CHAPTER 1

About Engineering

Identifying a Framework

1.1 A Capsule History

The first documented reference to a term suggestive of the presently conventional meaning of the word *engineer* or *engineering* can be traced to early Roman times when the Latin expression *ingenium* was used to suggest some ingenious attribute of an object or a person. Soon after, this term was specialized to characterize an ingenious device useful for exceptional and important purposes. Eventually, its derivative *ingeniator* was applied to a person possessing an innovative mind and skillful hands in the making of such devices.

Though the Romans may be credited with assigning a label to individuals who were both clever and dexterous in the making of useful devices, they did not invent the practice of making ingenious devices. The primal instinct for innovative artifacts and the skills required in their making, had emerged during the earliest stirrings of the human imagination. Indeed, one may identify a long and systemic progression of such activities as suggested by the following: from prehistoric making of stone tools to the building of ancient pyramids; from medieval construction of cathedrals and fortresses to the intricate crafting of mechanical clocks and moveable-type printing; from isolated discoveries of glass lenses and iron casting to the development of the tower mill and steam power; from automobile assembly plants to modern jet aircraft manufacture, and more recently to deep-space probes and microchips. Throughout this vast range of adaptive progressions, innovative thought and skilled actions in the making of ingenious devices were essential to the emergence of communities, cultures, and civilizations. Hence, one may well assert that by demonstrated practice rather then by specific label, *ingeniatore* have a long and stimulating history.

About 400 years ago, the designation *engineer* as a substitute for *ingeniator* gradually appeared in common use. Then, some 200 years ago, a movement arose to endow the theory and practice of engineering with a more visible form of organized professionalism. With time, this included an emphasis on engineering identity, sharing of technical knowledge, standardization of practice, systematized instructional curricula, and projection of a public service function. These and similar considerations continue to evolve even today.

Engineering is now a highly technical and continuously evolving academic and professional discipline taught at universities and polytechnic institutions. Its foundational knowledge rests on parts of the natural sciences, its methodological foundations is based on rational thought, its obligatory justification relates to a societal interest, and its specialized professional practice is circumscribed by accreditation and licensing provisions. A variety of industrial organizations have emerged simultaneously and synergistically with the evolution of engineering, thereby providing a vast range of products and services to individuals and institutions. Indeed, engineering may now claim to be both a shaper and a reflector of contemporary times.

1.2 Core of Engineering

The innovative Roman *ingeniatore* were evidently engaged not only in tactile actions but also in a cognitive process. They must have thought about properties of natural materials, considered devices for specific purposes, proceeded by trial and error, and learned from failures. Now and then a particularly useful and ingenious device emerged and was duly noted by some writers of the day. Thus, an *ingenium* came about because of the thought and actions of some innovative *ingeniator* who had become familiar with the properties of natural materials and then imaginatively shaped and assembled them in particular ways so as to yield a device of particular utility. An astute observer could conclude that this interactive endeavor constituted a technical process involving naturally available materials which an *ingeniator*, by thought and skill, shaped and combined to create an *ingenium* of subsequent interest. This dynamic could be modeled as an input-output process

$$\textit{materials} \rightarrow \boxed{\textit{ingeniator}} \rightarrow \textit{ingenium} \qquad (1.1)$$

with the rectangle suggesting creative thought and skilled actions of the *ingeniator* in combining natural materials and phenomena into an ingenious and useful device. Note however that this symbolic depiction is evidently both primal and universal since even for Stone Age Man we may write

$$\begin{matrix} \textit{natural} \\ \textit{stone} \end{matrix} \rightarrow \boxed{\begin{matrix} \textit{human action} \\ \textit{of stone chipping} \end{matrix}} \rightarrow \begin{matrix} \textit{stone} \\ \textit{tool} \end{matrix}, \tag{1.2a}$$

as well as for a contemporary engineer

$$\begin{matrix} \textit{natural} \\ \textit{materials} \end{matrix} \rightarrow \boxed{\begin{matrix} \textit{engineering thought and actions} \\ \textit{of design and manufacture} \end{matrix}} \rightarrow \begin{matrix} \textit{computer} \\ \textit{chip} \end{matrix}. \tag{1.2b}$$

Hence, and with considerable generality, a progression of much engineering relevance, may be typically characterized as

$$\begin{matrix} \textit{natural materials} \\ \textit{and their properties} \end{matrix} \rightarrow \begin{matrix} \textit{creative thought} \\ \textit{and skilled actions} \end{matrix} \rightarrow \begin{matrix} \textit{ingenious and} \\ \textit{useful device} \end{matrix} \tag{1.3a}$$

with the rectangular enclosure omitted. A label and component listing is suggested by

$$\textit{Nature} \begin{Bmatrix} \textit{materials} \\ \textit{phenomena} \end{Bmatrix} \rightarrow \textit{Engineering} \begin{Bmatrix} \textit{thought} \\ \textit{actions} \end{Bmatrix} \rightarrow \textit{Devices} \begin{Bmatrix} \textit{ingenious} \\ \textit{useful} \end{Bmatrix}, \tag{1.3b}$$

or, to explicitly recognize time as the pervasive variable and using a functional notation to be used hereafter, we write

$$N(t) \begin{Bmatrix} \textit{materials} \\ \textit{phenomena} \end{Bmatrix} \rightarrow E(t) \begin{Bmatrix} \textit{thought} \\ \textit{actions} \end{Bmatrix} \rightarrow D(t) \begin{Bmatrix} \textit{ingenious} \\ \textit{useful} \end{Bmatrix}. \tag{1.3c}$$

Finally, we represent these various expressions in compact form as

$$N(t) \rightarrow E(t) \rightarrow D(t). \tag{1.3d}$$

We take this three component dynamic relation as primal to engineering and comment on the meaning of these constituent terms, as perceived in contemporary times, in the following sections. But first a comment about notation.

1.3 Symbolic Notation and Engineering

The preceding has introduced some conceptual constructions and associated symbolic notation of particular relevance to *Engineering in Time*. Such symbolic notation is useful in our context for three reasons:

(a) *Familiarity*
It represents aspects of thought and actions in graphical form which are familiar to students of all engineering disciplines.
(b) *Empiricism*
It constitutes a practical way of depicting complex processes of central importance to the theory and practice of engineering.
(c) *Heuristics*
It suggests useful and efficient means of organizing and exploring the historical progression and contemporary context of engineering.

We emphasize that symbolic and graphical notation has long proven to be a most effective and powerful instructional and operational tool in engineering. While such notation can take many forms — for example force diagrams, circuit representations, electromagnetic field depictions, vector notation, phase-plane projections, etc. — its pedagogical power rests in the effectiveness of graphical-geometrical depictions providing a valuable cognitive focus for complex physical phenomena and processes. Indeed, engineers have become particularly adept at this type of *visual and imaginative thinking* and it is for this reason that symbolic and graphical notation is commonly introduced and will be also here be used, adapted, and expanded[†].

1.4 Essential Components

The leading term $N(t)$ in Eq. (1.3d) represents nature as the basic starting point of a most relevant progression. For purposes of elucidating this progression, $N(t)$ may be characterized by several attributes:

(a) Nature constitutes the resource of basic materials essential to the practice of engineering (e.g. stone, wood, fiber, water, metal, petroleum, . . .).

[†]Appendix A provides a brief discussion of mathematical ideas and notation in history.

(b) Nature embodies the physical phenomena of foundational importance to the theory of engineering (e.g. hardness, diffusion, heat, elasticity, friction, turbulence, . . .).
(c) Nature possesses autonomous dynamical features of relevance to the performance of engineered devices (e.g. earthquakes, water cycle, hurricane winds, flash floods, . . .).

In Sec. 9.7, we add two additional but highly personal and private features to this list: nature may induce a transcendental sense of *engagement* and it may also stimulate a deep sense of *place-attachment*.

The term $D(t)$ in Eq. (1.3d) identifies engineered devices — the ingenious and useful human-made objects so judged by common pragmatic criteria. Contemporary engineering practice suggests the following as helpful working definitions for this term:

(a) A device may be an artifact, constructed or adapted but invariably based on considerations of synthesis; it may be a hardware object such as a tool, prosthesis, sensing instrument, interactive machine, small-scale appliance, large-scale assemblage, adapter/converter, passive/dynamic network, etc., or it may be a cognitive object such as a strategic idea, optimal process, action program, information management schema, heuristic algorithm, software package, experimental know-how, etc.
(b) A device may be associated with a commodity providing selected functions: projection of information (e.g. book, clock face, monitor display, . . .), means of transportation (e.g. wagon, parachute, aircraft, . . .), serve the needs of sustenance (e.g. water pipe, cutlery, flour mill, . . .), supply entertainment (e.g. guitar, video, dynamic art, . . .), provide physical comfort (e.g. furnace, lawn chair, mosquito spray, . . .), etc.
(c) A device may also be characterized as a synthesized object which *engages*, *stimulates* and *enables* its makers and users.
(d) A device may further be viewed as a convenient unit of engineering theory and practice.

These four characterizations evidently span considerable breadth and hence provide much opportunity for association with specific examples.

With $N(t)$ and $D(t)$ so characterized, it is evident that engineering $E(t)$ constitutes the central and uniting connection in the progression from $N(t)$ to $D(t)$, Eq. (1.3d). A definition and two corollaries for engineering may now be introduced:

(a) *Definition*
Engineering represents creative thought and skilled actions associated with the use or adaptation of natural materials and natural phenomena in the conceptualizing, planning, designing, developing, manufacture, testing, implementing, improving, and disposing of devices.
(b) *Corollary I*
Engineering may be interpreted as the rational activity concerning specifics of *how to make devices* and *how they might be made better*.
(c) *Corollary II*
Engineering constitutes the domain of thought and action which uses *what is* to create *what may be*.

Note that these characterizations evidently define engineering not only as a *creative* activity but also as a *goal-seeking* activity. Table 1.1 provides a summary characterization of the primal.

Table 1.1 Component characterization of the primal $N(t) \rightarrow E(t) \rightarrow D(t)$.

$N(t)$	$E(t)$	$D(t)$
1. Resource	1. Creative thought	1. Material artifact
2. Phenomena	2. Skilled actions	2. Cognitive object
3. Dynamics		3. Commodity support
4. Engagement		4. Maker/user stimulant
5. Attachment		5. Engineering unit

1.5 Change and Engineering

All contemporary professions need to consider change and all describe change in terms which are specific to their interests. Thus, economists speak of *business cycles*, chemists have found the notion of *reaction chains* useful, human resource managers consider *career progressions*, physicists express a number of dynamical processes using the concept of *phase transitions*, historians have identified *sequences of historical causation*, environmentalists have found *cascading sequences* as vital, biologists have for the past century devoted much effort to *biological evolution*, and mathematicians have introduced a specialty known as *stochastic methods*. Even popular terminology makes use of *chains of events* and the recognition that *the only constant in life is change*. Indeed, changes are foundational to life and living.

For engineers, the term *progression* is especially informing in the characterization of some important changes in their work. To begin, relations (1.1) to (1.3) suggests features well-known in engineering such as input → output processes involving materials, energy, ingenuity, and information. Our interest here, however, is more extensive and we view such relations and associated expressions as a catalyst to suggest other time-ordered connected terms central to our conceptualization of *Engineering in Time*. To clarify this emphasis we consider four classes of progressions.

1.5.1 *Homogeneous Progressions*

As a first illustration, consider an aircraft cleared for take-off. Evidently it may have its subsequent dynamical features specified by the homogeneous progression

$$\begin{matrix}\textit{zero speed}\\ \textit{at time } t_0\end{matrix} \rightarrow \begin{matrix}\textit{intermediate speed}\\ \textit{at time } t_1\end{matrix} \rightarrow \begin{matrix}\textit{take-off speed}\\ \textit{at time } t_2\end{matrix} \rightarrow \cdots . \qquad (1.4a)$$

As another illustration, the sequential changes of the mean temperature in a reaction vessel in the process of start-up or shut-down may be represented in general as

$$T(t_0) \rightarrow T(t_1) \rightarrow T(t_2) \rightarrow T(t_3) \rightarrow T(t_4) \rightarrow \cdots . \qquad (1.4b)$$

These two examples represent homogeneous progressions and involve some specific measurable variable $X(t)$ at successive time coordinates; in complete generality we may write for such changes in time

$$X(t_0) \rightarrow X(t_1) \rightarrow X(t_2) \rightarrow X(t_3) \rightarrow \cdots . \qquad (1.4c)$$

Thus, homogeneous progressions describe the magnitude of a time-dependent variable which is associated with some device or devices. Note that in a homogeneous progression each term possesses the same units.

1.5.2 *Heterogeneous Progressions*

The practice of engineering involves many informing progressions which are not fully describable by one homogeneous variable, Eq. (1.4). Consider the following three historical examples:

$$\textit{chariots} \rightarrow \textit{wagons} \rightarrow \textit{trains} \rightarrow \textit{automobiles} \rightarrow \cdots, \qquad (1.5a)$$

$$\begin{matrix}\textit{shadow}\\ \textit{clocks}\end{matrix} \rightarrow \begin{matrix}\textit{water}\\ \textit{clocks}\end{matrix} \rightarrow \begin{matrix}\textit{weight-driven}\\ \textit{clocks}\end{matrix} \rightarrow \begin{matrix}\textit{pendulum}\\ \textit{clocks}\end{matrix} \rightarrow \begin{matrix}\textit{spring}\\ \textit{clocks}\end{matrix} \rightarrow \cdots, \qquad (1.5b)$$

$$\begin{matrix}\textit{animal}\\ \textit{power}\\ (\sim 10^4\ BP^\dagger)\end{matrix} \rightarrow \begin{matrix}\textit{water}\\ \textit{power}\\ (\sim 3000\ BP)\end{matrix} \rightarrow \begin{matrix}\textit{wind}\\ \textit{power}\\ (\sim 700\ CE)\end{matrix} \rightarrow \begin{matrix}\textit{steam}\\ \textit{power}\\ (\sim 1700)\end{matrix} \rightarrow \cdots. \qquad (1.5c)$$

In addition to these explicit retrospective expressions, some general engineering projective progressions are suggested by the following:

$$\textit{opportunity} \rightarrow \textit{invention} \rightarrow \textit{enhancement} \rightarrow \cdots, \qquad (1.5d)$$

$$\begin{matrix}\textit{innovative}\\ \textit{proposal}\end{matrix} \rightarrow \begin{matrix}\textit{design}\\ \textit{study}\end{matrix} \rightarrow \begin{matrix}\textit{prototype}\\ \textit{testing}\end{matrix} \rightarrow \begin{matrix}\textit{device}\\ \textit{modification}\end{matrix} \rightarrow \cdots, \qquad (1.5e)$$

$$\begin{matrix}\textit{emerging}\\ \textit{societal}\\ \textit{interest}\end{matrix} \rightarrow \begin{matrix}\textit{responding}\\ \textit{government}\\ \textit{policies}\end{matrix} \rightarrow \begin{matrix}\textit{engineering}\\ \textit{project}\\ \textit{organization}\end{matrix} \rightarrow \begin{matrix}\textit{plans}\\ \textit{and}\\ \textit{proposals}\end{matrix} \rightarrow \cdots. \qquad (1.5f)$$

In distinction to the general homogeneous progression (1.4c), the progressions (1.5a)–(1.5f) are evidently heterogeneous and may be written in the general form of

$$A(t_0) \rightarrow B(t_1) \rightarrow C(t_2) \rightarrow D(t_3) \rightarrow \cdots. \qquad (1.5g)$$

While the meaning of the terms of homogeneous progressions (1.4c) generally follow from some appropriate differential equation, no comparably compact and explicit defining expression can be specified for the terms of the heterogeneous progressions (1.5g). What can however be done is to enumerate some relevant features of such heterogeneous

†BP: Before Present in units of years, Appendix B.

progressions of specific interest to engineering and to our objectives in this text:

(a) The initial stimulant $A(t_0)$ generally determines the nature of the progression
(b) The terms may relate to a class of devices, a class of functions, or various combinations
(c) The terms may possess a range of sequential dependencies or strength of connections
(d) The terms may relate to specifics of experience and/or knowledge-base of participating individuals
(e) The terms may be influenced by the extent of cooperation or competition among various participating or affected individuals
(f) The terms may reflect upon selective preferences associated with affected societal institutions and motivating political ideologies.

Note also that what is actually *flowing* in a heterogeneous progression is a combination of forms of matter, energy, information, ingenuity, and authority.

Then, to further amplify the distinction between these two types of progressions, one may also conclude that homogeneous progressions generally tend to possess a predictive and inorganic character, while heterogeneous progressions possess a probabilistic and organic character; that is, heterogeneous progressions display the contingent role of the human imagination and community preferences.

Finally, observe that heterogeneous progressions are also used in other dynamical contexts; this includes business plans, strategic procedures, resource explorations, institutional development, optimality scheduling, and critical-path programming.

It is becoming increasingly essential that engineers think in terms of heterogeneous progressions for such evolutions invariably characterize important aspects of the practice of engineering.

1.5.3 *Primal Progression*

For our purposes here, we assign a very special meaning to the family of heterogeneous progressions represented by Eqs. (1.1)–(1.3). These three-node progressions with engineering explicitly indicated as $E(t)$ in Eqs. (1.3b)–(1.3d), or implicitly suggested as in Eqs. (1.1), (1.2), and (1.3a), will be labeled the engineering *primal progression* — or simply the primal:

$$N(t) \rightarrow E(t) \rightarrow D(t). \qquad (1.6)$$

We will repeatedly encounter this short progression as a focus for description.

1.5.4 *Connectivity Progression*

Further, there are good reasons to expand on the primal progression (1.6) by the addition of terms which suggest processes such as feedback, feed-forward, recursion, and branching; this expanded formulation will take on the appearance of a directed graph and, for purposes of terminological consistency, will be labeled the engineering *connectivity progression* — or simply connectivity:

$$\underbrace{N(t) \rightarrow E(t) \rightarrow D(t) \rightarrow (\textit{additional terms})}_{(\textit{additional processes})}. \qquad (1.7)$$

Note that while both Eqs. (1.6) and (1.7) are progressions, the primal (1.6) will serve as the enduring kernel of the connectivity (1.7). Table 1.2 provides a summary table of the four progressions of interest here.

Table 1.2 Summary tabulation of engineering progressions.

Label	Functional Form
Homogeneous	$X(t_o) \rightarrow X(t_1) \rightarrow X(t_2) \rightarrow X(t_3) \rightarrow \cdots$
Heterogeneous	$A(t_o) \rightarrow B(t_1) \rightarrow C(t_2) \rightarrow D(t_3) \rightarrow \cdots$
Primal	$N(t) \rightarrow E(t) \rightarrow D(t)$
Connectivity	$\underbrace{N(t) \rightarrow E(t) \rightarrow D(t) \rightarrow \text{(additional terms)}}_{\text{(additional processes)}}$

We emphasize that engineering consists not only of a chronology of invention, innovations and specific engineering events — traditionally described in literary form — but also of a simultaneously evolving and increasingly complex pattern of the workings of engineers, well described by a connectivity based on considerations of heterogeneous progressions. A combined literary and symbolic connectivity description offers a more informing characterization of the state and evolution of engineering.

1.6 Engineering and Time

Engineering has, over time, become increasingly identified by association with classes of devices: Civil Engineering with *civic* devices, Mechanical Engineering with *mechanical* devices, Chemical Engineering with *chemical* processing devices, Electrical Engineering with *electrical–electronic* devices, and so on. The association between a specific engineering discipline and associated class of devices may be indicated by subscript notation to the primal progression,

$$N(t) \rightarrow E_i(t) \rightarrow D_{i,j}(t) \tag{1.8}$$

to suggest therefore the time-varying workings of an engineer associated with the ith engineering discipline in the making of ingenious j-type devices.

An evidently significant feature of the primal (1.8) is now apparent: devices $D_{i,j}(t)$ do not appear in isolation but emerge from a broad historical context and relate to conceivable engineering projections about the future. To highlight this creative and goal-seeking feature of engineering, we introduce the following explanatory interconnection:

$$\begin{array}{c} N(t) \rightarrow E_i(t) \rightarrow D_{i,j}(t) \\ \updownarrow \\ \left\{\begin{array}{c} \textit{Historical evolution} \\ \textit{of devices which relate} \\ \textit{to and predate } D_{i,j}(t) \end{array}\right\} \begin{array}{c} \searrow \\ \rightarrow \\ \nearrow \end{array} D_{i,j}(t) \begin{array}{c} \nearrow \\ \rightarrow \\ \searrow \end{array} \left\{\begin{array}{c} \textit{Future development} \\ \textit{of devices which relate} \\ \textit{to and postdate } D_{i,j}(t) \end{array}\right\}. \end{array} \tag{1.9}$$

Thus, the primal progression embodies a unique evolutionary past and a contingent future, establishing thereby a distinctive temporal complexity to the evolution of engineering. Engineers need to understand the related past for their creative thoughts and skilled actions become operational in the future. An important component of professional engineering relates to the depth and breadth of understanding of this relation.

Evidently then, the range of heterogeneous progressions of interest here provides for a domain of preserved knowledge and experience so that

Engineering is Cumulative.

Then, the emergence and implementation of new devices is influenced by a variety of uncertain developments and therefore

Engineering is Contingent.

And finally, the simultaneous accommodation of selected domains of cumulative knowledge and experience in anticipation of a contingent future suggests a third feature, namely that

Engineering is Dynamic.

Engineering is thus a profession of considerable breadth and depth — and therein lies the challenge which has long attracted creative and skilled individuals.

1.7 To Think About

- Consider common devices such as bicycles, cars, household appliances, aircraft, etc. What events or developments have enhanced or could have frustrated their particular evolution?
- Progression (1.3d) appears like a conventional input $\rightarrow$ output model applicable to many areas of engineering. Explain the reasons for this similarity emphasizing in particular the thoughts and actions of engineers.
- Homogeneous progressions are generally describable using the calculus; in contrast, heterogeneous progressions are equally common but very difficult to describe analytically. Why? In addition to particular device developments, consider also specific historical subjects such as biography, corporate histories, national evolutions, etc.