be found in any good designer's office. The best designers work long and hard in a domain, performing many calculations and experiments themselves to find out what works and what does not. Their offices also contain many reference books, periodicals, and sketches of concept ideas.

A good source of information is manufacturers' catalogs and, even better, manufacturers' representatives. A competent designer usually spends a great deal of time on the telephone with these representatives, trying to find sources for specific items or trying to find "another way to do it." One way to find manufacturers is through indexes such as the *Thomas Register,* a gold mine of ideas. All technical libraries subscribe to the 23 annually updated volumes, which list over a million producers of components and systems usable in mechanical design. Beyond a limited selection of reprints of manufacturers' catalogs, the *Thomas Register* does not give information directly but points to manufacturers that can be of assistance. The hard part of using the *Register* is finding the correct heading, which can take as much time as the patent search. The *Thomas Register* is easily searched on the website (see sources in Section 7.10 for the URL).

7.6 THE MORPHOLOGICAL METHOD

The technique presented here uses the functions identified to foster ideas. It is a very powerful method that can be used formally, as presented here, or informally as part of everyday thinking. There are two steps to this technique. The goal of the first is to find as many concepts as possible that can provide each function identified in the decomposition. The second is to combine these individual concepts into overall concepts that meet all the functional requirements. The design engineer's knowledge and creativity are crucial here, as the ideas generated are the basis for the remainder of the design evolution. This technique is often called the "morphological method," and the resulting table a "morphology," which means "a study of form or structure."

7.6.1 Step 1: Developing Concepts for Each Function

The goal of this first step is to generate as many concepts as possible for each of the functions identified in the decomposition. There are two activities here that are similar to each other. First, for each function develop as many alternative functions as possible. This can be done using the steps in Section 7.3. Second, for each subfunction the goal is to develop as many means of accomplishing the function as possible. For example, in Fig. 7.9 one of the functions that must be performed is to store energy from large bumps. Common ways of mechanically storing energy are with steel springs, air springs, and elastomers (i.e., rubber or flexible plastics). Two points can be made about this list. First, there are other ways to store energy. Wild, impractical ideas often lead to good ideas (see Section 7.5). We could use flywheels or pumping water into a reservoir. These ideas are not practical for this product, so they will not appear on the list of possibilities. Second, the concepts on the list are all abstract in that they have no specific geometry. Rough sketches of these concepts or word descripts are best.

If there is a function for which there is only one conceptual idea, this function should be reexamined. There are few functions that can be fulfilled by only one concept. The situations discussed next explain the lack of more concepts.

First, the designer has made a fundamental assumption. For example, one function that has to occur in the suspension system is "transfer vertical wheel force to the suspension system" (Fig. 7.9). This is commonly done on a bicycle by putting a vertical slot in the structure for the wheel axle to fit in. This slot and its surrounding structure are called a "dropout." It is reasonable to assume that a dropout is the only concept that needs to be developed to transfer energy from the wheel to the suspension system *only if the designer is aware that an assumption has been made.*

***Second, the function is directed at* how*, not* what.** If one idea gets built into the function, then it should come as no surprise that this is the only idea that gets generated. For example, if "store energy" in Fig. 7.9 had been stated as "store energy in a coil spring," then only coil spring ideas are possible. If the function statement has nouns that tell *how* the function is to be accomplished, reconsider the function statement.

Finally, domain knowledge is limited. In this case, help is needed to develop other ideas. (See Sections 7.2, 7.5, 7.6, or 7.7.)

It is a good idea to keep the concepts as abstract as possible and at the same level of abstraction. Suppose one of the functions is to move some object. Moving requires a force applied in a certain direction. The force can be provided by a hydraulic piston, a linear electric motor, the impact of another object, or magnetic repulsion. The problem with this list of concepts is that they are at different levels of abstraction. The first two refer to fairly refined mechanical components. (They could be even more refined if we had specific dimensions or manufacturers' model numbers.) The last two are basic physical principles. It is difficult to compare these concepts because of this difference in level of abstraction. We could begin to correct this situation by abstracting the first item, the hydraulic piston. We could cite instead the use of fluid pressure, a more general concept. Then again, air might be better than hydraulic fluid for the purpose, and we would also have to consider the other forms of fluid components that might give more usable forces than a piston. We could refine the "impact of another object" by developing how it will provide the impact force and what the object is that is providing the force. Regardless of what is changed, it is important that all concepts be equally refined.

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It's hard to make a good product out of a poor concept.

Developing Concepts for Each Function: The BikeE Suspension System Example

Figure 7.15 is a morphology for the suspension system. It is a good starting place for generating ideas.

7.6.2 Step 2: Combining Concepts

The result of applying step 1 is a list of concepts generated for each of the functions. Now we need to combine the individual concepts into complete conceptual designs. The method here is to select one concept for each function and combine those selected into a single design. So, for example, we may consider combining a truss with a steel coil and a gas orifice. There are pitfalls to this method, however.

First, if followed literally, this method generates too many ideas. The suspension system design team generated four concepts for the "dissipate energy" function and five concepts for the "store energy" function. These two functions alone combine to yield 20 possible designs. For the entire example there would be thousands of possibilities.

The second problem with this method is that it erroneously assumes that each function of the design is independent and that each concept satisfies only one function. Generally, this is not the case. For example, if a cantilever is used to transmit the chain force, then it must be used to transmit the other forces. Nonetheless, breaking the function down this finely helps with understanding and concept development.

Third, the results may not make any sense. Although the method is a technique for generating ideas, it also encourages a coarse ongoing evaluation of the ideas. Still, care must be taken not to eliminate concepts too readily; a good idea could conceivably be prematurely lost in a cursory evaluation. A goal here is to do only a coarse evaluation and generate all the ideas that are reasonably possible. In Chap. 8 we will evaluate the concepts and decide between them.

Even though the concepts developed here may be quite abstract, this is the time that back-of-the-envelope sketches begin to be useful. Prior to this time, most of the design effort has been in terms of text, not graphics. Now the design is developing to the point that rough sketches must be drawn. Sketches of even the most abstract concepts are increasingly useful from this point on because (1) as discussed in Chap. 3, we remember functions by their forms; thus our index to function is form; (2) the only way to design an object with any complexity is to use sketches to extend the short-term memory; and (3) sketches made in the design notebook provide a clear record of the development of the concept and the product.

Keep in mind that the goal is only to develop concepts and that effort must not be wasted worrying about details. Often a single-view sketch is satisfactory; if a three-view drawing is needed, a single isometric view may be sufficient.

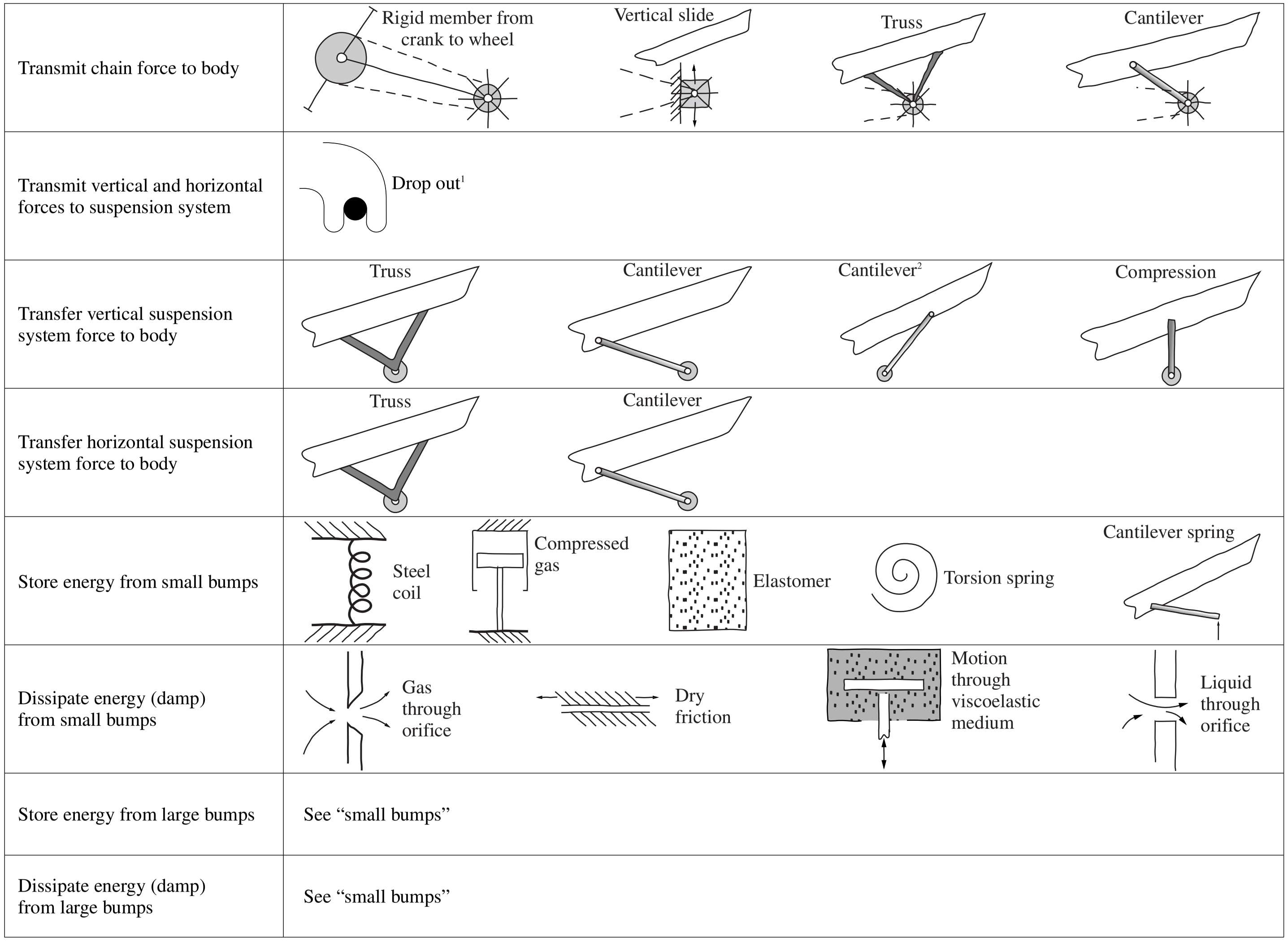


Figure 7.15 Morphology for BikeE suspension system.
[1] See first note in step 1.
[2] An inverse (see Section 7.5.4).

Combining Concepts: The suspension system example

Figure 7.16 shows selections from the notebooks of the members of the design team. Each concept sketch is followed by notes abstracted from notebooks. These are broken down into two main subproblems: the bicycle's structure and the energy storage/dissipation method. The sketches labeled with an "S" are structural and those labeled with an "E" are energy management.

During the exercise of developing these concepts the team found that they learned much about the project:

- Three of the four structural concepts use pivots. The development of pivots requires a new subproject complete with requirements, function consideration, and concept generation.
- The energy management with springs and dampers can be implemented with an off-the-shelf unit or made from basic components. Part of selecting among these will be consideration of whether or not it will be better to make the system or buy one off the shelf.
- The four structural ideas can be combined with the three energy management ideas in up to twelve different ways. Evaluation will help reduce this number to one or two ideas for detailed development.

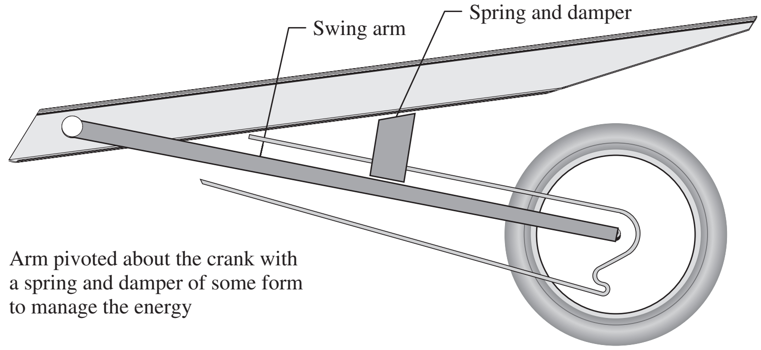
Although simplistic, the morphological technique is widely used. One feature that appeals to industry is that it can be used to keep a history of different methods of satisfying a function. This history serves as a source of design ideas for future products. For example, Unilever Ltd., a multinational manufacturer of a wide variety of consumer and grocery products has a computerized system, called Modessa, to support engineers. A sample window from this program is shown in Fig. 7.17. This window supports an engineer developing a system to create and move a layer of boxes of ice cream bars prior to putting them into a larger box for shipment. The concepts for each function are ones that have been used in previous assembly line products developed at Unilever. Selecting an icon such as "form closed," for example, will yield information on previous uses of this type of concept in fulfilling the function "grip layer."

7.7 LOGICAL METHODS FOR CONCEPT GENERATION

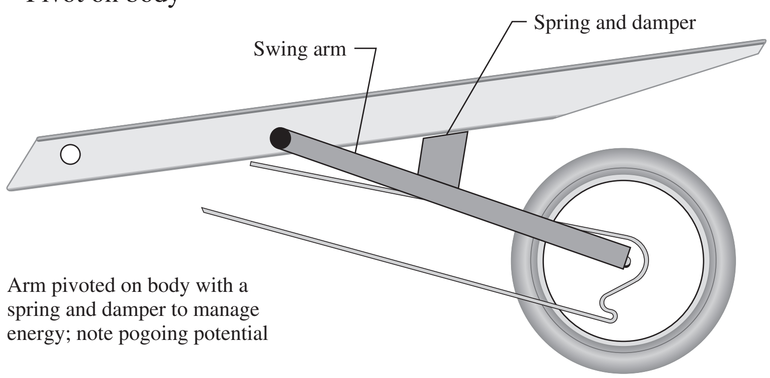
In the 1990s, two logical methods for developing concepts evolved. Actually, the first of these, TRIZ, developed in the Soviet Union beginning in the 1950s and is based on patterns found in patented ideas. Even though well known behind the Iron Curtain, TRIZ was only introduced to the Western world with the opening of communication between East and West. TRIZ is a complex collection of methods that takes extensive study. References to it are in the sources in Section 7.10. Some of the basics are introduced in Section 7.7.1.

The second of these methods, axiomatic design, evolved at MIT and is based on academic theory of how a product should be developed. It is the first such theory that has gained much popularity. It too will only be introduced; see Section 7.7.2.

S1 Pivot on crank



S2 Pivot on body



S3 Truss

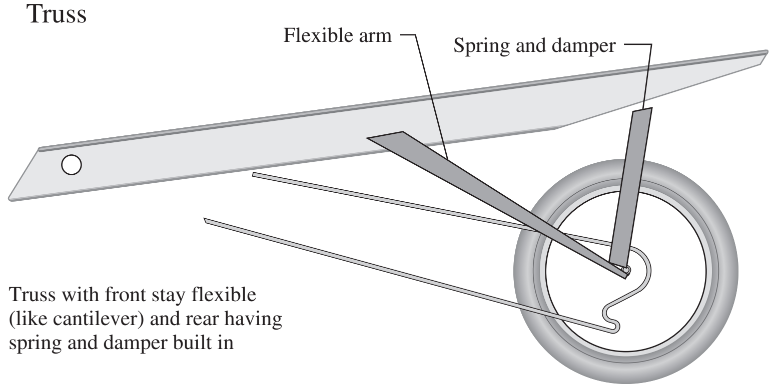
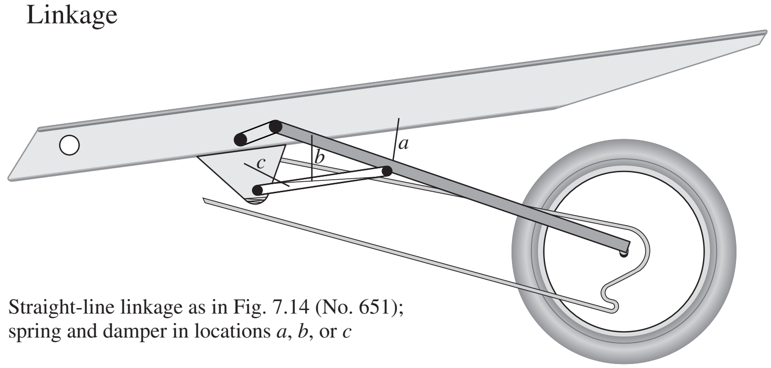


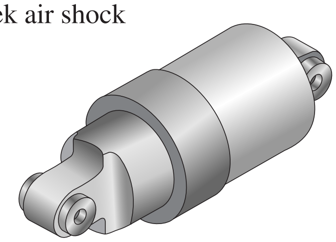
Figure 7.16 Concepts for suspension system.

S4 Linkage



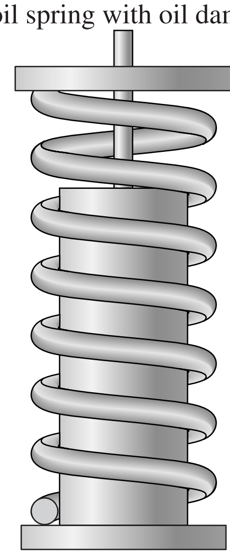
Straight-line linkage as in Fig. 7.14 (No. 651); spring and damper in locations *a*, *b*, or *c*

E1 Stock Cane Creek air shock



Cane Creek uses compressed air for the spring and different sized orifii for different compression and extension damping.

E2 Steel coil spring with oil damper



Available from a number of manufacturers and the most common type of spring/dampers in the bike industry

E3 Elastomeric spring with internal damping. This is generally a polyurethane material much like a rubber baby buggy bumper (see Fig. 8.3).

Figure 7.16 (*Continued*)

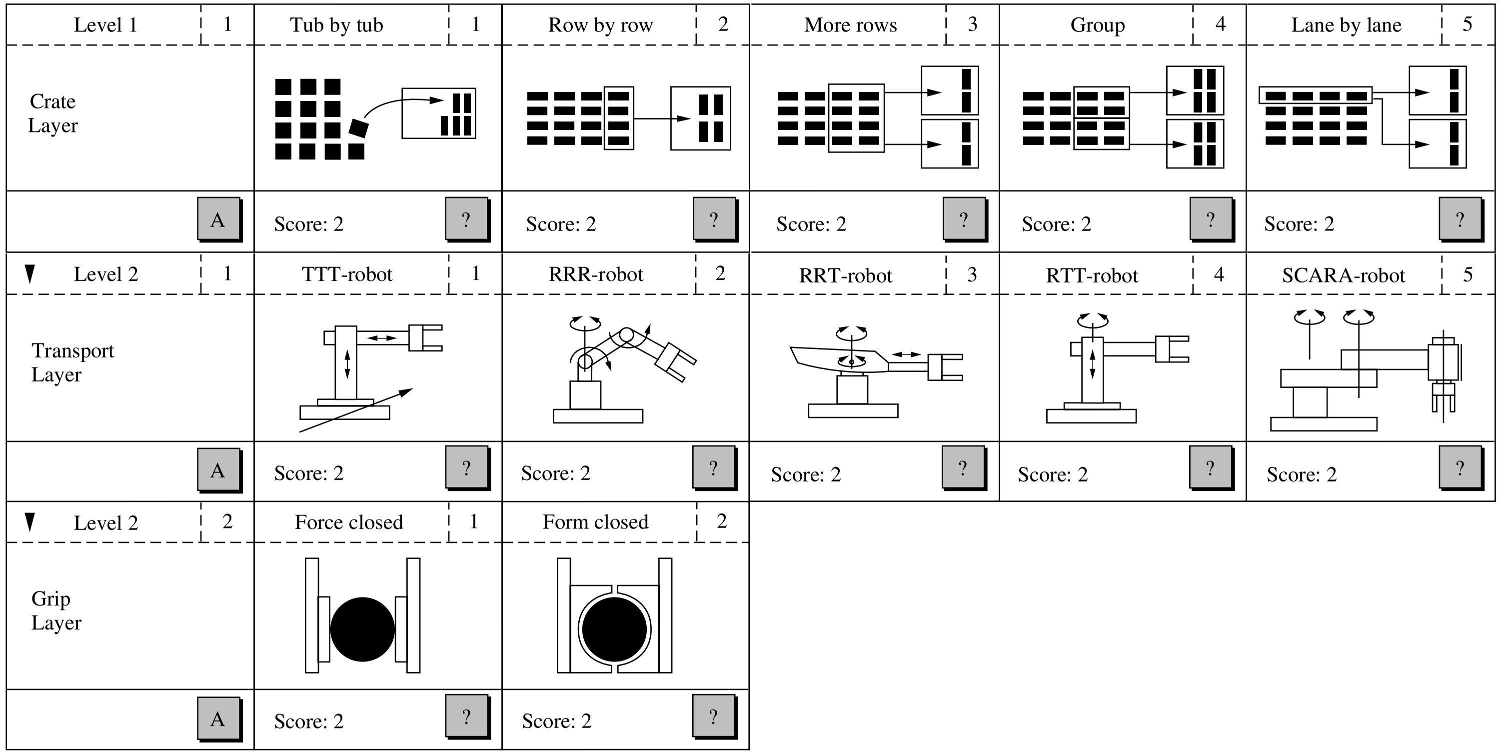


Figure 7.17 Example of a morphology.

7.7.1 The Theory of Inventive Machines, TRIZ

TRIZ (pronounced "trees") is the acronym for the Russian phrase "The Theory of Inventive Machines." TRIZ is based on the idea that many of the problems that engineers face contain elements that *have already been solved,* often in a *completely different industry,* for a totally *unrelated situation,* that uses an entirely *different technology* to solve the problem. The theory is that with TRIZ we can *systematically innovate;* we don't have to wait for an "inspiration" or use the trial and error common to the other methods presented earlier. Practitioners of TRIZ have a very high rate of developing new, patentable ideas. To best understand TRIZ, its history is important.

This method was developed by Genrikh (or Henry) Altshuller, a mechanical engineer, inventor, and Soviet Navy patent investigator. After World War II Altshuller was tasked by the Russian government to study worldwide patents to look for strategic technologies the Soviet Union should know about. He noticed that some of the same principles were used over and over again by totally different industries, often separated by many years, to solve similar problems.

Altshuller conceived of the idea that inventions could be organized, and generalized by function rather than the traditional indexing system discussed in Section 7.2.3. From his findings Altshuller began to develop an extensive "knowledge base," which includes numerous physical, chemical, and geometric effects along with many engineering principles, phenomena, and patterns of evolution. Altshuller wrote a letter to Stalin describing his new approach to improve the rail system along with products the U.S.S.R. produced. The Communist system at the time didn't value creative, free thinking. His ideas were scorned as insulting, individualistic, and elitist, and as a result of this letter, he was imprisoned in 1948 for these capitalist and "insulting" ideas. He was not released until 1954, after Stalin's death. Since the 1950s, he has published numerous books and technical articles and has taught TRIZ to thousands of students in the former Soviet Union.

Altshuller's initial research in the late 1940s was conducted on 400,000 patents. Today the patent database has been extended to include over 2.5 million patents. This data has led to many TRIZ methods. Only part of the most basic one will be described here. This method makes use of *contradictions* and *inventive principles*.

Contradictions are engineering "trade-offs." A contradiction occurs when something gets better, forcing something else to get worse. This means that the ability to fulfill the target for one requirement adversely affects the ability to fulfill another. Some examples are

- The suspension absorbs big bumps (good) but is too stiff to absorb the small bumps caused by road roughness (bad).
- The product gets stronger (good) but the weight increases (bad).
- An automobile airbag should deploy very fast, to protect the occupant (good), but the faster it deploys, the more likely it is to injure somebody (bad).

Using the TRIZ method, the goal is to find the major contradiction that is making the problem hard to solve. Then, use TRIZ's 40 inventive principles, to generate ideas for overcoming the contradiction.[1] The inventive principles were found by Altshuller when researching patents from many different fields of engineering and reducing each to the basic principle used. He found that there are 40 inventive principles underlying all patents. These are proposed "solution pathways" or methods of dealing with or eliminating engineering contradictions between parameters. The entire list of principles is included in Appendix E.

To see how this works, consider the first contradiction in the list on page 170, "The suspension absorbs big bumps (good) but is too stiff to absorb the small bumps caused by road roughness (bad)." Reviewing the list of 40 inventive principles these three ideas were generated. Each inventive principle is listed as a title and clarifying statements followed by, the idea generated.

Principle 1. **Segmentation**

a. Divide an object into independent parts
b. Make an object sectional
c. Increase degree of an object's segmentation

This leads to the idea of having two shock absorbers in series, the soft one takes small bumps and, when it is fully compressed, the stiffer one takes the big bumps. In fact, this two-stage action is used in many shock absorbers.

Principle 10. **Prior action**

a. Carry out the required action in advance in full, or at least in part
b. Arrange objects so they can go into action without time loss waiting for action

This leads to the idea of an active suspension, one where the motion is sensed and some form of control system anticipates what is going to happen next to control the suspension stiffness and damping. Active suspensions on bicycles began to appear commercially in the late 1990s.

Principle 17. **Moving to a new dimension**

a. Remove problems in moving an object in a line by two-dimensional movement (along a plane)
b.–d. Others are not important here

This leads to the idea of using a linkage to get a more complex motion than what can be obtained with a simple swing arm. Linkages are used on most high-end mountain bikes.

[1]Here, the method has been greatly shortened. In traditional TRIZ practice the contradictions are used with a large table to find which inventive principles might best be used. The table is too large for inclusion here and simply exploring the 40 principles is not much more time consuming and is more fun than using the table.

There are many other ideas to be discovered by working through the inventive principles and other TRIZ techniques (see Section 7.10 for TRIZ information sources).

7.7.2 Axiomatic Design

Axiomatic design was developed by Professor Nam Suh of MIT in an effort to make the design process logical. This section provides a very brief introduction to the method. Details can be found in the sources given in Section 7.10. Axiomatic design is based on two axioms that were developed in the 1970s and more than 30 corollaries and theorems that support these axioms. Here we will discuss only the axioms.

Axiomatic design is based on the relationships between four design domains: customer, function, physical, and process. The customer needs (CNs) should give rise to functional requirements (FRs), as in the QFD method in Chap. 6. A function represented by the functional requirements is fulfilled by the interaction of physical elements in the product. These physical elements are characterized by design parameters (DPs). Typical design parameters are dimensions and other geometric properties, and physical properties such as density and yield strength. We will begin to worry about these in detail in Chaps. 10–12. Finally, process variables (PVs) relate elements of the manufacturing process that affect the design parameters. If all the relationships among these four types of variables are known, then each PV's effect on each CN should be identifiable. The focus of the design axioms is the relationship between the FRs and the DPs, the functions and the description of the form that fulfills the function.

The first axiom is called the Independence Axiom. It states, "Maintain the independence of functional requirements." What this means is that, ideally a change in a specific design parameter should have an effect only on a single function. This is an interesting design philosophy that ties in nicely with the morphological method discussed in Section 7.6. There, many ideas were developed for each function and then combined to develop a complete configuration. The morphology works perfectly if the functions are all independent, but as discussed, they usually are not. In axiomatic design the amount of coupling between functions can be analyzed and used to guide the development of the product.

The limitations of this axiom can be seen by considering the handlebar of a bicycle. As discussed in Chap. 2, this single part plays a role in the steering, balancing, braking, weight support and gear shifting on most bikes. It does not provide for any of these functions by itself and nearly every design parameter of it (e.g., its length, shape, stiffness, etc.) contributes to each of the functions. This limitation will be further addressed in Section 12.5.1. This counterexample is not intended to say that the first axiom should be ignored, as it does give a basis for a rich theory of design.

The second axiom is, "Minimize the information content of the design." Although this statement has mathematical meaning not developed here, the core of the axiom is that the simplest design has the highest probability of success and is the best alternative. This thought will prove to be important in concept evaluation and will be further developed in Chap. 8.

7.8 COMMUNICATION DURING CONCEPT GENERATION

The techniques outlined in this chapter have focused on generating potential concepts. In performing these techniques, these documents are produced to support communication to others and archiving the design process: functional decomposition diagrams, literature and patent search results, function-concept mapping, and sketches of overall concepts.

7.9 SUMMARY

- The functional decomposition of existing products is the best method to understanding them.
- The patent literature is a good source for ideas.
- Functional decomposition encourages breaking down the needed function of a device as finely as possible, with as few assumptions about the form as possible.
- Listing concepts for each function helps generate ideas; this list is often called a *morphology.*
- Sources for conceptual ideas come primarily from the designer's own expertise; this expertise can be enhanced through many basic and logical methods.

7.10 SOURCES

Sources for Patent Searches

http://www.uspto.gov/patft/index.html. The website for the U.S. Patent and Trademark Office. Easy to search but only has complete information on recent patents.

http://www.delphion.com/home. IBM originally developed this web site. Also, easy to search for recent patents.

http://gb.espacenet.com/. Source for European and other foreign patents. Supported by the European Patent Organization, EPO.

Artobolevsky, I. I.: *Mechanisms in Modern Engineering Design,* MIR Publishers, Moscow, 1975. This five-volume set of books is a good source for literally thousands of different mechanisms, many indexed by function.

Chironis, N. P.: *Machine Devices and Instrumentation,* McGraw-Hill, New York, 1966. Similar to Greenwood's *Product Engineering Design Manual.*

Chironis, N. P.: *Mechanism, Linkages and Mechanical Controls,* McGraw-Hill, New York, 1965. Similar to the last entry.

Damon, A., H. W. Stoudt, and R. A. McFarland: *The Human Body in Equipment Design,* Harvard University Press, Cambridge, Mass., 1966. This book has a broad range of anthropometric and biomechanical tables.

Design News, Cahners Publishing, Boston. Similar to *Machine Design.* **http://www.manufacturing.net/magazine/dn/.**

Edwards, B.: *Drawing on the Right Side of the Brain,* Tarcher, Los Angeles, 1982. Although not oriented specifically toward mechanical objects, this is the best book available for learning how to sketch.

Greenwood, D. C.: *Product Engineering Design Manual,* Krieger, Malabar, Fla., 1982. A compendium of concepts for the design of many common items, loosely organized by function.

Greenwood, D. C.: *Engineering Data for Product Design,* McGraw-Hill, New York, 1961. Similar to the above.

Human Engineering Design Criteria for Military Systems, Equipment, and Facilities, MIL-STD 1472, U.S. Government Printing Office, Washington, D.C. This standard contains 400 pages of human factors information.

Machine Design, Penton Publishing, Cleveland, Ohio. One of the best mechanical design magazines published, it contains a mix of conceptual and product ideas along with technical articles. It is published twice a month. **www.machinedesign.com.**

Norman, D.: *The Psychology of Everyday Things,* Basic Books, New York, 1988. This book is light reading focused on guidance for designing good human interfaces.

Plastics Design Forum, Advanstar Communications Inc., Cleveland, Ohio. A monthly magazine for designers of plastic products and components.

Product Design and Development, Chilton, Radnor, Pa. Another good design trade journal. **www.pddnet.com.**

Thomas Register of American Manufacturers, Thomas Publishing, Detroit, Mich. This 23-volume set is an index of manufacturers and is published annually. Best used on the Web at **www.thomasregister.com.**

URL for TRIZ **www.triz-journal.com.** A good source for an introduction to TRIZ.

URL for axiomatic design **www.axiomaticdesign.com.**

7.11 EXERCISES

7.1 For the original design problem (Exercise 4.1), develop a functional model by

- **a.** Stating the overall function.
- **b.** Decomposing the overall function into subfunctions. If assumptions are needed to refine this below the first level, state the assumptions. Are there alternative decompositions that should be considered?
- **c.** Identifying all the objects (nouns) used and defending their inclusion in the functional model.

7.2 For the redesign problem (Exercise 4.2), apply items a–c from Exercise 1 and also study the existing device(s) to establish answers to these questions.

- **a.** Which subfunction(s) must remain unchanged during redesign?
- **b.** Which subfunctions (if any) must be changed to meet new requirements?
- **c.** Which subfunctions may cease to exist?

7.3 For the functional decomposition developed in Exercise 1,

- **a.** Develop a morphology as in Fig. 7.17 to aid in generating concepts.
- **b.** Combine concepts to develop at least 10 complete conceptual designs.

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7.4 For the redesign problem functions that have changed in Exercise 2,

a. Generate a morphology of new concepts as in Fig. 7.17.

b. Combine concepts to develop at least five complete conceptual designs.

7.5 Find at least five patents that are similar to an idea that you have for

a. The original design problem begun in Exercise 4.1.

b. The redesign problem begun in Exercise 4.2.

c. A perpetual motion machine. In recent times the patent office has refused to consider such devices. However, the older patent literature has many machines that violate the basic energy conservation laws.

7.6 Use brainstorming to develop at least 25 ideas for

a. A way to fasten together loose sheets of paper.

b. A device to keep water off a mountain-bike rider.

c. A way to convert human energy to power a boat.

d. A method to teach the design process.

7.7 Use brainwriting to develop at least 25 ideas for

a. A device to leap tall buildings in a single bound.

b. A way to fasten a gear to a shaft and transmit 500 watts.