Chapter 4
Will Any Old Model Do?

4.1 Paradigms and Revolutions

Thomas Kuhn's (1922–96) philosophy of science arose from the historical investigations he conducted regarding the progress of science. Those investigations led him to propose the idea that science progressed through significant *revolutions* that occurred from time to time—an example he uses frequently is the Copernican revolution that placed the sun, and not the earth, at the centre of the solar system. In between such unsettling periods of change, *normal science* was conducted within what he called a 'ruling paradigm'. He also described the way that *paradigm shifts* occurred during revolutions.

One of the main questions raised by Kuhn's philosophy is the extent to which the practice and progress of science is influenced by psychological, sociological, cultural and historical forces. In other words, he asked whether it was culture or nature that determined the shape of science (Weinberg 1998). He also suggested that science did not progress *towards* the 'truth' through its revolutions, but only *away from* its primitive beginnings. After Kuhn, others have moved to rather extreme positions, which hold that scientific knowledge is only a 'social construct', i.e. merely a product of sociological influences and not a true description of nature (Barnes and Bloor 1982). We shall examine how relevant these ideas are to engineering (see also Dias 2008).

4.2 Normal Science Within the Ruling Paradigm

The main sense in which Kuhn used the term 'paradigm' was to denote the shared commitments of a scientific community. He later preferred the term 'disciplinary matrix' to describe this. A disciplinary matrix would certainly include a common education; a body of literature that was commonly read; and a shared acceptance of methods and equipment that are deemed to be appropriate for tackling problems,

P. Dias, *Philosophy for Engineering*, SpringerBriefs in Applied Sciences and Technology, https://doi.org/10.1007/978-981-15-1271-1_4

which in turn should only be 'admissible' ones. It could also involve metaphysical factors, and other guiding principles such as 'predictions should be accurate', 'quantitative is better than qualitative' and 'the principle of parsimony'.

Kuhn went on to describe the way that scientists were educated, and suggested that there was close correspondence between such education and the practice of normal science within the ruling paradigm. The student was trained essentially on text books, which contained bodies of *established* knowledge. Scientists were not exposed to cutting edge knowledge (in journals for example) until very late in their training. In addition, science text books contained little if any descriptions of the historical development of their subject matter. Paradigms or frameworks that operated previously were not considered important; only the prevailing one was (Kuhn 1970). There was very little scope for teaching students to discriminate between different points of view, because all scientific text books in a given field had the same point of view—i.e. the one based on the ruling paradigm (Kuhn 1977). The solving of (generally numerical) problems after studying topics in a text book was also typical of such education. This was an exercise in training the budding scientist to apply established knowledge to new problem areas (Kuhn 1977).

The objective was to form the students into a very definite mould—i.e. the ruling paradigm. Such education has been described by Kuhn (1970, p. 166) as "a narrow and rigid education, probably more so than any other except perhaps in orthodox theology". This led to a mode of thinking that would be called *convergent*. *Divergent* thinking could be important for architects, inventors, artists and philosophers, since it promoted creativity. Kuhn argued however, that scientists had to be convergent thinkers, since most of them had to work within a given paradigm, during long periods of normal science (Kuhn 1977).

A scientific education also promoted a spirit of dogmatism, which was required for the practice of normal science. Words such as 'faith', 'trust' and 'taken for granted' figure in Kuhn's writings (Hoyningen-Huene 1993); such words are more usually associated with religious faith. However, Kuhn argued that such faith and dogmatism created the background within which error or anomaly could 'stick out' (Kuhn 1977) and lead to a change in the paradigm. The very rigidity of the tradition ensured the shattering of that selfsame tradition. He endorsed Bacon's maxim that "truth emerges more readily from error than from confusion" (Kuhn 1970), in preferring a single paradigm to govern normal science, rather than to have several simultaneous alternatives, as preferred by other philosophers of science (Feyerabend 1981; Lakatos 1981).

4.3 Scientific Revolutions and Progress

4.3.1 The Nature of Revolutions

Kuhn (1970) used the metaphor of a political revolution to describe a scientific revolution that occurred from time to time. Just as a political revolution arose out of growing *discontent*, a scientific one did so out of growing *anomaly*. A growing number of anomalies was considered to constitute a *crisis*, just as in a political revolution. Kuhn used the word 'anomaly' in a fairly specific way to denote unexpected discovery and 'crisis' to suggest mismatches between theory and observation. The mere existence of an anomaly (however significant) did not lead to a paradigm shift. In order for that to happen, there had to be a competing paradigm that would explain the anomaly, as well as everything else the previous paradigm explained. If such an alternative was not available, the existing paradigm would be modified, even by some ad hoc measures.

During a period of crisis, the anomalies became the focus of research within the scientific community. Many versions or interpretations of the paradigm were proposed, together with a willingness to 'try anything' and work outside the existing paradigm. There were debates over fundamentals that had always been part of the paradigm and taken for granted during the period of normal science. There was even a turning to metaphysics and philosophy. In short, a period of crisis was one of great insecurity. Such a crisis was described by Kuhn as the signal to move from a period of normal science to a scientific revolution. Just as in a political revolution, a new order was brought into existence, with considerable disjunction from the previous one, although adherents to the old order continued for a while. History was also re-written in some cases, from the viewpoint of the new order (Kuhn 1970).

4.3.2 A Different World

Kuhn said that "though the world does not change with a change of paradigm, the scientist afterwards works in a different world" (Kuhn 1970, p. 121). There were many ways of understanding this. First, scientists acquired different definitions of words that relate to the world, and pursued different problems too; this could require new equipment and methodology as well. For example, a number of new planets and comets were discovered after the Copernican Revolution, because scientists were looking for them; a number of new types of rays were also discovered after Roentgen's discovery of X-rays (Kuhn 1977).

Next, the world could also be perceived differently. To Galileo, a stone at the end of a chain was a pendulum (which has the same period whatever the amplitude), whereas Aristotle had seen it as a 'constrained fall'—i.e. the fall of the stone to the ground was constrained by the chain. The measurements considered important by Galileo were very different to those made (if any) by Aristotle. Galileo's perception was very 'fruitful', leading as it did to other problems being solved by using the same principle of potential energy conversion to kinetic energy—e.g. flow through an orifice under a falling head of water.

Finally, because data was always 'seen' through the eyes of theory, a perceptual change could actually cause a change in data. Consider Kuhn's account of the change in chemical composition of compounds after Dalton's atomic theory that atoms combined in simple whole-number ratios (Kuhn 1970, pp. 134–5):

> When Dalton first searched the chemical literature for data to support his physical theory, he found some records of reactions that fitted, but he can scarcely have avoided finding others that did not. Proust's own measurements on the two oxides of copper yielded, for example, an oxygen weight-ratio of 1.47:1 rather than the 2:1 demanded by the atomic theory; and Proust is just the man who might have been expected to achieve the Daltonian ratio. He was, that is, a fine experimentalist, and his view of the relation between mixtures and compounds was very close to Dalton's. But it is hard to make nature fit a paradigm. That is why the puzzles of normal science are so challenging and also why measurements undertaken without a paradigm so seldom lead to any conclusions at all. Chemists could not, therefore, simply accept Dalton's theory on the evidence, for much of that was still negative. Instead, even after accepting the theory, they had still to *beat nature into line*, a process which, in the event, took almost another generation. When it was done, even the percentage composition of well-known compounds was different. The *data themselves had changed*. (Italics by present author)

It must be emphasized that Kuhn distinguished between interpretation and perception, saying that it was *perception* that changed during a revolution, and not merely interpretation. This has been likened to a 'Gestalt-shift' that enables Fig. 4.1 to be viewed as either a duck or a rabbit. Kuhn however said that perceptual changes were permanent, and compared them to a person wearing inverting spectacles—once the change was made, it was difficult to see the world in the previous way (Kuhn 1970).

The above idea of the world is what has led to Kuhn's ideas being used by some—mostly social scientists rather than natural scientists—to suggest that science is purely a social construct, and not grounded in any reality or truth of nature (Barnes 1982). Hoyningen-Huene's (1993) interpretation of Kuhn's philosophy is however that the 'world-in-itself' always shows 'resistance' to socially constructed paradigms. It does so by raising anomalies that make paradigm changes necessary—and in many cases such anomalies occur simultaneously among different groups of scientists; these

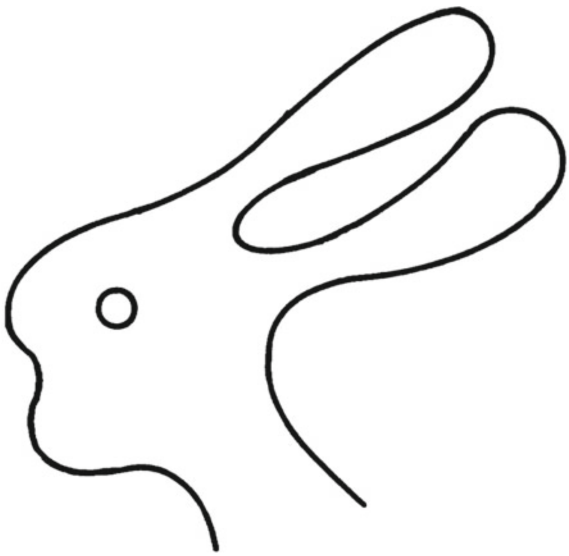

Fig. 4.1 "Duck-Rabbit" image that produces "Gestalt-switching" (from Dias 2008)

anomalies have historically been explained by science, together with the previously explainable phenomena, by a better paradigm. In other words, although a paradigm cannot fully encapsulate nature—because much of it would still be unknown—it is certainly governed by it.

4.3.3 Progress Through Revolutions

We have described the progress *of* a revolution. Kuhn also made some comments as to what progress in science was made *through* a revolution, and generated much controversy in the process. According to Kuhn, science did not progress *towards* 'truth', but rather *away from* its primitive beginnings. He drew parallels between this idea and that of Darwinian evolution, which was based on survival, and not goal directed (Kuhn 1970). This is diametrically opposed to Popper's idea of truth as a goal that we kept aiming for (Blockley 1980). Most scientists too would reject the idea that they were not getting closer to a correspondence with nature through their theories (Weinberg 1998).

Kuhn's thoughts regarding progress were probably based on his ideas that scientific revolutions were essentially changes in a scientific community's perceptions of the world; also that such perceptions were socially conditioned to a considerable extent. Furthermore, he gave a number of examples where elements of a previously overthrown paradigm were 'resurrected' after a subsequent revolution (see Table 4.1). It must be noted of course that the 'resurrected' forms differed from their previously 'buried' ones, not only in form, but also in sophistication and accuracy. Kuhn (1977) also acknowledged that scientific revolutions always resulted in greater quantitative accuracy, and that our ability to predict phenomena had therefore increased steadily with time.

Returning to Table 4.1, we see that Aristotelian science was governed by the idea that objects and materials had certain 'essences' which determined their behavior, including motion—so a stone fell to the earth because that was its nature or 'essence'. This notion was considered too shallow during the scientific revolution, especially to explain motion, and even before Newton, it had been replaced by the 'corpuscular' theory of matter—i.e. that the properties of matter could be explained by the

Table 4.1 Examples of some reversals in paradigm shifts (from Dias 2008)

Subject area	Original idea	Changed idea	Reversed idea
Nature of matter	'Essential' properties (Aristotelian)	Corpuscles (pre-Newtonian)	'Innate' properties (Newtonian)
Nature of space	'Place' has potency (Aristotelian)	'Space' is referential (Newtonian)	'Space-time' is curved (Einsteinian)
Nature of universe	Heliocentric universe (Aristarchus)	Geocentric universe (Aristotle)	Heliocentric solar system (Copernicus)

interaction of particles—so the reason we could smell substances was because they emanated particles that could reach our noses. When Newton had to explain gravity however, he had to revert back to the idea of ‘innate’ properties of matter (since ‘particles’ such as celestial bodies could not interact at great distances), an idea very close to Aristotle’s ‘essences’. This idea of ‘innate’ properties was also very useful in the subsequent development of chemistry and electricity (Kuhn 1970).

Another example was Aristotle’s notion of ‘place’, which was supposed to exert an influence on objects—so another reason a stone fell towards the earth was because of the earth’s place at the centre of the universe. This was replaced by Newton’s idea of space as a ‘frame of reference’ that had no influence on objects. However, Einstein’s space-time continuum is both influenced by the mass of celestial bodies and also influences the path of light rays. Hence Aristotle’s notion of space could be considered closer to Einstein’s in some respects than Newton’s was (Kuhn 1985). Probably the clearest example of paradigm reversal is that Aristarchus, a pre-Socratic philosopher, proposed a heliocentric universe in the 3rd century BC (Kuhn 1985). This theory of course ‘lost out’ to Aristotle’s geocentric universe, and it was only in the 16th century AD that science returned to heliocentricism, albeit of the solar system and not the universe.

4.4 Revolutions in Structural Design

4.4.1 Some Historical Revolutions

The relevance to engineering of Kuhn’s ideas about paradigms and revolutions in science has been cogently presented by William Addis (1990) in his book *Structural Engineering: The Nature of Theory and Design*. Addis does this by using the history of structural design. The design of structures is carried out today largely using the theories of structural mechanics; those theories however are of rather recent origin. Structures have been designed and constructed long before the advent of mechanics. Therefore, they would have had a different basis for their design. A close look at the history of structural design will indicate that there were many different bases for design, and that these changed over the years. In some cases, these different bases co-existed, and still do. This points therefore to the existence of design paradigms. It also raises the question as to how accurate or realistic the various bases for design have been and are for that matter, thus suggesting the relativity of knowledge. The term ‘revolution’ as used by Kuhn conveys the idea that scientific knowledge is not purely cumulative. Paradigm shifts constitute changes in viewing or perceiving natural and physical phenomena. Similarly, it can be argued that changes in the bases of design constitute changes in the way structures and their behavior have been viewed. We shall now consider some shifts in the ruling paradigm for structural design that have taken place over the centuries, drawing heavily on Addis (1990).

In ancient Greece, the 7th century BC saw a quick transition from small-scale construction to monumental architecture, primarily in the form of temples. The layouts of these temples indicate clearly that some principles of proportion were used in their design. For example, Addis (1990) gives flowcharts for design according to the Doric and Ionic orders, as compiled by Vitruvius in the 1st century BC, where sizing is based largely on proportions. These may have been influenced by harmonic ratios, the discovery of which is attributed to Pythagoras in the 6th century BC. He is credited with finding that small number ratios (e.g. 2:1, 3:2, 4:3 etc.) correspond to the most consonant musical intervals (e.g. octave, fifth, fourth etc.). Anaximander thought that such ratios characterized the structure of the universe, which he considered as analogous to Greek temple architecture (Hahn 2001).

Geometry also played an important part in Greek thought. Its application to structural design was not mathematical however, as in Bow's graphical statics or Heyman's (1982) geometrical factor of safety. Rather, geometry was used to encapsulate harmonic ratios. Furthermore, in the Greek worldview, which was *rational* (i.e. based on reason) but largely not *empirical* (i.e. not based on observation), symmetrical or 'perfect' geometric shapes such as the circle were considered to reflect the nature of the universe. It is therefore not surprising that Roman arches, which followed the Greek period, were all circular ones.

We shall next consider the tremendous developments, primarily in Cathedral architecture, that took place around the 12th century in Europe, characterized by the advent of the Gothic form. In many ways, the bases for these developments were extensions of those used by the ancient Greeks. Geometry also continued to play an important part in the Gothic revolution. It is interesting to note that Adelard of Bath, who was a student of the master builder Thierry at Chartres, translated a copy of Euclid's *Elements of Geometry* from Arabic to Latin just a few years prior to the construction of Chartres Cathedral. However, the use of geometry was now more sophisticated. There was a distinction made between theoretical and practical geometry. Theoretical geometry was concerned with ideal shapes and how structural form could be justified on the basis of those shapes. Practical geometry on the other hand drew on theoretical shapes, but also on experience and thought experiments regarding structural behaviour, in order to derive sometimes complex rules for arriving at appropriate shapes for arches and thicknesses for voussoirs and abutments. Hence, it was possible to move away from a purely circular arch form to pointed and flat arches.

One new basis for design that emerged during this Gothic Revolution was the use of physical scale models. Although their use in most cases may have been architectural as opposed to structural, the 1/8th full size model of the San Petronio Cathedral in Bologna would have constituted a reasonable test of the stability of the proposed cathedral, since the model was made of brick and plaster, materials similar to those to be used in the cathedral itself. Another basis for design that emerged in the Gothic period, simple though it may seem, was the use of precedent in design. In many cases master builders visited other cathedrals prior to commencing their own work. In other cases, the 'client' city consulted master builders who had experience in constructing cathedrals.

The next revolution was the shift from geometry to statics, seen once again in the design of arches. One of the greatest problems with arch design is to carry the horizontal thrust via abutments. In the early 17th century, Blondel proposed a purely geometric approach, which was publicized in a textbook by Belidor in 1729. However, in the middle of the 17th century, Blondel's rule was criticized by Christopher Wren (the designer of St. Paul's Cathedral in London), who argued that principles of statics relating to stability had to be employed in the design of abutments. There were others too who found a lack of rationality in purely geometric approaches. Hence, the geometric design procedure could be seen as having undergone a 'Kuhnian' crisis around the latter half of the 17th century.

Both the geometric and statical approaches were subsumed in the 19th century by the 'elastic design revolution', which was largely concerned with determining the internal stresses and deformations of structural elements. The term 'elastic' conveys the idea that the above stresses and strains are reversible during loading and unloading, with no permanent deformations experienced—so structures are designed to remain within the 'elastic region' during their use. The need to determine internal stresses and deformations arose due to the use of slender elements made of steel and timber that experienced bending and tensile forces in structures such as beams and trusses. Such structures were far more likely to have localized material failures in elements, as opposed to stability failures of the entire structure as in masonry construction. The results of the above stress analyses could also be compared with the increasing body of data that had been acquired in laboratory testing on the properties of materials.

It should be noted that both the geometric and statical approaches were preserved, albeit in transformed fashion, by the elastic design revolution. Statics had to apply to the structure as a whole, in order to ensure equilibrium. It was also applied to parts of the structure as well (e.g. the force equilibrium at a truss joint). The actual application of statical principles to structures was carried out largely by using the graphical (or 'geometric') procedures of the triangle of forces and Bow's notation. The interesting thing about the elastic design revolution is that although it arose in the context of beams and trusses (made of steel and timber), its methods were subsequently applied to all structural forms, including masonry arches. This illustrates Kuhn's proposition that the world (in this case a masonry structure) is viewed in a new light (in this case internal stresses) after a scientific revolution (in this case the elastic design revolution).

4.4.2 The Plastic Design Revolution

The 'plastic design revolution', as masterfully narrated by Addis (1990), contains all the elements of a Kuhnian revolution. Prior to the plastic design revolution, elastic design was the ruling paradigm. Under this earlier paradigm, there was much growth of knowledge in cumulative fashion (as in a Kuhnian period of *normal* science), with the paradigm being applied to an increasing number of situations. The paradigm was supported by advances in structural mechanics and data from laboratory testing. However, the application of elastic theories to indeterminate structures proved to be very tedious and computation-intensive; they could not readily be used for everyday design. As such, many simplifications had to be made.

For example, a steel frame building was seen as a grid of vertical columns, connected by horizontal beams. When designing for vertical loads, the beams were considered to be simply supported at connections to columns; in assessing the loading on columns, some eccentricity in the beam-column connection was allowed for, based on the designer's judgment. On the other hand, when designing for lateral loads, the connections between beams and columns were considered to be fully rigid. Despite the above simplifications and contradictions, steel frame buildings were constructed after being elastically designed for over half a century (in Britain at least), without any recorded instance of collapse. Furthermore, elastic design principles were used and resulted in safe structures of many other forms (e.g. trusses, arches) and materials (e.g. timber, masonry).

An *anomaly* in an existing design paradigm can manifest itself in many ways. One of the most spectacular is through structural failure. Even without failure however, when a paradigm is seen to lack justifying power, an anomaly can be said to have arisen. This is precisely what happened in Britain with regard to the elastic design paradigm. The anomaly arose in, or was focused on the design of steel structures, particularly framed buildings but also bridges. There were many contradictions and deficiencies in the elastic design paradigm. As described above, the beam-column connections were viewed in two different ways when designing for vertical and lateral loads. Furthermore, the eccentricities allowed for were found to be inaccurate when compared with laboratory tests. In addition, the localized elastic stresses due to manufacturing and the internal stresses due to 'lack of fit' during construction could not easily be dealt with using an elastic analysis. In 1929, The British Steelwork Association set up the Steel Structures Research Committee (SSRC) to review the elastic design procedures and to propose design procedures that were more efficient (with respect to design office practice) and economical (with respect to use of construction materials).

The initial work of the SSRC was directed at trying to remedy the above anomalies within the paradigm of elastic design itself. This is typical of a first response to anomaly, according to Kuhn. It resulted in design procedures that were considerably more difficult to follow than the previous ones, with no gain in economy either. This situation, where the remedy was worse than the illness, constituted a *crisis*. There was also the increasing awareness that the use of an 'elastic working stress' (i.e. the maximum possible elastic stress divided by a safety factor) as a design parameter gave wide discrepancies between theoretical and measured values. Furthermore, there was the parallel awareness that elastic stresses gave no information regarding the collapse behaviour of structures. It was also felt that the plasticity of steel (i.e. ability to deform safely even beyond the maximum elastic stress or strain) would constitute reserves of strength that could result in more economical structures.

The crux of the plastic design *revolution* was the shift from calculating elastic stresses in structural elements while in service, to determining loads that structures could carry at the point of collapse. There were many new concepts that had to be introduced, such as ‘perfect plasticity’, ‘plastic hinges’, ‘load factors’ and ‘collapse loads’. The focus of attention too changed from the service state of a structure to its ultimate or collapse state. The technique of ‘superposition’, used for elastic design, was replaced with that of ‘proportional loading’. New theorems such as the safe and unsafe theorems of plastic theory were developed. There were many advantages that resulted from the revolution. It was found that predicting the actual (i.e. measured) collapse loads by plastic theory was far more accurate than predicting measured working stresses by elastic theory. The plastic theory solutions were also not as sensitive to variations in dimensional and connection details as were the elastic ones. Hence, the new paradigm had greater justifying ability. Furthermore, as a result of utilizing the plasticity of the material and the redundancy of the structure, greater reserves of structural strength were available for the designer, thus leading to economical design. The plastic design methods were not tedious either, and could deal with redundancy very easily via the concept of plastic hinges. All of the above contributed towards the gradual acceptance of the new plastic design paradigm over that of the elastic design one.

Articulation of the new paradigm was carried out in many ways. For one thing, the paradigm was applied to many other design procedures as well. Today, structures constructed out of virtually all construction materials are designed according to plastic (or ‘ultimate limit state’) design principles. For another, there was a ‘re-writing of history’ as observed by Kuhn, when work done by Coulomb and others in the 18th century that bore some similarity to the plastic design paradigm was recast by Heyman in the categories of the new paradigm. There was also an interesting ‘return to history’ in the case of the plastic design procedures for masonry arches, since the importance of geometry was re-emphasized by the new paradigm over that of stress analysis (Heyman 1982). Finally, the new paradigm found articulation in a new design community, trained largely in some universities that had their academic staff members in the SSRC. It should be noted that the elastic design community too continued, with periodic academic debate regarding the suitability of the rival paradigm. This is reminiscent of the ‘rearguard’ action, described by Kuhn, by adherents to the overthrown paradigm. It must be said however that the plastic design paradigm has rapidly gained acceptance because of its greater justifying ability, its simplicity and robustness, and its capacity to arrive at more economical structures.

4.4.3 Relativity and Progress of Knowledge

The design revolutions described above all indicate that knowledge is relative, in the sense that we begin to ‘see’ structures and their behaviour in different ways after such revolutions. This however is not to say that each way of seeing things was or is as good as the other. To take such a position of randomness, such as advocated by Feyerabend (1981), would be anarchic. Where structural design is concerned, the design revolutions over the years have certainly contributed to progress in knowledge, particularly with regard to greater justifying ability. We could also say that the models are able to pass an increasing number of 'tests'—i.e. the truth contents of our models have increased. They have also given us greater confidence and in some cases improved quantitative accuracy, thus enabling us to construct slender and more economical structures.

It may be that sometimes a ruling paradigm returns to a previous one; as in the case of masonry arch design, when the plastic design revolution rekindled a geometric approach to design, after it had previously been ousted by the stress analysis approach of the elastic design paradigm. Nevertheless, such a return always takes place with increased understanding and fresh perspectives. Hardly ever have there been simple and complete returns to previous approaches. The question could then be asked as to how close our models can get to the 'real world'. As we shall see in the next section, such perfect correspondence, apart from being practically impossible and philosophically futile according to Kuhn, is not the primary concern of engineering models either.

4.5 Engineering Models

The models used by engineers could be considered as part of their paradigm. We shall compare engineering *models* with scientific *theories*, following Blockley (1992). Although the idea of a model is used in science too, the term there refers to some sort of analogy—for example a fluid flow model for an electrical circuit. Engineering models are primarily calculation procedure models (CPMs) (Sects. 3.4 and 3.5)—i.e. tools for making changes in the world, incorporating both scientific and heuristic aspects. Now both an engineering model and a scientific theory are *representations* of the world. They are both used to make *predictions* about the world. How then do they differ?

The discussion below is summarized in Table 4.2. The goal of science is *understanding*, while that of engineering is *transformation* or useful change (see Fig. 2.1).

Table 4.2 Scientific theories compared with engineering models (after Dias 2008)

Feature	Scientific theory	Engineering model
Goal	Understanding	Transformation
Grounding	Truth	Safety
Basis	Necessity	Contingency
Form	Simplicity	Completeness
Applicability	Comprehensiveness	Practicality
Specification	Precision	Appropriateness
Improved by	Calibration	Comparison
Characteristic	Accuracy	Dependability

So, while both scientific theories and engineering models represent and make predictions about the world, their purposes are very different, as unfolded in the rest of the table. For example, we can say that a scientific theory is grounded in *truth*, in the sense that a good theory has a good correspondence with the world (or natural phenomena). Hence, the basis of a scientific theory is *necessity*, in that the theory cannot do anything other than to reflect the laws of nature (Goldman 2004).

An engineering model is however grounded more in *safety*, in that a good model will help us to make safe artefacts or objects. This is why Kuhn's view of science is probably more relevant for engineers than for scientists. In the various historical stages of structural design, structures were viewed through the 'eyes' of proportions, geometry, statics, elasticity and plasticity. While there has undoubtedly been an increase in the truth content of engineering models with time, what is perhaps more important is that each historical stage was served by its own model or paradigm for the purpose of constructing safe structures. Furthermore, the basis of an engineering model used for designing useful things is *contingency*—while the design has to respect the laws of nature, it is influenced by a variety of context dependent factors that have to be recognized and accounted for (Goldman 2004).

This pragmatic engineering approach is reflected in the aphorism that "it's true because it works"; whereas scientists are probably more interested in claiming for their theories that "it works because it's true". It also explains why engineers are reluctant to make changes in a CPM once it has been shown to result in safe artefacts—"if it ain't broke, don't fix it"—however 'unjustifiable' parts of that CPM may be. This pragmatism is also reflected in the form, applicability and specification of engineering models.

Scientific theories aim at *simplicity*. One of the best expositions of this quality has been made by Einstein (1934) himself, in an address delivered in 1918 at a celebration of Max Planck's sixtieth birthday:

> What place does the theoretical physicist's picture of the world occupy among all these possible pictures? It demands the highest possible standard of *rigorous precision* in the description of relations, such as only the use of mathematical language can give. In regard to his subject matter, on the other hand, the physicist has to limit himself very severely: he must content himself with describing the *most simple* events which can be brought within the domain of our experience; all events of a more complex order are beyond the power of the human intellect to reconstruct with the subtle accuracy and logical perfection which the theoretical physicist demands. Supreme purity, clarity and certainty at the cost of *completeness*. But what can be the attraction of getting to know such a tiny section of nature thoroughly, while one leaves everything subtler and complex shyly and timidly alone? Does the product of such a modest effort deserve to be called by the proud name of a theory of the universe? In my belief the name is justified: for the general laws on which the structure of theoretical physics is based claim to be valid for any natural phenomenon whatsoever. (Italics by present author)

Compare this with the importance given to handling incompleteness in engineering. While simplicity may be important in scientific theories for clarity of explanation, engineering models by contrast focus on *completeness*. Consider for example the part plan view in Fig. 4.2 of a series of combined footings on weak soil connecting two lines of peripheral columns. The foundation design for the typical 'combined

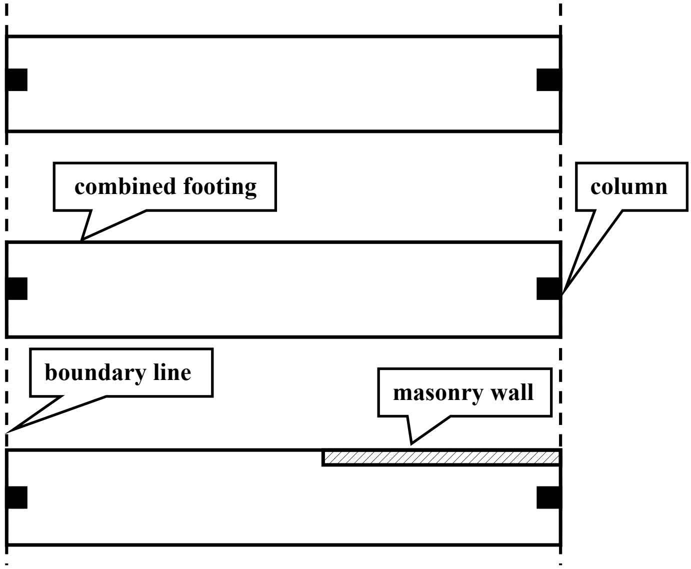

Fig. 4.2 Part plan view of combined footings supporting two lines of boundary columns (from Dias 2008)

footings' are simple, and standard engineering science solutions will suffice. One footing however, has an 'inconvenient' wall segment founded on it too. Such situations abound in the practice of engineering, because it is contingent on context. The artefacts to be designed cannot be fitted neatly into standard solutions. There are peculiarities that have to be dealt with—they cannot be ignored. This is one aspect of completeness. The notion of *uncertainty*, which is part of everyday life, leads us to another aspect of completeness that needs to be tackled by engineering models. There are three aspects of uncertainty, namely randomness, fuzziness and incompleteness (Blockley 2013); they have been addressed in Sect. 2.3

We come next to applicability. For scientific theories, *comprehensiveness* is the important aspect of applicability. A scientist (perhaps an engineering scientist) looking at Fig. 4.2 would have his eye attracted to the typical footings. He may then think of writing a spreadsheet program that can solve such foundation problems for any combination of column load, footing span and soil bearing pressure. This would of course be of considerable value. But it does not solve the practical engineer's problem that one of the footings has an eccentric wall load along part of its length. For engineering models therefore, *practicality* is the relevant aspect of applicability.

How about specification? As stated by Einstein above, scientists would aim for *precision* in their predictions. On the other hand, the important thing for engineering models is *appropriateness*. Consider again the atypical footing in Fig. 4.2. Our (engineering) scientist would want to analyze this precisely (e.g. locating the wall in its exact location), perhaps by using some computerized analysis program. There are a number of questions that arise in this regard. First, is it appropriate to spend the time and effort required for very precise modelling to solve a relatively inconsequential problem such as this (given that the masonry wall loads would be much less than those from the columns)? Second, is it of any value to use such precise analysis when the properties of the underlying soil could be quite variable and known only approximately? Third, if we aim at such precision, will we be in danger of getting too close to the point of failure, especially if the actual parameters differ from the assumed ones (due either to variability in the soil or deficiency in construction)?

A practising engineer may prefer to use a cruder analysis, assuming for example that the wall runs along the entire length of the footing; or that such wall segments are present on both edges of the footing (so that some symmetry is introduced). More than one simple approximation could be used and the design made to accommodate the worst cases. Such approaches are probably more appropriate, and characteristic of engineering. For this however, practitioners must have a qualitative feel for structural behaviour, so that the approximations used are more as opposed to less conservative.

The other insight raised by Fig. 4.2 is that its peculiarities are part of its *context*, something that is crucial for the practice of engineering. Context generates *constraints*, or limits what we can do. While they appear to be curtailing our freedoms, they in fact give us challenges to face and also provide a 'solution space' within which to work—and hence unleash creativity. So, although the location of the masonry wall in Fig. 4.2 complicates our calculations a little, the final solution is elegant and efficient, in that the wall is founded on the combined footing itself, dispensing with any need for a separate foundation of its own.

The penultimate row in Table 4.2 indicates that scientific theories are improved by *calibration* with the world, whereas engineering models are improved by *comparison*. Calibration is relatively easy when theories are simple and pay 'selective inattention' to factors that cannot be easily quantified (Schon 1983); provided that the experiment or observation that is used for calibration is 'freed' or 'decontextualized' from such factors too—see the Einstein quotation above. Engineering however is carried out within a complex social fabric, and such decontextualization is neither possible nor even desirable. Creative engineers have to pit their wits against the cunning adversary of nature and the indeterminism of human action. However, this means that their models cannot be calibrated as such against the world. Comparison is a better word to use for the feedback that engineering models receive from completed artefacts. If there are problems or failures that are revealed from such comparisons, engineers seek to remedy the appropriate component of their CPM (Dias 1994)—see also Sect. 3.6.

Most of the differences above stem from those expressed in the first two rows of Table 4.2, and this results in the distinctive characteristics of scientific theories and engineering models (last row of table). Because scientists seek to understand the world, their goal is truth. Engineers on the other hand are interested in changing the world, and want to do it safely. The concept of safety involves an asymmetry between predictions that are to the two different sides of a 'target' that the concept of truth does not—see Fig. 4.3. So, a scientist predicting a lunar eclipse will want to get the time as accurately as possible. There is no practical difference if her prediction was slightly earlier or later than the actual time of the eclipse; she does however want to be

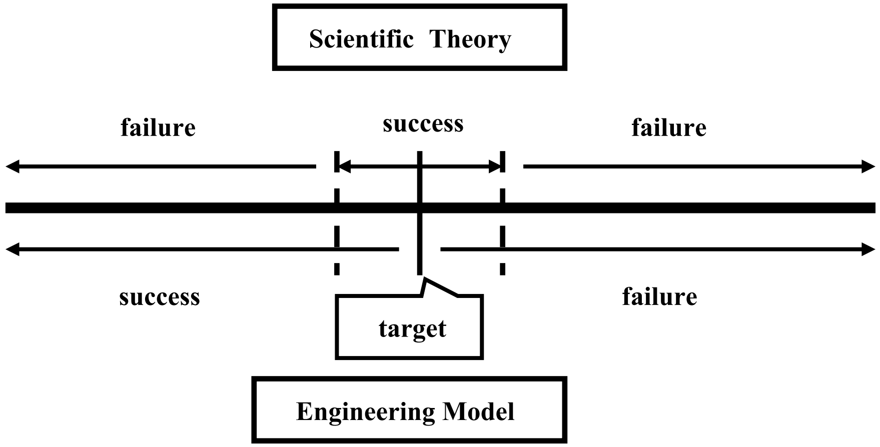

Fig. 4.3 Success and failure for predictions in science and engineering (from Dias 2008)

as close as possible to the actual time and will therefore aim for the highest *accuracy*. For an engineer on the other hand, there is a large difference between underestimating the stability of a structure or reliability of a system and overestimating it. The latter would cause failure and violate his pursuit of safety. This is why engineering models tend always to be underestimates of safety; an engineer requires *dependability*.

This also explains why very different theories, ranging from proportions to plastic analysis, were satisfactory for constructing structures. It demonstrates too that engineers, like social scientists, can more easily accommodate the relativity of knowledge suggested by Kuhn than can natural scientists. Note also that codes of practice, which formalize design procedures, despite varying from country to country sometimes in very fundamental ways, still manage to produce safe structures and artefacts in those different countries. This is another example of how engineering CPMs, of which codes of practice are an important part, reflect the above relativity of knowledge. It must be noted however, that concerns regarding economy will tend to push engineers closer to the 'target' in Fig. 4.3—we want safe structures, but not at unreasonable cost.

Engineers are drilled in engineering science during their formal education, because engineering is founded on science. In such courses they become used to getting a single correct answer or a *unique* solution. They are however given a good dose of design too in an engineering first degree. Such courses in design emphasize that engineering models should be characterized by *dependability* rather than accuracy. In other words, solutions must have generous *margins of safety*, not only in the design assumptions and calculation procedures, but also in the selection of structural forms that can, through their robustness, accommodate unforeseen actions.

Design is also founded on creativity and an artistic outlook. These require divergent thinking. Engineers cannot be divergent thinkers when it comes to engineering science—all our structural solutions are constrained by Newton's laws and energy theorems. However their creativity can be unleashed in the selection of structural form for both robustness and aesthetics. This could involve a return to previous design paradigms. For example Bobrowski (1982) was drawn to the stability of a circle (*geometry*) in developing the plan form for his Calgary Saddledome. Some work has also been done on the importance of *proportions* for creating aesthetic forms (Kulasuriya et al. 2002). So, although history is not important for scientists, as argued by Kuhn, structural engineers can and should draw on historical paradigms when appropriate. It is this recourse to history and to nature as well, that will stimulate creativity and generate a pool of *alternatives*, as opposed to a unique solution.

4.6 Summary

– Thomas Kuhn's investigations on the history of science led him to conclude that scientists worked within a 'ruling paradigm' during relatively long periods of 'normal science'. From time to time however this paradigm could be replaced by another through the process of a 'scientific revolution'.
– The history of structural design has been presented by William Addis as one of changing paradigms, with the bases of design moving from proportions though geometry, statics and elastic design to the current one of plastic design. The plastic design revolution has features that closely resemble a scientific revolution as described by Kuhn.
– Both a scientific theory and engineering model are representations of the world that are used to make predictions about it. However, because their goals (of *understanding* vs. *transformation*) and groundings (in *truth* vs. *safety*) are different, there are also significant differences in their bases, form, applicability, specification, methods of improvement and chief characteristics (*accuracy* vs. *dependability*).
– Kuhn's notions about the relativity of knowledge are not easily accepted by most practising scientists, because they believe largely in a world that is real, the truth about which can be found by inquiry, both theoretical and experimental. However, because engineers are more concerned about safety than truth, an engineering outlook can more easily accommodate the relativity of knowledge, provided that 'erring' from the 'target' is towards the safe side.

Acknowledgements Adapted from *The Structural Engineer 86*(2), 33–38, Paradigms, revolutions and models: some insights from Thomas Kuhn for an engineering outlook by W. P. S. Dias, 2008, published by the Institution of Structural Engineers, London.

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