NRC Publications Archive Archives des publications du CNRC

The History and future of limit states design

Allen, D. E.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. / La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.

For the publisher's version, please access the DOI link below. / Pour consulter la version de l'éditeur, utilisez le lien DOI ci-dessous.

Publisher's version / Version de l'éditeur:

<https://doi.org/10.1177/109719639401800101>

Journal of Thermal Insulation and Building Envelopes, 18, July, pp. 3-20, 1994-07

NRC Publications Record / Notice d'Archives des publications de CNRC:

<https://nrc-publications.canada.ca/eng/view/object/?id=78914e26-0af9-4677-ba6b-01055a7ac938>

<https://publications-cnrc.canada.ca/fra/voir/objet/?id=78914e26-0af9-4677-ba6b-01055a7ac938>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

National Research
Council Canada

Conseil national de
recherches Canada

Canada

<http://www.nrc-cnrc.gc.ca/irc>

The History and future of limit states design

NRCC-38475

Allen, D.E.

July 1994

A version of this document is published in / Une version de ce document se trouve dans:
Journal of Thermal Insulation and Building Envelopes, 18, (July), pp. 3-20,
July, 1994, DOI: [10.1177/109719639401800101](https://doi.org/10.1177/109719639401800101)

The material in this document is covered by the provisions of the Copyright Act, by Canadian laws, policies, regulations and international agreements. Such provisions serve to identify the information source and, in specific instances, to prohibit reproduction of materials without written permission. For more information visit <http://laws.justice.gc.ca/en/showtdm/cs/C-42>

Les renseignements dans ce document sont protégés par la Loi sur le droit d'auteur, par les lois, les politiques et les règlements du Canada et des accords internationaux. Ces dispositions permettent d'identifier la source de l'information et, dans certains cas, d'interdire la copie de documents sans permission écrite. Pour obtenir de plus amples renseignements : <http://lois.justice.gc.ca/fr/showtdm/cs/C-42>

National Research
Council Canada

Conseil national
de recherches Canada

Canada

The History and Future of Limit States Design*

D. E. ALLEN

*Institute for Research in Construction
National Research Council of Canada
Ottawa, Ontario
K1A 0R6 Canada*

ABSTRACT: This article discusses limit states design as it relates to practical thinking, provides a brief history of its development, and finally discusses future developments such as limit states design for durability and for the design of materials.

INTRODUCTION

THE MOTIVATION FOR this paper is the happy association the author has had in the development of limit states design in Canada with professors of the University of Alberta who are retiring, plus the fact that the author is also going to retire (but not stop working) within the next year.

THINKING

Like the professors who are retiring, I have always enjoyed doing research. Basically I want to learn something about the world I live in, and tell it to others in a way that will be *useful* to them. Einstein said that "*research is the application of everyday thinking*," but this is also true of engineering practice or any other human activity. If we can think better, then we can do better, both in practice and in research. Limit states design is directly related to the way we think. The following discussion is based on two pocket books by DeBono (1971, 1976).

*Presented at a symposium, 35 Years of Structural Engineering, University of Alberta, June 24, 1994.

EDITOR-IN-CHIEF

MARK BOMBERG
National Research Council of Canada

EDITORIAL BOARD

MARK A. ALBERS
Manville Sales Corporation

CLAES BANKVALL
Swedish National Testing and Research Institute

GEORGE E. COURVILLE
Oak Ridge National Laboratory

FRANCESCO DE PONTE
University of Padova, Italy

CATHERINE LANGLAIS
Isover Saint-Gobain, France

R. GERRY MILLER
Jim Walter Research Corporation

JERZY A. POGORZELSKI
Building Research Institute, Poland

CAO SHENGHAN
Henan Building Materials Research Institute

CLIFF J. SHIRTLIFFE
National Research Council of Canada

TIMOTHY W. TONG
Arizona State University

HAROLD A. TRETHOWEN
Building Research Association of New Zealand

RONALD P. TYE
A-R

JOSEPH F. WEBBER
Webber-Smith Associates, Inc.

NIHAL E. WIJEYSUNDERA
National University of Singapore

DAVID W. YARBROUGH
Tennessee Technological University

The basic biological purpose of thinking is to enable a living organism (including a human) to survive by getting the things that it needs and keeping clear of the things that are dangerous. This is what motivates our thinking. It is basically a matter of knowing what to do about a situation that confronts us. For humans, the basic thinking processes are:

- *instinct*—a prewired reaction to a situation
- *learning*—do/don't rules based on experience
- *understanding*

Understanding is a thinking process that changes a new and unfamiliar situation into one or more familiar ones that we can handle. Understanding is the basis of all scientific and engineering theories and models. One model is the free body diagram based on Newton's law of statics. Another model, load transfer, is illustrated in Figure 1. A third model, a model of how the mind works, is described in Figure 2. Being a construction of the human mind, the models never perfectly represent reality. But if they contain the essential features, and are simple to reconstruct in the mind, they are very useful.

Understanding is extremely powerful because it explains and predicts what happens based on a few generic ideas. The ideas or models, however, must be based on experience. As structural engineers we must understand

FIGURE 1. A living model of the Forth Bridge.

Jelly Model

A dish of jelly initially has a flat surface, onto which drops of water are spooned in a pattern sequence. The water melts the jelly, forming depressions before evaporating. Water subsequently spooned onto or adjacent to a depressed area flows into it and deepens it. Accumulated water in a depression flows into a deeper depression, and eventually a well established system of flow is carved out. Even when no water falls on the surface, there is a flow of water droplets in well-established directions.

FIGURE 2. A model of the mind.

why structures fail, and the way we understand why they fail is by the use of models—ideas we can manipulate. It is these ideas by which we explain why a structure will or will not fail; it is these ideas we use to explain to others why something will or will not work. Understanding is therefore a powerful tool for communication. Lack of communication is behind most of the failures that occur in the practice of structural engineering. The book of Genesis, Chapter 11, describes the failure of the building of the city of Babel, including a very high tower, that was caused by lack of communication because the Lord “confounded their language, that they may not understand one another’s speech.” Hence the word “babble.”

Learning (do/don’t rules) based on experience is another important thinking tool, and prior to Newton, was the only way to design new structures (essentially by trial and error). My feeling is, however, that early builders made use of concepts such as statics (load transfer), at least qualitatively.

LIMIT STATES DESIGN

The basic biological purpose of thinking is to survive by getting the things that we need (structures for different purposes) and to avoid the things that are dangerous or make life difficult (failures of various kinds). The limit states define the things that are dangerous (ultimate limit states) and the things that make life difficult (serviceability limit states). Newton’s Laws of statics and dynamics, testing and theories of structural behaviour

(e.g., elastic theory), provide the means for calculating whether the structure will fail and how. This gives the engineer an understanding useful for practice. Safety factors (load and resistance factors) are incorporated to keep the risk due to the uncertainty in the calculation assumptions sufficiently low. In reality, to make the method practical, limit states design is not quite as realistic as this.

Limit States

It is true that the limit states are based on the things that go wrong, but they also must be predictable, which usually means calculable. For example, exceeding strength may mean collapse or it may mean local damage. Exceeding a deflection limit does not necessarily mean failure unless it causes damage of non-structural components, gaps that allow leakage, or poor drainage. Limit states design makes use of strength and deflection because they are calculable. The more complex failure phenomena of collapse, damage, leakage, etc. are not usually directly calculable; consequently, we use strength and deflection as primary indicators of safety and serviceability failures and, by experience and testing, determine critical values for design and evaluation. Better practical theories help improve the connection to reality; for example, the vibration limit state for human annoyance is now expressed in terms of an acceleration limit rather than a deflection limit. The limit states are categorized as follows:

Ultimate limit states (safety):

- loss of equilibrium (overturning, sliding, etc.)
- structural failure (exceeding the strength of components or parts of the structure)

Serviceability limit states (performance of structure or its appearance):

- local damage (cracking, spalling, slip of components)
- excessive displacement
- excessive vibration

Theories or Models

Although Newton's Laws are essentially unchanged for civil engineering practice, in recent years theories of structural behaviour (mechanics of materials) have broadened to include plastic or slip theory as well as elastic theory, or a convenient mixture of them. Many simplifying assumptions are used to obtain practical formulae for design. It is important, however, that the formulae reflect the essence of the structural behaviour so that intelligent designs are obtained.

Calculations

Calculations range all the way from mental estimates and back-of-the-envelope calculations to finite element calculations, including the determination of dynamic response. In all cases, the essence of structural behaviour under applied load should be self-evident (transparent). Simple calculations are preferred for preliminary design and checking because they tend to generate more thinking (modelling) about the structure than computer calculations. All limit states design calculations are carried out to satisfy the following criteria:

Ultimate limit states:

$$\text{Load effect (force)} < \text{Resistance} \quad (1)$$

Serviceability limit states:

$$\begin{array}{ll} \text{Load effect (deflection, strain, acceleration, etc.)} < \text{Limit indicating onset of} \\ \text{serviceability failure} \end{array} \quad (2)$$

Risk

Load and resistance factors are introduced into the calculations to keep the risk due to uncertainty in the calculation assumptions sufficiently low. The greater the consequences of failure, the lower should be the probability of failure. Ultimate limit states therefore require greater safety margins than the serviceability limit states. In addition, there are greater uncertainties associated with the serviceability limit states, especially regarding the definition of failure. Therefore, safety margins are generally not used for serviceability criteria.

Complexity

When limit states design was introduced, concern was expressed that it was too complicated for practice. In fact, limit states design is as simple or complicated as required to do the job. A key decision in the development of limit states design for buildings was to establish the same load factors and load combinations for all materials in the National Building Code of Canada prior to the development of resistances and resistance factors in the material design standards of the Canadian Standards Association (CSA). The complexity of our structural codes and standards, however, is a serious issue which will be discussed later.

HISTORY OF LIMIT STATES DESIGN

Following some initial studies by Gallileo in 1638, Hooke established the basis of elastic theory (*ut tensio sic vis*) in 1660. In 1686, Newton published his famous book showing how, from three axioms or laws, we can calculate the motions not only of apples falling to the ground, but also of planets and other bodies of the universe, as well as the nature of forces acting on them. This theory was eventually applied not only to separate bodies, but to the structural behaviour of the bodies themselves (Appendix A contains some excerpts from this book). It is clear that Newton was one of the great masters of the thinking process of understanding by modelling.

In 1741, someone investigated damage to the dome of St. Peter's Cathedral, carried out calculations based on Newton's law of statics, determined the cause of damage to be yielding of the circular tie at the base of the dome, and recommended adding more ties (Institution of Structural Engineers, 1980). The report caused a tremendous reaction because, until that time, all structures had been designed and evaluated by experience only.

As an application of his new calculus of variations, Euler, in 1757, derived the height of a pole which would buckle under its own weight. His method provided the basis for determining the elastic buckling resistance of compression members.

In 1773, Coulomb derived the critical height of a vertical embankment for a cohesive soil:

$$H_c = 4c \cdot \cos \phi / [\gamma(1 - \sin \phi)] \quad (3)$$

where H_c is the critical height and c , ϕ and γ are the cohesion, the angle of internal friction, and the density of the soil. The formula is based on Newton's law of statics, the shear strength of the soil (equal to the sum of its cohesive and frictional resistance), and the assumption that the soil fails by sliding along a plane. This is a version of the limit state formula, Equation (1), useful for civil engineering practice. In 1846, Collin advanced Coulomb's theory to include sloped embankments:

$$H_c = 4c \cdot \cos \phi \cdot \sin \beta / \{\gamma[1 - \cos(\beta - \phi)]\} \quad (4)$$

where, in addition to the previous notation, β is the slope of the bank. Actually, the slip plane is curved (Figure 3), but Equation (4) is a reasonably close solution. In 1857, Rankine established the limit states of active and passive pressure in a cohesionless soil, an application of the theory of plasticity (as compared to simple sliding).

In 1807, Young provided a comprehensive approach to analyzing struc-

FIGURE 3. Embankment—surface of failure (Collin, 1846).

tures by the application of statics, geometry and the modulus of elasticity, as well as available test data. This was based on scientific investigations since the time of Galileo. In 1822, Cauchy developed the theory of elasticity using the concepts of stress and strain.

Despite these events, design by experience only continued well into the nineteenth century because, in fact, it worked very well. It worked well because changes in construction materials and procedures were very slow. For example, the first iron bridge built in 1779 (Figure 4) was essentially a replica of a masonry arch bridge, although this was an intelligent decision because cast iron is weak in tension (similar to masonry). The industrial revolution, however, changed this approach based on experience only. To handle the rapid changes in materials (in particular, steel) and construction techniques, civil engineers developed the methods of Young and Cauchy into practical allowable stress design. An early example is a book on carpentry by Tredgold (1820) in which he showed how to calculate the deflection as well as the stresses (pressures) in wood structures which, along with test data for resistance in tension, compression (parallel and perpendicular to the grain) and flexure, allowed engineers to design wood structures. In this book, he recommended a deflection limit of $\text{span}/480$ to prevent damage to plaster ceilings and excessive floor vibration, a criterion that has not changed much over the years. The gradual development of allowable stress design is reflected in subsequent editions of Tredgold's book up to 1884.

Allowable stress design provided engineers with a better understanding of what makes structures fail and, as a result, they were able to successfully

FIGURE 4. The Iron Bridge, Coalbrookdale, England (1779).

design and build structures never dreamed of before — long-span bridges and tall buildings. Allowable stress design began to appear in building codes towards the end of the nineteenth century. During this development, different modes of failure had to be incorporated, such as buckling and fatigue. Allowable stress design was a revolution because it provided engineers with a unified tool for the design and evaluation of any structure. It therefore has features similar to Newton's "system of the world" (see Appendix A).

In the twentieth century, even more rapid changes have taken place. Terzaghi introduced soil mechanics in 1925 as a tool for practice. We also know more about how structures behave, and elastic theory has been replaced by plastic and other theories, particularly for the ultimate limit states. Equation (4), for example, is based on plastic slip theory, not elastic stresses. In addition, new construction techniques have resulted in lighter structures with longer spans, and serviceability problems such as movements and vibrations have increased as a consequence. Finally, safety factors can be determined using risk and reliability methods as well as experience. Limit states design is an evolution of allowable stress design, with the accent changed from elastic theory and material failure to failure of the structure to perform its function.

The first development of limit states design as a unified procedure for all structures was initiated in the USSR in 1954. Outside the USSR, the first

It handles only structural and soil mechanics—that is strength, stability, deflection, vibration and local damage. It ignores all other considerations. To illustrate this narrow perspective, Table 1 reviews the contents of a typical structural standard to see how well it addresses the problems that occur in practice. The first conclusion of Table 1 is that structural engineers understand ultimate limit states and therefore there are fewer problems (collapses). In fact, the space in structural standards devoted to ultimate limit states, currently close to 200 pages, is disproportionate and should be shortened (i.e., simplified).

The second conclusion of Table 1 is that more should be done about durability. An example for the need for a better approach to durability is the bridge deck/parking garage disintegration problem—a problem that costs billions of dollars every year to repair (a hidden tax). This problem arose from two changes: the introduction of salt as a de-icer for roads and the introduction of multistorey parking garages. This was not a new problem in the practice of civil engineering, however. This problem was well known for many years to engineers who design marine structures. Why was it that this problem was not communicated to bridge and building engineers when salt was introduced on roads? The answer is that we, as a profession, did not understand the problem. We did not understand that water gradually penetrates concrete (a porous material) and that the dissolved chlorides in the water depassivate the oxide layer on the steel, causing active corrosion of the steel and, as a consequence, either delamination of the concrete cover or fracture of prestressing wires. If we understood this basic failure mechanism, and the environmental conditions that cause it to occur, the communication would have been much better, and more timely action would have been taken to prevent the problem from becoming a major epidemic.

I recall that when the problem first occurred for parking garages in the 1970s, it was blamed on the introduction of limit states design. Actually, both allowable stress design and limit states design completely missed this particular failure mechanism. However, it should have been covered by limit states design. Delamination of concrete is local damage which restricts the use of the garage and promotes further corrosion. Fracture of prestressing wires threatens life safety. The legal state-of-the-art answer was “we did not

Table 1. Typical structural design standard.

Limit States	Length	Requirements	Problems	Recommendation
Ultimate	100 Pages	Many	Few	Simplify
Serviceability	1 Page	Few	More	Pull together
Durability	1 Sentence	Vague	Most	Improve understanding

know it would happen." We have since done something about this epidemic, a new CSA standard on parking garages, but what if some other epidemic rears its head?

Limit States Design for Durability

Efforts are being made to prevent or at least minimize these kinds of epidemics in the future. One effort is a CSA guideline on durability in buildings (CSA S478), which is under preparation. The recommendations of the guideline are expressed as follows:

$$\text{Predicted service life} > \text{Design service life} \quad (5)$$

where design service life of a building component is based on a number of considerations, including life-cycle cost. Hard-to-replace components such as piles or wall connectors obviously require a much longer service life than easy-to-replace components such as paint or shingles. Life-threatening failures must also be checked for safety, as currently required in structural standards.

The CSA guideline recommends the following methods for predicting service life:

- experience with the same assembly of components (such as a roof, wall, foundation or balcony) in similar environments
- modelling of the deterioration process
- testing

The first and third methods are not new but the second one, modelling, is. Modelling requires a consideration of:

1. The environment adjacent to and within components of an assembly, determined from a consideration of the environment outside the building (including the ground), the environment within the building, and the transport and accumulation of environmental agents on the surface and within building assemblies and their components
2. The relative movement of adjacent components, determined from the dimensional changes of the components due to stress, temperature, moisture changes and ground movements
3. The deterioration or damage mechanisms that occur as a consequence of the environment and the relative movements of connected components
4. The limit state (e.g., fracture, damage and gaps; also, discolouration is

added to the category of serviceability limit states above) defining functional failure of the component (e.g., air barrier, pile, shingle, caulking, connector, protective membrane, visual facade)

These considerations show that the prediction of service life is obviously much more complicated to model than the structural-mechanics failures embodied in current limit states design. Hence the word used is "consideration," not "calculation." These considerations are currently evaluated by the application of "building science principles," as described in a number of Canadian Building Digests published by the Natural Research Council of Canada (NRC). Practical limit states calculations are therefore not yet developed for durability. Aspects of the modelling, however, have been developed, mainly for research purposes. Research is underway at NRC to pull these aspects together into something more nearly like limit states design. One may, for example, determine the moisture content (degree of saturation) of any component in an assembly by computer simulation and apply the following approximate limit states criteria (Bomberg and Shirtliffe, 1993):

1. Freeze-thaw: failure occurs if the moisture content (degree of saturation) is greater than that for which freezing causes fracture.
2. Corrosion/rotting: the predicted service life is determined when the time of wetness (period of time when the moisture content and temperature are suitable for the process to occur, including weighting functions for its intensity) is sufficient to cause failure.

At this stage of development, it is better for practitioners to simply be well aware of the basic mechanisms of failure, the conditions under which they occur (moisture with or without contaminants, O_2 , CO_2 , UV, temperature, etc.), and the basic mechanisms of transport and accumulation of these agents, particularly moisture and air. Guidance on these mechanisms, and the conditions under which they occur, will be contained in the Appendices to the CSA guideline on the durability of buildings. Some models that appear to be useful in describing these mechanisms are:

1. The corrosion cell (Figure 5): this model is useful to indicate the conditions under which corrosion occurs and the type and intensity of corrosion, but it requires explanation (as will be provided in an Appendix of CSA S478).
2. Mechanisms of rain penetration: the forces causing rain penetration are the kinetic energy of rain drops, capillary suction, gravity and air pressure. The rain screen (Figure 6), a model solution for the prevention of rain penetration, is based primarily on the concept of gravity drainage. A more effective solution is the pressure equalized rain screen, which not

FIGURE 5. The corrosion cell.

FIGURE 6. The rain screen.

only provides gravity drainage but also prevents rain penetration due to air pressure.

Research is underway towards limit states design for durability, and the features of limit states design will change as a consequence. It appears that the development of limit states design for durability is at the same stage as structural-mechanics in the early nineteenth century, so it will take some time.

Limit States Design for Materials

We are beginning to have the ability to design and build materials (micro-structures). Prescribed molecular arrangements of materials are already being achieved in the laboratory. In addition, a new scientific endeavor "nanotechnology" is devoted to the construction of new materials (essentially a prescribed biological self-building process). These materials should be designed not only to produce objects useful for people, but also to avoid failures of various kinds, including deterioration failures. This is another potential application of limit states design concepts.

CONCLUSION

The following paraphrases a comment in a recent magazine article (Peters, 1994). *The best practitioners keep simple models of structures and how they behave in their mind . . . so simple that you can mull them over while laying awake at night, driving a car, walking, or keeping yourself occupied during a dull meeting or talk. In addition to this, you have to explain your ideas to others, and the only way to do this is by simple models.*

It is therefore important that the models we researchers recommend are suitable for this purpose. Black boxes (formerly handbook tables, now computer printouts) are not acceptable.

APPENDIX A: EXCERPTS FROM NEWTON, 1686

From "Preface to the First Edition"

Since the ancients (as we are told by Pappus) esteemed the science of mechanics of greatest importance in the investigation of natural things, and the moderns, rejecting substantial forms and occult qualities, have endeavored to subject the phenomena of nature to the laws of mathematics, I have in this treatise cultivated mathematics as far as it relates to philosophy. The ancients considered mechanics in a twofold respect; as rational, which proceeds accurately by dem-

onstration, and practical. To practical mechanics all the manual arts belong, from which mechanics took its name. But as artificers do not work with perfect accuracy, it comes to pass that mechanics is so distinguished from geometry that what is perfectly accurate is called geometrical; what is less so, is called mechanical. However, the errors are not in the art, but in the artificers. He that works with less accuracy is an imperfect mechanic; and if any could work with perfect accuracy, he would be the most perfect mechanic of all, for the description of right lines and circles, upon which geometry is founded, belongs to mechanics. Geometry does not teach us to draw these lines, but requires them to be drawn, for it requires that the learner should first be taught to describe these accurately before he enters upon geometry, then it shows how by these operations problems may be solved. To describe right lines and circles are problems, but not geometrical problems. The solution of these problems is required from mechanics, and by geometry the use of them, when so solved, is shown; and it is the glory of geometry that from those few principles, brought from without, it is able to produce so many things. Therefore geometry is founded in mechanical practice, and is nothing but that part of universal mechanics which accurately proposes and demonstrates the art of measuring. But since the manual arts are chiefly employed in the moving of bodies, it happens that geometry is commonly referred to their magnitude, and mechanics to their motion. In this sense rational mechanics will be the science of motions resulting from any forces whatsoever, and of the forces required to produce any motions, accurately proposed and demonstrated. This part of mechanics, as far as it extended to the five powers which relate to manual arts, was cultivated by the ancients, who considered gravity (it not being a manual power) no otherwise than in moving weights by those powers. But I consider philosophy rather than arts and write not concerning manual but natural powers, and consider chiefly those things which relate to gravity, levity, elastic force, and resistance of fluids, and the like forces, whether attractive or impulsive; and therefore I offer this work as the mathematical principles of philosophy, for the whole burden of philosophy seems to consist in this — from the phenomena of motions to investigate the forces of nature, and then from these forces to demonstrate the other phenomena; and to this end the general propositions in the first and second Books are directed. In the third Book I give an example of this in the explication of the System of the World; for by the propositions mathematically demonstrated in the former Books, in the third I derive from the celestial phenomena the forces of gravity with which bodies tend to the sun and the several planets. Then from these forces, by other propositions which are also mathematical, I deduce the motions of the planets, the comets, the moon, and the sea. I wish we could derive the rest of the phenomena of Nature by the same kind of reasoning from mechanical principles, for I am induced by many reasons to suspect that they may all depend upon certain forces by which the particles of bodies, by some causes hitherto unknown, are either mutually impelled towards one another, and cohere in regular figures, or are repelled and recede from one another. These forces being unknown, philosophers have hitherto attempted the search of Nature in vain; but I hope the principle here

laid down will afford some light either to this or some truer method of philosophy.

Is. Newton

Cambridge, Trinity College, May 8, 1686.

From Book I

AXIOMS, OR LAWS OF MOTION

Law I

Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it.

Projectiles continue in their motions, so far as they are not retarded by the resistance of the air, or impelled downwards by the force of gravity. A top, whose parts by their cohesion are continually drawn aside from rectilinear motions, does not cease its rotation, otherwise than as it is retarded by the air. The greater bodies of the planets and comets, meeting with less resistance in freer spaces, preserve their motions, both progressive and circular, for a much longer time.

Law II

The change of motion is proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed.

If any force generates a motion, a double force will generate double the motion, a triple force triple the motion, whether that force be impressed altogether and at once, or gradually and successively. And this motion (being always directed the same way with the generating force), if the body moved before, is added to or subtracted from the former motion, according as they directly conspire with or are directly contrary to each other; or obliquely joined, when they are oblique, so as to produce a new motion compounded from the determination of both.

Law III

To every action there is always opposed an equal reaction: or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.

Whatever draws or presses another is as much drawn or pressed by that other. If you press a stone with your finger, the finger is also pressed by the stone. If a horse draws a stone tied to a rope, the horse (if I may so say) will be equally drawn back towards the stone; for the distended rope, by the same endeavor to relax or unbend itself, will draw the horse as much towards the stone as it does the stone towards the horse, and will obstruct the progress of the one as much

as it advances that of the other. If a body impinge upon another, and by its force change the motion of the other, that body also (because of the equality of the mutual pressure) will undergo an equal change, in its own motion, towards the contrary part. The changes made by these actions are equal, not in the velocities but in the motions of bodies; that is to say, if the bodies are not hindered by any other impediments. For, because the motions are equally changed, the changes of the velocities made towards contrary parts are inversely proportional to the bodies. This law takes place also in attractions, as will be proved in the next Scholium.

From Book III

RULE III

The qualities of bodies, which admit neither intensification nor remission of degrees, and which are found to belong to all bodies within the reach of our experiments, are to be esteemed the universal qualities of all bodies whatsoever.

For since the qualities of bodies are only known to us by experiments, we are to hold for universal all such as universally agree with experiments; and such as are not liable to diminution can never by quite taken away. We are certainly not to relinquish the evidence of experiments for the sake of dreams and vain fictions of our own devising; nor are we to recede from the analogy of Nature, which is wont to be simple, and always consonant to itself. We no other way know the extension of bodies by our senses, nor do these reach it in all bodies; but because we perceive extension in all that are sensible, therefore we ascribe it universally to all others also. That abundance of bodies are hard, we learn by experience; and because the hardness of the whole arises from the hardness of the parts, we therefore justly infer the hardness of the undivided particles not only of the bodies we feel but of all others. That all bodies are impenetrable, we gather not from reason, but from sensation. The bodies which we handle we find impenetrable, and thence conclude impenetrability to be an universal property of all bodies whatsoever. That all bodies are movable, and endowed with certain powers (which we call the inertia) of persevering in their motion, or in their rest, we only infer from the like properties observed in the bodies which we have seen. The extension, hardness, impenetrability, mobility, and inertia of the whole, result from the extension, hardness, impenetrability, mobility, and inertia of the parts; and hence we conclude the least particles of all bodies to be also all extended, and hard and impenetrable, and movable, and endowed with their proper inertia. And this is the foundation of all philosophy.

REFERENCES

- Bomberg, M. T. and C. J. Shirtliffe. 1993. "A Conceptual System of Moisture Performance Analysis," Chapter 26 of *Moisture Control in Buildings*, ASTM Manual Series: MNL 18.

- Collin, A. 1846. *Landslides in Clays*. Translated by W. R. Schriever, University of Toronto Press, 1956.
- DeBono, E. 1971. *The Mechanism of Mind*. Pelican Books.
- DeBono, E. 1976. *Practical Thinking*. Pelican Books.
- Institution of Structural Engineers. 1980. *Appraisal of Existing Structures*. London: The Institution of Structural Engineers, p. 60.
- Newton, I. 1686. *Mathematical Principles of Natural Philosophy and the System of the World*. Translated by A. Motte in 1729, revised and annotated by F. Cajori, University of California Press, Berkeley, CA, 1960.
- Peters, T. 1994. *Information Is the Enemy of Intelligence*. Canadian, pp. 51-52.
- Rankine, W. J. M. 1857. "On the Stability of Loose Earth," *Philosophical Transactions, Royal Society*, 147(1):9-27.
- Tredgold, T. 1820. *Elementary Principles of Carpentry*. First Edition 1820, Third Edition 1840 printed by Nuttall and Hodgson, London.
- Young, T. 1807. *Lectures on Natural Philosophy* (unpublished).

Royal Bank Letter

Published by Royal Bank of Canada

The Power of Little Things

Details, details, details! Most of us get annoyed with them sometimes, but we ignore them at our peril. We only have to make sure that they don't become an end in themselves. Otherwise, we should show a respect for little things, because they are crucial to living. Especially to living happily . . .

NUCLEAR SCIENTISTS ARE more conscious than most that the smallest things in existence are, in a sense, the biggest. The energy released by splitting atoms is, of course, the strongest force ever produced by artificial means. On top of that, physicists are convinced that the inconceivably tiny bits of matter they call elementary particles are the basic building blocks of the universe. Without them, nothing else could exist.

Science in general holds many lessons in the importance of little things. Perhaps the greatest advance in medical history came when the French chemist and biologist Louis Pasteur proved that microscopic organisms cause disease and death among animals and human beings. Having hunted down several strains of infectious microbes in thousands of experiments, Pasteur was able to develop safeguards against them. More than anyone else, he was responsible for a near-doubling of the average human life span since he did his work in the latter part of the 19th century.

Through his painstaking methods and towering prestige, Pasteur pointed the way to the modern approach to research. It is based on the simple principle that nothing that is big enough to be detected, if only partly, can be overlooked. The same respect for detail shows in the statistical analysis of observations which often leads to scientific break-throughs. Today, re-