# Engineering design

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**Engineering is concerned with the creation of systems, devices, and processes useful to, and sought by, society. The process by which these goals are achieved is engineering design.**

The process can be characterized as a sequence of events as suggested in **Fig. 1**, with the recognition that no final, universally accepted description of so complex an intellectual and physical exercise, applicable to an enormously broad spectrum of products and processes, is possible. The process may be said to commence upon the recognition of, or the expression of, the need to satisfy some human want or desire, the "goal," which might range from the detection and destruction of incoming ballistic missiles to a minor kitchen appliance or fastener.

## Concept formulation

Since the human aspiration is usually couched in nonspecific terms as a sought-for goal, the first obligation of the engineer is to develop more detailed quantitative information which defines the task to be accomplished in order to satisfy the goal, labeled on Fig. 1 as task specification. At this juncture the scope of the problem is defined, and the need for pertinent information is established. The source of the original request is questioned to establish the correspondence between the developing specifications and the initial definition of the goal.

But to know that a need exists and to have started on the task of qualitatively and quantitatively defining its substance and bounds should not be confused with the generation of ideas for possible solutions to the problem. This creative stage is called the concept formulation. When great strides in engineering are made, this represents ingenious, innovative, inventive activity; but even in more pedestrian situations where rational and orderly approaches are possible, the conceptual stage is always present.

The concept does not represent a solution, but only an idea for a solution. It can only be described in broad, qualitative, frequently graphical terms. Concepts for possible solutions to engineering challenges arise initially as mental images which are recorded first as sketches or notes and then successively tested, refined, organized, and ultimately documented by using standardized formats.

At this point it is important to note that the necessarily two-dimensional description of Fig. 1 and this sequential textural description should not be construed as an implication that the goal, task specification, and concept always appear in a simple, sequential temporal order. In fact, a central characteristic of the design process is the

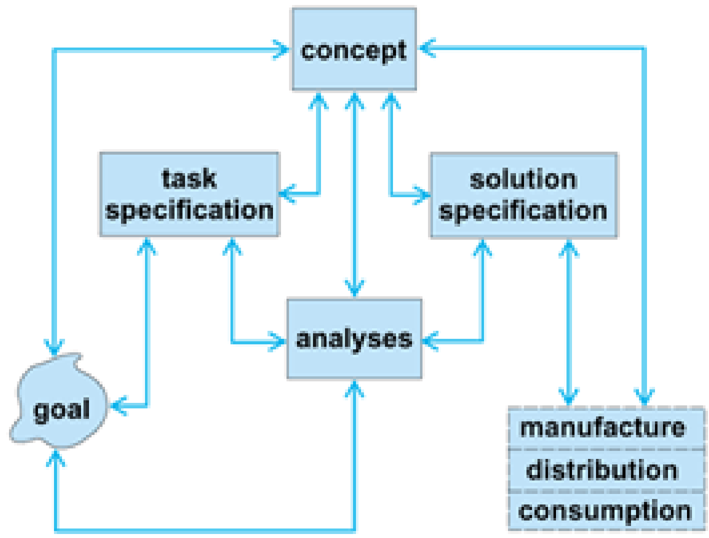


**Fig. 1** **Engineering design process.**

unpredictable emergence of, and iterations between, the various steps. This stochastic character can be suggested by drawing two-way connections between the various steps. For example, the definition of a task and emergence of a concept might precipitate restudy and possible alteration of the original goal. Consider the not infrequent experience of the serendipitous emergence of a new and interesting concept, and then subsequent search for a goal (application or market) to which to apply the idea.

Concepts are accompanied and followed by, sometimes preceded by, acts of evaluation, judgment, and decision. It is in fact this testing of ideas against physical, economic, and functional reality that epitomizes engineering's bridge between the art of innovation and science. The process of analysis is sometimes intuitive and qualitative, but it is often mathematical, quantitative, careful, and precise. The iteration of concept and analysis invariably gives rise to a focusing and sharpening, possibly a complete change, of the concept. Frequently, in light of the analyses conducted, what can or might be accomplished is illuminated and task specifications changed. Even goals may be altered. That which was sought may be beyond accomplishment, or perhaps solutions more sophisticated or more useful than initially undertaken may prove achievable.

Production considerations can have a profound influence on the design process, especially when high-volume manufacture is anticipated. Evolutionary products manufactured in large numbers, such as the automobile, are tailored to conform to existing production equipment and techniques such as assembly procedures, interchangeability, scheduling, and quality control. Techniques such as those associated with space exploration, where volume production is not a central concern, factor into the engineering design process in a very different fashion.

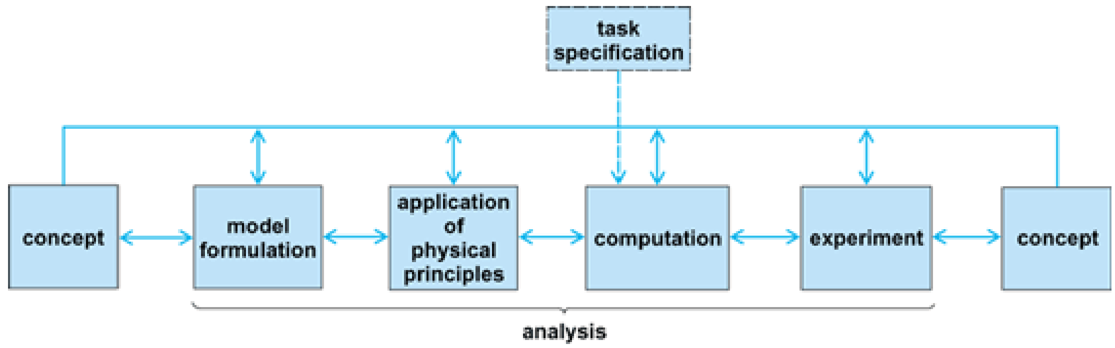


**Fig. 2** **Role of analysis in concept formulation.**

Similarly, the design process must anticipate and integrate provisions for distribution, maintenance, and ultimate replacement of products. Well-conceived and executed engineering design will encompass the entire product cycle from definition and conception through realization and demise and will give due consideration to all aspects.

The iterations of analysis and concept and considerations of manufacture develop information which defines a sequence of progressively specific solutions. In final form the solution specification consists of all drawings, materials and parts lists, manufacturing information, and so on necessary for construction of the device, system, or process.

It is important to note that, while the culmination of a particular engineering design process defines but one solution, inspection of the process during its evolution indicates a complex series of discrete partial, temporary, interim solutions which are compared one with another, and out of this comparison emerges the final compromise solution. The limitations on this scrutiny of alternative approaches are the practical contingencies of time and personnel, or other ways of measuring resources. When these assets reach their budgetary limits, the most satisfactory solution is accepted; however, in as dynamic a field as engineering the final design is not necessarily an ultimate or optimal best.

Figure 1 provides a broad overview of the engineering design process. Some expansion of the interaction between conceptualization and analysis is warranted, as shown in **Fig. 2**. On the left- and right-hand sides is concept; everything between is characterized as analysis.

Any physical entity, existing or hypothesized, of any degree of complexity cannot be analyzed in its entirety because of inadequate knowledge of the relevant physical laws, or inadequate time or facilities for the required computation, or a combination of these shortcomings. For these reasons, plus its inherent initial vagueness, the concept cannot be analyzed completely. Instead, simplified models are deliberately and precisely defined by applying established physical principles and laws to describe the model via mathematical equations. By using numerical values from the task specifications for parameters, the requisite computational tasks are performed.

In many engineering situations, particularly those where there is no body of experience with similar geometries, materials, and so on, the model from which the analysis is derived cannot be confidently assumed to characterize completely all significant attributes of the ultimate physical system. In some cases certain relevant processes are not completely understood; other times adequate resources to perform all pertinent analyses are not available. Thus, recourse to experiment is necessary. Since nature is the final arbiter of all physical proposals, however analyzed, experiment or test always precedes final acceptance of any proposal.

As previously suggested for Fig. 1, where all possible interconnections occurred between various stages and the process underwent a dynamic evolution, complex interactions occur also in the concept-analysis loop of Fig. 2. For example, the model is defined, based on the concept recognizing existing physical knowledge about included processes and phenomena, and the effort that will be involved in the reduction of the resulting mathematical equations into quantitative results is anticipated. For example, an initial model might be a greatly simplified, or perhaps oversimplified, characterization of the concept in order that the computational results might quickly identify the utility of the idea or its ranges of applicability. Subsequently, more refined models of aspects of the concept of greater subtlety might be subject to scrutiny.

Where the function of the part is critical or the physical knowledge is inadequate, the engineer might, in fact, eliminate computation and move rapidly to experiment, perhaps on an analog or scaled-down version of important attributes of the concept.

## Hierarchy of design

An adequate description of the engineering design process must have both general validity and applicability to a wide variety of engineering situations: tasks simple or complex, small- or large-scale, short-range or far-reaching. That is to say, there is a hierarchy of engineering design situations.

Systems engineering occupies one end of the spectrum. The typical goal is very broad, general, and ambitious, and concepts are concerned with the interrelationships of a variety of subsystems or components which, when taken together, make up the system to accomplish the desired goal. *See also:* SYSTEMS ENGINEERING.

At a subsidiary level of the design problem hierarchy, the same engineering design process applies to creation of a device which might be one component of the overall system. And at the most detailed end of this hierarchy the same process diagrams the engineering design of a single element of a component. Obviously, as the engineering design process is applied to create one of these several elements, components, or systems, different phases of the process come into play in different ways and to different degrees, depending upon the particular problem.

## Time–source dynamics

Another dimension of the dynamics of the engineering design process is the elapse of time and expenditure of worker effort in the evolution of an engineering design project. **Figure 3** plots time as the abscissa and resources

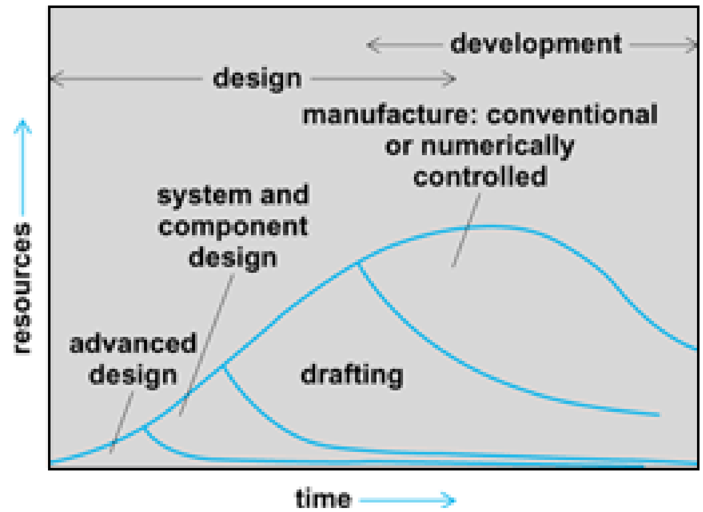


**Fig. 3** **Elapse of time and resources in an engineering design project showing various stages in sequence.**

(worker-hour or dollars) as the ordinate. The various stages of the engineering design process are set out in time sequence from left to right.

Goal refinement, task specification, and first-order concept and analyses iterations are conducted by one to a few engineers in the early stages to establish the feasibility of the idea and to block out possible approaches. This is called the advanced design stage.

As the design concept becomes more specific and substantive, more and more engineers, technicians, and draftsmen become involved in the project. For example, in the case of a modern aircraft probably fewer than a dozen extremely talented engineers carry through the early feasibility and configuration studies, while at a later stage hundreds of engineers, drafters, expediters, and coordinating personnel are involved. This deployment aspect of the design process cannot be overemphasized. In projects of significant size, the problem of coordinating and integrating the efforts of the many participants of different talents and skills becomes itself a major consideration. While some of the coordination involves judgment and decisions, much of this coordination is purely clerical and some involves prosaic application of standard reference material. *See also:* PERT.

Ultimately the process culminates in the solution specification—manufacturing drawings and specifications, parts lists, and so on. Where automated manufacturing techniques are warranted, the efforts of computer programmers are devoted to the transformation of graphic and numeric manufacturing information into a form decipherable by computers and machine-tool directors. Ultimately, the physical parts are realized through the manufacturing process.

The efforts of this large group of people demand a high level of coordination and integration if each of the thousands of separate parts of the aircraft are to satisfy its function, be compatible with one another, and be

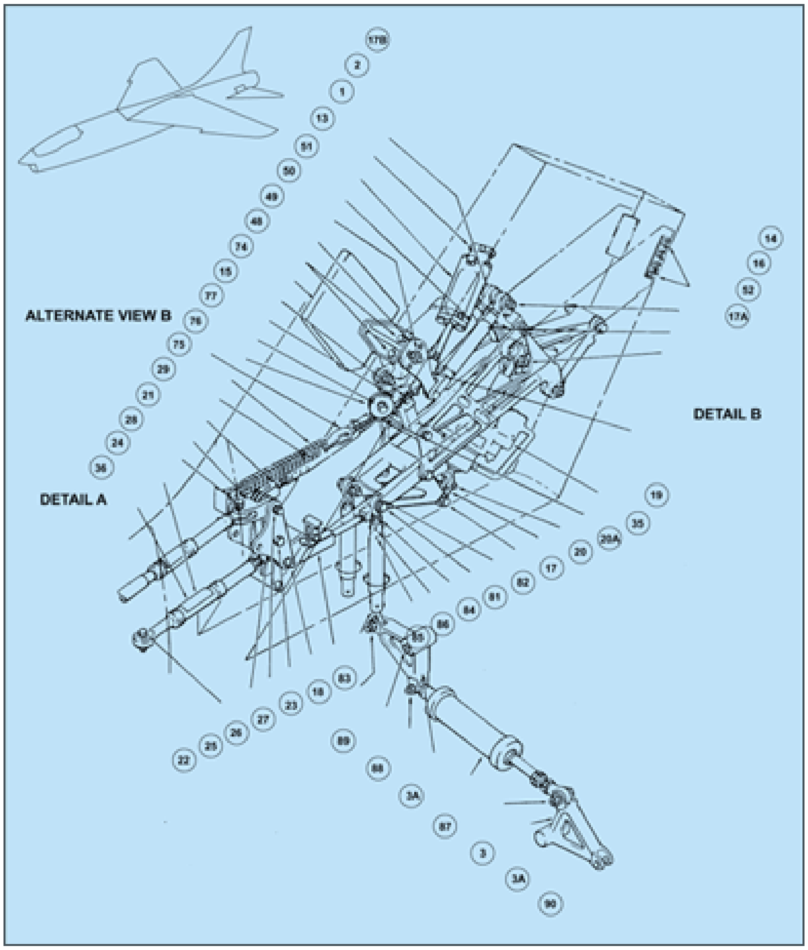


**Fig. 4** **One of the 10,000 sheets involved in the design engineering of a military aircraft. Numbers refer to the various components and are an indication of the tremendous bookkeeping involved in a project of this type.**

adequately strong and yet of minimum weight and volume. **Figure 4** suggests a few of the individual elements which must undergo design, one sheet of a 2-ft-high (0.67-m) pile of similar diagrams for a typical jet aircraft. The parts shown represent only a few of the better than 10,000 parts that make up the typical jet aircraft.

## Use of the computer in design

Reference to the role of analysis in Fig. 1 and to computation in Fig. 2 highlights the ever increasing use of the computer, both analog and digital, in the engineering design process. As a high-powered successor to the slide rule and desk calculator, the computer is used routinely for much of the calculation, computation, and data reduction which constitute a major activity in design. Where repetitive series of calculations are carried out, programs are prepared to relegate to the computer more and more of the responsibility for analysis. Where economically justified, the overall engineering design process for a product is mechanized via computer programming. For example, **Fig. 5** describes the flow chart of a branching computer program which, given vital

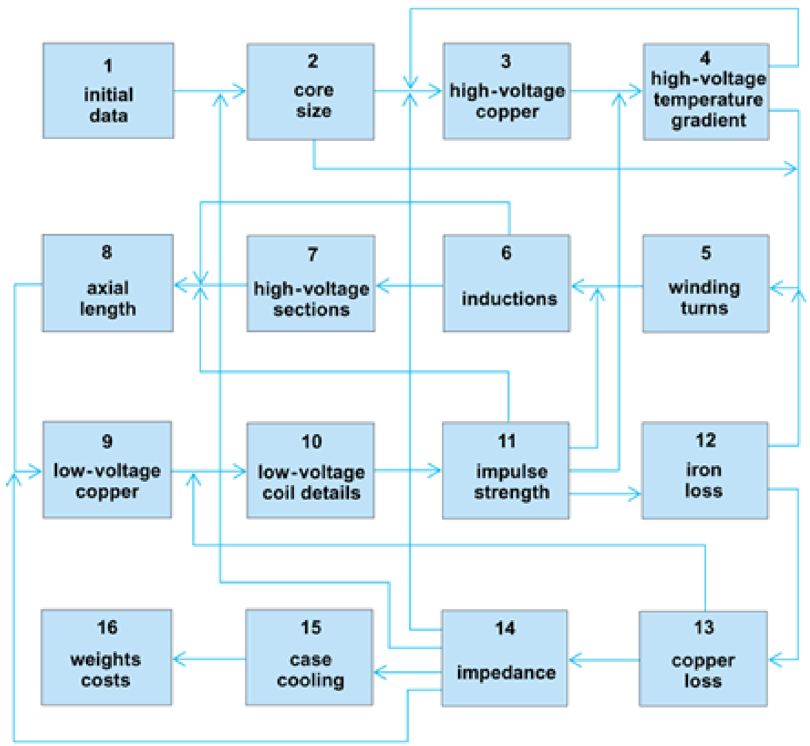


**Fig. 5** **Flow chart of a computer program.**

data on the requirements of an electrical power transformer, carries out the design automatically. In the process the program, having made assumptions on core size and copper windings, calculates temperature gradient, impedance, and so on; checks these against preprogrammed constraints; and optimizes its choices considering, among other things, the current cost of copper. **Figure 6** illustrates typical iterations of the computer design as it "homes" in on the lowest weight and cost design satisfying the initial data and the internal constraints. *See also:* COMPUTER; COMPUTER PROGRAMMING.

The speed, memory, and accuracy of the computer to iteratively calculate, store, sort, collate, and tabulate have greatly enhanced its use in design and encouraged the study, on their own merits, of the processes and subprocesses in the design process. These include optimization or sensitivity analysis, reliability analysis, and simulation as well as design theory. *See also:* DIGITAL COMPUTER.

Optimization analysis, given a model of the design and using linear and nonlinear programming, determines the best values of the parameters consistent with stated criteria and further studies the effects of variations in the values of the parameters. *See also:* OPTIMIZATION.

Reliability is a special case of optimization where the emphasis is to choose or evaluate a system so as to maximize its probability of successful operation, for example, the reliability of electronics. *See also:* CIRCUIT (ELECTRONICS); RELIABILITY, AVAILABILITY, AND MAINTAINABILITY.

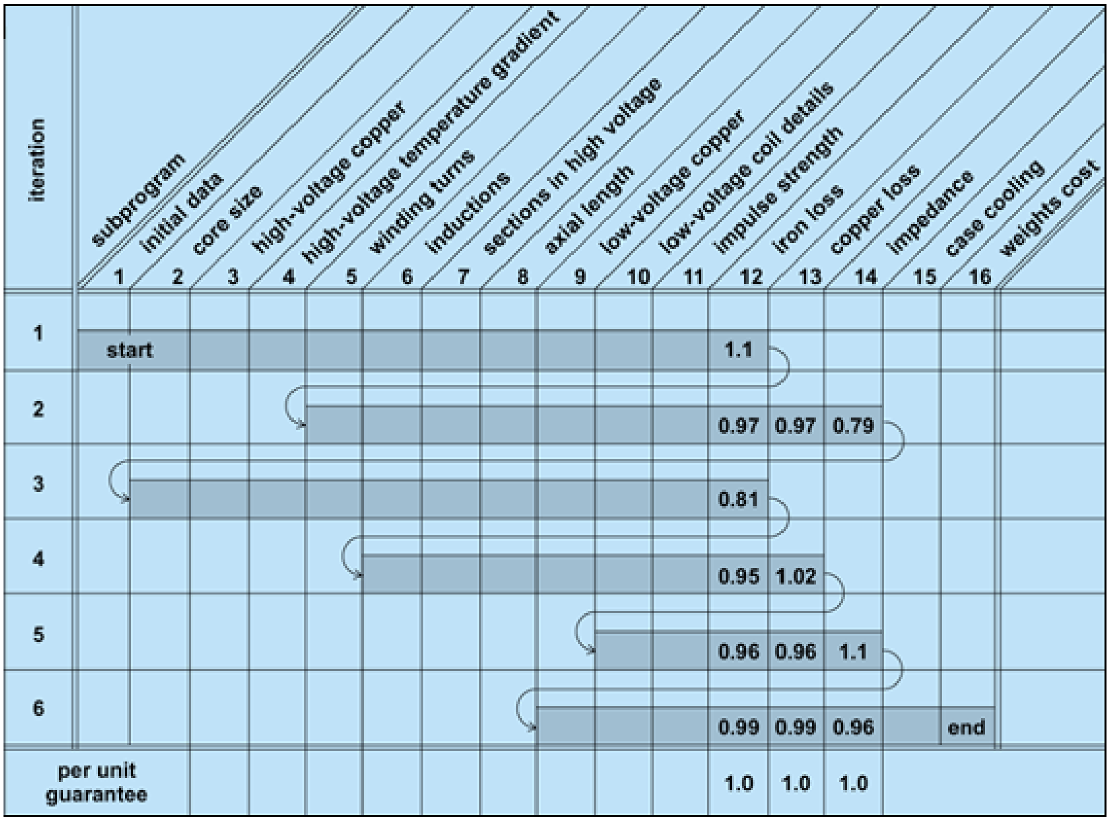


**Fig. 6** **Iterations of the computer program shown by the flow chart in Fig. 7.**

Simulation as of dynamic systems, is mathematical modeling to study the response of a design to various inputs and disturbances. The analog computer was formerly widely used for simulation through its physical modeling of the mathematic analytical relationships of the proposed design. The digital computer's use of numerical data adapts it more readily to nonlinear or probabilistic situations by using random or Monte Carlo techniques, as well as to those situations requiring higher accuracy. *See also:* ANALOG COMPUTER; MONTE CARLO METHOD; SIMULATION.

Decision theory deals with the general question of how to choose between a great number of alternatives according to established criteria. It proposes models of the decision process as well as defining techniques, that is, programs or algorithms, of calculation by which to make choices. *See also:* DECISION THEORY.

Artificial intelligence or its less pretentious subdiscipline, expert systems, strives to identify and codify human thought processes and produce computer algorithms and programs for automatic problem solving, including facets of the design process. *See also:* ALGORITHM; ARTIFICIAL INTELLIGENCE; EXPERT SYSTEMS.

Although each of these techniques represents either a gross oversimplification or but a part of the overall design process of Fig. 1, their study and application are useful. Even where not strictly applicable, the awareness of a model of a process enhances its qualitative evaluation by providing a guide to action. The utility and comprehensiveness of these techniques are already advancing and will mature rapidly, largely because of the ability of the high-speed digital computer to carry out evaluations which heretofore were impractical. Finally, the record-keeping capacity of the computer makes possible the recording and reutilization of past action. This integration of prior results into new endeavors represents a “mechanization of experience.”

## Computer utilization

Notwithstanding the present contribution and unlimited promise of the computer to the design process, there are certain limitations. In reflecting on the model of the engineering design process and especially on the interaction between concept and analysis, it is useful to consider the nature of the activities involved. Concepts, or really new ideas, usually do not come about as a result of any ponderous, systematic, organized effort; rather they appear in an undisciplined, creative, spectacular fashion. The short-duration exultation of concept creation is then followed by usually very much longer, more regular, systematic periods of analysis. The typical use of a computer does not lend itself to the kind of person-analysis interaction implicit in the engineering design process and essential to its successful negotiation. Usually, the solution process for a piece of work must first be well thought out and known in the most intricate detail; only then can the user write a program to describe to the computer the sequence of steps necessary. But when the nature of the problem is only vaguely grasped and much learning has to be done, the computer may not be as helpful as pencil and paper.

The reason is that in the thinking process one needs to advance in steps and to test these steps frequently. While the steps may be large, as in the first gross examination of an idea, or small, as in an exercise of refinement, these tests need not be elaborate or even precise. What is wanted first is only a qualitative result or perhaps a quantitative result of only moderate precision, a confirmation or a denial of tentative guess work.

By conventional computer programming, it is virtually impossible to obtain quick answers to small discrete problems, even though the computer can work very rapidly. To solve a problem, the user must first prepare a program, a detailed ritual of calculations and comparisons of quantities for the computer to carry out. It is hoped that data so processed will yield the solution.

If there is a mistake in the program, the computer either will detect the mistake and refuse to waste time by trying to run the program, or if the mistake is more subtle, perhaps an error in principle, will go ahead and compute a mass of meaningless nonsense. This dependence on programming, waiting, and error finding and correcting frustrates the formulation and testing of concepts essential to a creative effort.

Another point is that the creative process is, virtually by definition, unpredictable. The sequence of the steps is never known at the beginning. If it were, the whole process could be accomplished by the computer since the information prerequisite to the computer program would be available. Indeed, the creative process is the process of learning how to accomplish the desired result.

Clearly what is needed if the computer is to be of greater use in the creative process is a more intimate and continuous interchange between engineer and machine. This interchange must be of such a nature that all forms of thought congenial to humans, whether verbal, symbolic, numerical, or graphical, are also understood and acted upon by the machine in ways appropriate to the user's purpose. In reflecting on this human-machine symbiosis with the goal of designing a system with which to design, it is useful to identify the special attributes of each partner. *See also:* HUMAN-MACHINE SYSTEMS.

The speed of the computer is prodigious when measured against any term of reference and especially so when measured against the appropriate one, the human mind. A computer performs millions of arithmetic or logical operations per second. This rate outstrips by many orders of magnitude the human neurological responses to premeditated thoughts.

The machine's memory is likewise extraordinary, although restricted to an extremely narrow but nonetheless useful class of memory impression. It can store binary numbers of 32 digits and recall them unerringly at microsecond speeds, while the human memory system is very much slower and not nearly so reliable. Of course, in contrast, the human memory encompasses an indescribable universe of types and kinds, far beyond the range of a computer. The reliability routinely exercised by the computer is unattainable by people. Once properly instructed, the computer executes its routines faithfully, untiringly, yielding to no boredom or carelessness, and introducing no humanlike errors. *See also:* COMPUTER STORAGE TECHNOLOGY.

Counterposed against the computer's assets stands an open-ended list of human attributes. In terms of the engineering design process, these human characteristics would include reflection on, and evaluation of, the social, esthetic, and economic aspects of the original goals; the formulation of previously unforeseen and unanticipated questions at many points in the investigation; an unflagging curiosity about the way things are done and about the way they are proposed to be done; the flexibility of mind to shift from one approach to another, to sort out the significant from a great mass of information and misinformation on the basis of very few discernible criteria; powers of mental association which can detect, correlate, and amplify useful relevancies between bodies of normally disparate information; the devising and structuring of new and unusual approaches; the willingness, ability, and intellectual integrity to make decisions, frequently on the basis of inadequate data; the ability to recognize that the job must get on and some decisions must be made rapidly, though the right to reverse decisions whenever facts so indicate is reserved; exercise of judgment based on prior experience in making decisions; and finally the desire and willingness to develop such adjudicative ability through experience. While the computer demonstrates the capability of encroaching upon some of these attributes, but only to the extent that humans thoroughly understand them and can program them, clearly others are forever denied it. *See also:* COMPUTER-AIDED DESIGN AND MANUFACTURING; COMPUTER-AIDED ENGINEERING.

## Time-sharing

Communicating directly with a computer by keyboard with the computer replying immediately on a cathode-ray-tube monitor removes the obstacle to thought caused by waiting hours for a reply. The user has no compunctions about posing smaller problem fragments to the computer, in a way more consonant with the small steps of the creative process. The results are immediately available, and the course of further action is guided more precisely.

Such intimate “conversations” with a computer are scarcely economically feasible when only one person uses the computer at a time because, measured against the speed of a computer, human beings are intolerably slow. A person likes to ponder a problem and often needs time to decide what to try next. Even when a decision is reached, the instruction to the computer takes several seconds to type on the keyboard, and during even this short time the computer could perform hundreds of thousands to millions of calculations were it free to do so. It is logical to arrange to have large main-frame computers in conversation with a large number of people, so that when one user is idle the computer can turn to another and answer that question. Should all users be idle at once, the computer can work on some large problem left as a backlog. This type of effective computer utilization is quite routine, and is called time-sharing. On a rough average, if a user is intensely busy for 1 h, the computer can discharge its responsibilities to this particular user in short bursts that total about 3 min. The rest of the time it serves the other users.

The dramatic reductions in cost and increases in power of contemporary minicomputers have expanded their use in time-share environments. The advent of the microprocessor, or computer on a chip, made economic the personal computer where only one keyboard operator can afford to monopolize a whole computer system. The power of such stand-alone systems is as yet still very limited for design application; therefore, microcomputers are currently used, together with their keyboards and graphic displays, as “intelligent” terminals on larger minicomputers or mainframe computers, providing the operator access to the computing power and vast memory of the larger machine. *See also:* MICROCOMPUTER; MICROPROCESSOR.

## Graphical input/output

In many fields of design—notably architecture; design of airplanes, automobiles, and ships; consumer products; in almost all mechanical design and in electronic computer circuit design—the designer works largely in visual terms.

Initially limited to interpreting only binary digits, the digital computer was subsequently organized to understand ordinary numbers and words and combinations thereof via the various programming languages. Then, in the early 1960s Ivan Sutherland established bilateral graphical communication between the human and the digital computer. The essential link between the pictorial cognitive style of the design engineer and the speed, memory, and reliability of the digital computer had been forged, but there was a lag of more than a decade before the availability and economy of adequate main-frames and improved graphic interfaces made computer-aided graphics a practical reality. The computer has become an active partner in the act of drawing, so that it can provide a certain superskill in preparing the drawing once the intentions of the human operator have been made clear. *See also:* COMPUTER GRAPHICS.

## Computer-aided design (CAD)

The engineering design process, as aided by CAD capability, can be suggested via several examples.

Selecting from a task menu presented on a graphics console, a designer, using keyboard and cursor or light-pen, can then draw on the consol and into the computer the elemental parts of a machine; have the computer embody them as solids; assemble, section, and orient them under operator control; and finally document the parts following traditional drafting and specification standards, all electronically. The production engineer, with access to the common data base, can then invoke computer-aided manufacturing (CAM), optimize the machine tool cutter paths, with the coded information transferred to the actual numerically controlled (N/C) machine tool for part fabrication.

Comprehensive CAD systems provide for human-computer interaction in engineering analysis of the evolving design. A recurrent question in the concept-analysis iteration of Fig. 2 is: Will the strength be adequate? This is addressed in CAD, with a computer graphics portrayal of a hypothetical wrench turning a bolt. Using a stress-analysis technique known as the finite element method, the computer automatically superimposes a mesh into the region the engineer identifies as a potentially highly stressed region in the wrench. Then, having been provided the wrench material strength properties and the applied torque, the computer's finite element method program calculates, and the CAD graphics presents, coded in color, the resulting stress distribution. The engineer must then evaluate these data, accept the results, or intervene and alter the geometry, material, acceptable torque, and so on. The essence of the engineering design process has been retained in CAD, but the process has been vastly facilitated and accelerated. More iterations of more alternatives can be explored more rigorously and more rapidly when compared with traditional engineering design. The results are faster and better design and improved productivity. *See also:* FINITE ELEMENT METHOD.

Use of CAD (and CAM) will relegate increasingly to the computer tasks it can be programmed to perform automatically, leaving to the human the exercise of goal definition and setting and judgmental evaluation and decision. In one integrated system, progressive solutions of an automatic part design and analysis are produced by a computer program which, given functional geometrical constraints on a part and its structural strength requirements, automatically iterates geometrical designs and finite-element-method analyses to produce the minimum-mass part which satisfies the constraints.

## Computer effectiveness

The effect of using computers in the design and development stages of a manufacturing process is twofold. First, the costs are greatly reduced because fewer people are involved in the stages, and less time is required to accomplish the tasks. For example, the translation of a designer's sketch of the shape of an airplane fuselage into a full-size, precise, geometrical shape description suitable for manufacturing purposes using traditional methods used to take about 6 months. Conventional, that is, non-CAD, computer methods reduce this time to a few weeks. But the emergent computer techniques will cause a further reduction of this time, perhaps to seconds. The results will be far more accurate than have previously been obtained and will be tailored much more closely to manufacturing requirements.

Second, an important hidden benefit is the greatly increased lead time which a CAD/CAM manufacturer gains over a less computerized competitor; the former can be ready much sooner to begin production. The national military and the commercial aspects of this acceleration are obvious.

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## Bibliography

J. L. Adams, *Conceptual Blockbusting*, 4th ed., 2001

J. A. Collins, H. R. Busby, and G. H. Staab, *Mechanical Design of Machine Elements and Machines*, 2009

G. L. Glegg, *The Design of Design*, 1969

F. H. Jones, *Computer Aided Architecture and Design*, 1994

D. Schodek et al., *Digital Design and Manufacturing: CAD/CAM Applications in Architecture and Design*, 2004

J. E. Shigley and L. D. Mitchell, *Mechanical Engineering Design*, 9th ed., 2010

## Additional Readings

D. M. Buede, *The Engineering Design of Systems: Models and Methods*, 2d ed., John Wiley & Sons, Hoboken, NJ, 2009

R. de Neufville and S. Scholtes, *Flexibility in Engineering Design*, Massachusetts Institute of Technology, Cambridge, UK, 2011

Y. Haik and T. M. M. Shahin, *Engineering Design Process*, 2d ed., Cengage Learning, Stamford, CT, 2011