Appendix B

Mathematical formalities and style

We collect here a brief account of the various mathematical conventions used throughout this work, and discuss some basic mathematical issues that arise in probability theory. Careless notation has led to so many erroneous results in the recent literature that we need to find rules of notation and terminology that make it as difficult as possible to commit such errors.

A mathematical notation, like a language, is not an end in itself but only a communication device. Its purpose is best served if the notation, like the language, is allowed to evolve with use. This evolution usually takes the form of abbreviations for whatever expressions recur often, and reducing the number of symbols when their meaning can be read from the context.

But a living, changing language still needs a kind of safe harbor in the form of a fixed set of rules of grammar and orthography, hidden away in a dictionary for use when ambiguities threaten. Likewise, probability theory needs a fixed set of normative rules on which we can fall back in case of doubt. We state here our formal rules of notation and logical hierarchy; all chapters from Chapter 3 on start with these standard forms, and evolve from them. A notation which is so convenient that it is almost a necessity in one chapter might be only confusing in the next; so each separate topic must be allowed its own independent evolution from the standard beginning.

B.1 Notation and logical hierarchy

In our formal probability symbols (those with a capital P)

$$P(A|B) \tag{B.1}$$

the entries A, B always stand for *propositions*, with a sufficiently clear meaning (at least to us) that we are willing to use them as elements of Aristotelian logic, obeying a Boolean algebra. Thus $P(A|B)$ does not denote a 'function' in the usual sense.

We repeat the warning that a probability symbol is undefined and meaningless if the conditioning statement B happens to have zero probability in the context of our problem (for example, if $B = CD$, but $P(C|D) = 0$). Failure to recognize this can lead to erroneous calculations – just as inadvertently dividing by an expression that happens to have the value zero can invalidate all subsequent results.

To preserve the purity of our probability symbols (B.1) we must have also other symbols for probabilities. Thus, if proposition A has the meaning

$$A \equiv \text{the variable } q \text{ has the particular value } q' \,, \tag{B.2}$$

there is a tendency to write, instead of $P(A|B)$,

$$P(q'|B). \tag{B.3}$$

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But q' is not a proposition, and so the writer evidently intends the symbol (B.3) to stand now for an ordinary mathematical function of the variable q'. In our system this is illegitimate, and so, when an ordinary mathematical function is intended, we shall take the precaution of inventing a different functional symbol such as $f(\quad|\quad)$, writing (B.3) instead as

$$f(q'|B). \tag{B.4}$$

Now the distinction between (B.3) and (B.4) may appear to some readers as pedantic nitpicking; so why do we insist on it? Many years ago, the present writer would also have dismissed this point as too trivial to deserve mention; but later experience has brought to light cases where failure to maintain the distinction in clear sight has tricked writers into erroneous calculations and conclusions. The amount of time and effort this has wasted – and which is still being wasted in this field – justifies our taking protective measures against it.

The point is that a proposition A is a verbal statement that may indeed specify the value of some variable q; but it generally contains qualifying clauses also:

$$A \equiv \text{the variable } q \text{ has the value } q' \textit{ if the proposition } B \textit{ is true}. \tag{B.5}$$

If we try to take the short-cut of replacing A by q' in the probability symbol, we lose sight of the qualification. Later in the calculation, the same variable q may appear in a proposition A_1 with a different qualification B_1; and again one may be tempted to replace A_1 by q' in the probability symbol. Still later in the calculation the same probability symbol will appear with two different meanings, and one is tricked into supposing that they represent the same quantity.

This is what happened in the famous 'marginalization paradox', in which the same probability symbol was used to denote probabilities conditional on two different pieces of prior information, with bizarre consequences described in Jaynes (1980) and in Chapter 15. This confusion is still causing trouble in probability theory, for those who have not yet understood it.

However, we are not fanatics about this. In cases so simple that there is very little danger of error anyway, we allow a compromise and follow the custom of most writers, even though it is not a strictly consistent notation. In probability symbols with a small p, we shall allow the arguments to be either propositions or numbers, in any mix: thus, if A is a proposition and q a number, the equation

$$p(A|B) = p(q|B) \tag{B.6}$$

is permitted; but with the warning that when small p symbols are used, the reader must judge their meaning from the context, and there is a possibility of error from failure to read them correctly.

A common and useful custom is to use Greek letters to denote parameters in a probability distribution, the corresponding Latin letters for the corresponding functions of the data. For example, one may denote a probability average (the mean of a probability distribution) by $\mu = \langle x \rangle = E(x)$, and then the average over the data would be $m = \overline{x} = n^{-1} \sum x_i$. We shall adhere to this except when it would be confusing because of a conflict with some other long established usage.

B.2 Our 'cautious approach' policy

The derivation of the rules of probability theory from simple desiderata of rationality and consistency in Chapter 2 applied to discrete, finite sets of propositions. Finite sets are therefore our safe harbor, where Cox's theorems apply and nobody has ever been able to produce an inconsistency from application of the sum and product rules. Likewise, in elementary arithmetic finite sets are the safe harbor in which nobody has been able to produce an inconsistency from applying the rules of addition and multiplication.

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As soon as we try to extend probability theory to infinite sets, we are faced with the need to exercise the same kind of mathematical caution that one needs in proceeding from finite arithmetic expressions to infinite series. The 'parlor game' at the beginning of Chapter 15 illustrates how easy it is to commit errors by supposing that the operations of elementary arithmetic and analysis, that are always safe on finite sets, may be carried out also on infinite sets.

In probability theory, it appears that the only safe procedure known at present is to derive our results first by strict application of the rules of probability theory on finite sets of propositions; then, after the finite-set result is before us, observe how it behaves as the number of propositions increases indefinitely. There are, essentially, three possibilities:

(1) It tends smoothly to a finite limit, some terms just becoming smaller and dropping out, leaving behind a simpler analytical expression.
(2) It blows up, i.e. becomes infinite in the limit.
(3) It remains bounded, but oscillates or fluctuates forever, never tending to any definite limit.

In case (1) we say that the limit is 'well-behaved' and accept the limit as the correct solution on the infinite set. In cases (2) and (3) the limit is ill-behaved and cannot be considered a valid solution to the problem. Then we refuse to pass to the limit at all.

This is the 'look before you leap' policy: in principle, we pass to a limit only after verifying that the limit is well-behaved. Of course, in practice this does not mean that we conduct such a test anew on every problem; most situations arise repeatedly, and rules of conduct for the standard situations can be set down once and for all. But in case of doubt, we have no choice but to carry out this test.

In cases where the limit is well-behaved, it may be possible to get the correct answer by operating directly on the infinite set, but one cannot count on it. If the limit is not well-behaved, then any attempt to solve the problem directly on the infinite set would have led to nonsense, *the cause of which cannot be seen if one looks only at the limit, and not the limiting process*. The paradoxes noted in Chapter 15 illustrate some of the horrors that have resulted from carelessness in this regard.

B.3 Willy Feller on measure theory

In contrast to our policy, many expositions of probability theory begin at the outset to try to assign probabilities on infinite sets, both countable or uncountable. Those who use measure theory are, in effect, supposing the passage to an infinite set already accomplished before introducing probabilities. For example, Feller advocates this policy and uses it throughout his second volume (Feller, 1966).

In discussing this issue, Feller (1966) notes that specialists in various applications sometimes 'deny the need for measure theory because they are unacquainted with problems of other types and with situations where vague reasoning did lead to wrong results'. If Feller knew of any case where such a thing has happened, this would surely have been the place to cite it – yet he does not. Therefore we remain, just as he says, unacquainted with instances where wrong results could be attributed to failure to use measure theory.

But, as noted particularly in Chapter 15, there are many documentable cases where careless use of infinite sets has led to absurdities. We know of no case where our 'cautious approach' policy leads to inconsistency or error; or fails to yield a result that is reasonable.

We do not use the notation of measure theory because it presupposes the passage to an infinite limit already carried out at the beginning of a derivation – in defiance of the advice of Gauss, quoted at the start of Chapter 15. But in our calculations we often pass to an infinite limit at the end of a derivation; then we are in effect using 'Lebesgue measure' directly in its original meaning. We think that failure to use current measure theory notation is not 'vague reasoning'; quite the opposite. It is a matter of doing things in the proper order.

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Feller does acknowledge, albeit grudgingly, the validity of our position. While he considers passage to a well-defined limit from a finite set unnecessary, he concedes that it is 'logically impeccable' and has 'the merit of a good exercise for beginners'. That is enough for us; for in this field we are all beginners. Perhaps the beginners who have the most to learn are those who now decline to practice this very instructive exercise.

We note also that measure theory is not always applicable, because not all sets that arise in real problems are measurable. For example, in many applications we want to assign probabilities to functions that we know in advance are continuous. But Mark Kac (1956) notes that the class of continuous functions is not measurable; its inner measure is zero, its outer measure one.[1] Being a mathematician, he was willing to sacrifice some aspects of the real world in order to conform to his preconception that his sets should be measurable. So to get a measurable class of functions he enlarges it to include the everywhere discontinuous functions. But then the resulting measure is concentrated 'almost entirely' on just the class of functions that, for physical reasons, we need to exclude most strongly from our set! So, while Kac gets a solution that is satisfactory to him, it is not always the solution to a real problem.

Our value judgment is just the opposite; being concerned with the real world, we are willing to sacrifice preconceptions about measurable classes in order to preserve the aspects of the real world that are important in our problem. In this case, a form of our cautious approach policy will always be able to bypass measure theory in order to get the useful results we seek; for example, (1) expand the continuous functions in a finite-number n of orthogonal functions, (2) assign probabilities to the expansion coefficients in a finite-dimensional space R_n; (3) do the probability calculation; (4) pass to the limit $n \to \infty$ at the end. In a real problem we find that increasing n beyond a certain value makes a numerically negligible change in our conclusions (i.e. if we are calculating to a finite number of decimal places, a strictly nil change). So we need never depart from finite sets after all.[2] Useful results, in various applications from statistical mechanics to radar detection, are found in this way.

It appears to us that most – perhaps all – of the paradoxes of infinite sets that arise in calculations are caused by the persistent tendency to pass to infinite limits too soon. Usually, this means that crucially important information is lost before we have a chance to use it; the case of nonconglomerabilty in Chapter 15 is a good example. In any event, whatever the cause and the cure, our position is that the paradoxes of infinite sets belong to the field of infinite-set theory, and have no place in probability theory. Our self-imposed inhibition of considering only finite sets and their well-behaved limits enables us to avoid all of the useless and unnecessary paradoxing that has appeared in the recent statistical literature. From this experience, we conjecture that perhaps all correct results in probability theory are either combinatorial theorems on finite sets or well-behaved limits of them.

But on this issue, too, we are not fanatics. We recognize that the language of set and measure theory was a useful development in *terminology*, in some cases enabling one to state mathematical propositions with a generality and conciseness that is quite lacking in 19th century mathematics. Therefore we are happy to use that language whenever it contributes to our goal, and we could hardly get along without an occasional 'almost everywhere' or 'of measure zero' phrase. However, when we use a bit of measure theory, it is never in the thought that this makes the argument more rigorous; but only a recognition of the compactness of that language.

Of course, we stand ready and willing to use set and measure theory – just as we stand ready and willing to use number theory, projective geometry, group theory, topology, or any other part of mathematics – wherever this should prove helpful for the technique of finding a result or for

[1] A continuous function is defined everywhere by specifying it at each rational point, whose number is countable. Thus the class of continuous functions is very much smaller than the class of everywhere discontinuous functions.

[2] But, even in the limit, the number of expansion coefficients is only countable, corresponding nicely to the property of continuous functions noted in footnote 1.

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understanding it. But we see no reason why we must state every proposition in set/measure theory terminology and notation in cases where plain English is clearer and, as far as we can see, not only more efficient for our purposes but actually safer.

Indeed, an insistence that all of mathematics be stated in that language all of the time can place unnecessary burdens on a theory, particularly one intended for application in the real world. It can also degenerate into an affectation, used only linguistically rather than functionally. To give every old, familiar notion a new, impressive name and symbol unknown to Gauss and Cauchy has nothing to do with rigor. It is, more often than not, a form of gamesmanship whose real purpose is to conceal the Mickey Mouse triviality of what is being done. One would blush to state it in plain English.

B.4 Kronecker vs. Weierstrasz

At this point, a question will surely be in the reader's mind. After our emphasis on the safety of finite sets, it might appear that all of analysis, which seems to do everything on uncountable sets, is suspect. Let us explain why this is not the case, and why we do place full confidence in the analysis of Cauchy and Weierstrasz.[3]

In the late 19th century, both Karl Weierstrasz (1815–1897) and Leopold Kronecker (1823–1891) were at the University of Berlin,[4] lecturing on mathematics. A difference developed between them, which has been greatly exaggerated by later commentators, and it is only in the past few years that the real truth about their relationship has started to emerge.

Briefly, Weierstrasz was concerned with perfecting the tools of analysis – particularly power series expansions – with the specific case of elliptic functions in mind as an application. Kronecker was more concerned with the foundations of mathematics in number theory, and questioned the validity of reasoning that does not start back at the integers. On a superficial view, this might seem to deny us all the beautiful results of analysis. Even Morris Kline (1980) gives the impression that Kronecker's asceticism denies us some of the important advances in modern mathematics. But the record has been distorted.

For example, Bell (1937, p. 568) paints a picture of Weierstrasz as the great analyst, putting the final finishing touches on the work of Cauchy, and Kronecker as a mere gadfly, attacking the validity of everything he did without making any positive contribution. It is true that Kronecker annoyed Weierstrasz on at least one occasion, documented in Weierstrasz's correspondence; yet there was not really much conflict in their principles. To understand their positions, we just need a better witness than Eric Temple Bell, and fortunately we have two of them: Henri Poincaré and Harold M. Edwards.

When Weierstrasz died in 1897, Poincaré (1899) wrote a summary of his mathematical work, in which he pointed out that: '. . . all the equations which are the object of analysis and which deal with continuous magnitudes are nothing but symbols, replacing an infinite collection of inequalities relating whole numbers.' In the words of H. M. Edwards (1989), '. . . *both* Weierstrasz and Kronecker based their mathematics entirely on the whole numbers, so that all their work shared in the certitude of arithmetic.' Edwards notes also that several reactionary views commonly attributed to Kronecker are hearsay, for which no support can be found in Kronecker's own words.

For example, Bell (1937, p. 568) tells us, without any supporting documentation, that Kronecker, on hearing of Lindemann's proof that π is transcendental, asked of what use that could be, '. . . since

[3] Indeed, the writer's first love in mathematics was not probability theory, but the use of Cauchy's complex integration to solve systems of differential equations and boundary conditions, choosing the integrand to satisfy the differential equation, and then the contour of integration to satisfy the boundary conditions. Three generations of theoretical physicists have exploited this method enthusiastically; it is great fun to teach.

[4] More specifically, Weierstrasz was there from 1856–1897 and Kronecker from 1861–1891. E. T. Bell (1937) gives a portrait of the young Weierstrasz and a photograph of the old Kronecker; H. M. Edwards (1989) gives photographs of the old Weierstrasz and the young Kronecker.

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irrational numbers do not exist?' The documentable fact is that Kronecker's own work on number theory (Kronecker, 1901, p. 4) describes the formula of Leibniz:

$$\frac{\pi}{4} = 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \cdots \tag{B.7}$$

as 'one of the most beautiful arithmetic properties of the odd integers, namely that of determining this geometrical irrational number.' Evidently, Kronecker considered irrational numbers as possessing at least enough 'existence' to allow them to be precisely defined. It is true that he did not consider irrationals to be a necessary part of the foundations; indeed, how could he, or anybody else, think that, in view of relations like the above one, which allow irrationals to be defined entirely in terms of integers? Curiously, Weierstrasz also defined irrationals from the integers in just the same way; so where was the difference between them?

The difference between Kronecker and Weierstrasz was aesthetic rather than substantive: Kronecker wants to keep first principles (the origin in the integers) constantly in view, while Weierstrasz, having made a new construction, is willing to forget the steps by which it was made, and use it as an element in its own right for further construction. Put in modern computer terminology, Weierstrasz did not deny Kronecker's 'machine language' basis of all mathematics, but wanted to develop analysis in a higher level language. Edwards points out that Kronecker's principles, '... in his mind and in fact, were no different from the principles of his predecessors, from Archimedes to Gauss.'

Thanks largely to the historical research of H. M. Edwards, the truth is emerging and Kronecker is being vindicated and rehabilitated. Perhaps Kronecker was overzealous, and perhaps he misunderstood the position of Weierstrasz; but events since then suggest that he was not zealous enough in his own cause. His failure to respond to Georg Cantor (1845–1918) seems unfortunate, but easy to understand.

To Kronecker, Cantor's ideas were so *outré* that they had nothing to do with mathematics, and there was no reason for a mathematician to take any note of them. If the editors of the mathematical journals made the mistake of publishing such stuff, that was their problem, not his. But the messages that Kronecker did communicate contained some very important truth; in particular, he complained that much of set theory was fantasy because it was not algorithmic (i.e. it contained no rule by which one could construct a given element or decide, in a finite number of operations, whether a given element did or did not belong to a given set). Today, with our computer mentalities, this seems such an obvious platitude that it is hard to imagine anyone ignoring it, much less denying it; yet that is just what happened. We think that, had mathematicians paid more attention to this warning of Kronecker, mathematics might be in a more healthy state today.

B.5 What is a legitimate mathematical function?

Much of the difference between current pure and applied mathematics lies in their different conceptions of the notion of a 'function'. Historically, one started with the well-behaved analytic entire functions like $f(x) = x^2$ or $f(x) = \sin x$. Then these 'good functions' were generalized, but in two different ways. In pure mathematics, the idea was generalized in such a way that set theory notions remained valid; first to piecewise continuous functions, then to quite arbitrary rules by which, given a number x, one can define another number f. Then, perceiving that a function or its argument need not be limited to real or complex numbers, this was generalized further to an arbitrary mapping of one set X onto another set F, the elements of which could be almost anything.

In applied mathematics, the notion of a function was generalized in a very different way, so that the useful *analytical operations* that we perform on functions remain valid. Perhaps the most

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important hint was provided by the operation of the Fourier transform. This is still a mapping, but at the higher level of mapping one function $f(x)$ onto another $F(k)$. This mapping was defined by the integrals

$$F(k) = \int \mathrm{d}x \mathrm{e}^{\mathrm{i}kx} f(x), \qquad f(x) = \frac{1}{2\pi} \int \mathrm{d}x \mathrm{e}^{-\mathrm{i}kx} F(k). \tag{B.8}$$

If we indicate this Fourier transform pair symbolically as

$$\Big[f(x) \leftrightarrow F(k) \Big] \tag{B.9}$$

we find the interesting properties that under translation, convolution, and differentiation,

$$\Big[f(x-a) \leftrightarrow \mathrm{e}^{\mathrm{i}ka} F(k) \Big] \tag{B.10}$$

$$\Big[\int \mathrm{d}y f(x-y) g(y) \leftrightarrow F(k) G(k) \Big] \tag{B.11}$$

$$\Big[f'(x) \leftrightarrow \mathrm{i}k F(k) \Big], \qquad \Big[-\mathrm{i}x\, f(x) \leftrightarrow F'(k) \Big]. \tag{B.12}$$

In other words, analytical operations on one function correspond to algebraic operations on the other.

In practice, these are very useful properties. Thus, to solve a linear differential equation, or difference equation, or integral equation of convolution form $[\int \mathrm{d}y K(x-y) f(y) = \lambda\, g(x)]$, or, indeed, a linear equation which contains all three of these operations, one may take its Fourier transform, which converts it into an algebraic equation for $F(k)$. If this can be solved directly for $F(k)$, then taking the inverse Fourier transform yields the solution $f(y)$ of the original equation. Thus the Fourier transform mapping reduces the solution of linear analytical equations to that of ordinary algebraic equations. In the early 20th century, the theoretical physicist Arnold Sommerfeld in Munich became a great artist in the technique of evaluating these solutions by fancy contour integrals, and some of the greatest of the next generation learned this from him. Today, physicists and engineers could hardly survive without it.

This procedure seemed to apply only to a limited class of functions. In the Dirichlet form of Fourier theory, one shows that, if $f(x)$ is absolutely integrable, then the integral (B.8) surely converges to a well-behaved continuous function $F(k)$ on the real axis, and all is well. If $f(x)$ also vanishes for negative x, then $F(k)$ is analytic and bounded in one-half of the complex plane, and all is even better. But if $f(x)$ is absolutely integrable, then $f'(x)$ or $f''(x)$ may not be; and there is some doubt whether the useful properties are still valid. In the early work on Fourier transforms, such as Titchmarsh (1937), virtually all one's attention was concentrated on the theory of convergence of the integrals, and any function for which the integral did not converge was held not to possess a Fourier transform. This placed an intolerable restriction on the range of useful applications of Fourier theory.

Then a more sophisticated view emerged in theoretical physics. One realized that the usefulness of the Fourier transform lies, not in convergence of any integral, but in the above properties (B.10)–(B.12) of the mapping. Therefore, as long as our functions are sufficiently well-behaved so that the operations in (B.10)–(B.12) make sense, then, if by any means we can define the mapping such that those properties are preserved, then the customary use of Fourier transforms to solve linear integrodifferential equations will be perfectly rigorous, and *it does not make the slightest difference* whether the integrals (B.8) or the analogous Fourier series do or do not converge. A divergent Fourier series is still a unique ordered sequence of numbers, conveying all the needed information (i.e. it is uniquely determined by, and uniquely determines, its Fourier transform). It was only an historical accident that this mapping was first discovered through series and integral representations, which exist only in special cases.

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B.5.1 Delta-functions

Although its beginnings can be traced back to Duhamel and Green in the 19th century, this movement is commonly held to start with P. A. M. Dirac, who in the 1920s invented the notation of the delta-function $\delta(x - y)$ generalizing Kronecker's δ_{ij}, and showed how to use it to good advantage in applications. It is the 'Fourier transform of a constant' in the sense that as $F(k) \to 1$, we have $f(x) \to \delta(x)$. Mathematicians thinking in terms of the set theory definition of a 'function' were horrified and held this to be nonrigorous on the grounds that delta-functions do not 'exist'. But that was only because of their inappropriate definition of the term 'function'. A delta-function is not a mapping of any set onto any other. Laurent Schwartz (1950) tried to make the notion of a delta-function rigorous, but from our point of view awkwardly, because he persisted in defining the term 'function' in a way inappropriate to analysis.

Perceiving this, G. Temple (1955) and M. J. Lighthill (1957) showed how to remove the awkwardness simply by adopting a definition of functions as meaning 'good' functions and limits of sequences of good functions (thus, in our system, a discontinuous function is *defined* as the limit of a sequence of continuous functions). For this, there is almost no need to mention such things as open and closed sets. Lighthill saw that this definition of 'function' is the one appropriate to Fourier theory. It is now clear that it is also the one appropriate to probability theory and to all of analysis; with it our theorems become simpler and more general, without a long list of exceptions and special cases. For example, any Fourier series may now be differentiated term by term any number of times and the result, whether convergent or not, identifies (by 1:1 correspondence) a unique function in our sense of the word. Physicists had seen this intuitively and used it correctly long before the work of Schwartz, Temple, and Lighthill.

Lighthill produced a very thin book (1957) on the new form of Fourier analysis, which included a table of Fourier transforms in which every entry is a function which was held formerly not to possess a Fourier transform. Yet that table is a gold mine for the useful solution of linear integro-differential equations. In a famous review of Lighthill's book, the theoretical physicist Freeman J. Dyson (1958), a former student of the Cambridge mathematician G. H. Hardy, stated that Lighthill's book '. . . lays Hardy's work in ruins, and Hardy would have enjoyed it more than anybody.' Throughout the present work, we take Lighthill's approach for granted and assume that the reader is familiar with it.[5]

B.5.2 Nondifferentiable functions

The issue of nondifferentiable functions arises from time to time in probability theory. In particular, when one solves a functional equation such as those studied in Chapter 2, to assume differentiability is to have a horde of compulsive mathematical nitpickers descend upon one, with claims that we are excluding a large class of potentially important solutions. However, we noted that this is not the case; Aczel demonstrated that Cox's functional equations can all be solved without assuming differentiability (at the cost of much longer derivations) and with just the same solutions that we found above.

Let us take a closer look at the notion of nondifferentiable functions in general. This was not well-received at first by mathematicians. Charles Hermite wrote to Stieltjès: 'I turn away in horror from this awful plague of functions which have no derivatives.' The one generally blamed for this

[5] Lighthill defines the term 'good function' in a different way than we did above, which seems to us unnecessarily restrictive in its behavior at infinity. Apparently, this was because he did not like integrals over finite domains, whereas we do like them. But Lighthill's definition is more general than ours in that a 'good function' need not be analytic; however, this generality seems to us unnecessary because we have never seen a real problem in which the underlying good functions could not be chosen to be analytic.

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plague was Henri Lebesgue (1875–1941), although Weierstrasz had noted them before him. The Weierstrasz nondifferentiable function is

$$f(x) \equiv \sum_{n=0}^{\infty} a^n \cos(m^n x), \tag{B.13}$$

where $(0 < a < 1)$ and m is a positive odd integer. It is an ordinary Fourier series with period 2π, since m^n is always an integer. Furthermore, the series is uniformly convergent for all real x (since it must converge at least as well as does $\sum a^n$), so it defines a continuous function. But if $ma > 1$, term-by-term differentiation yields a badly divergent series, whose coefficients grow exponentially in n. The proof that the derivative

$$f'(x) \equiv \lim_{h \to 0} \frac{f(x+h) - f(x)}{h} \tag{B.14}$$

then does not exist for any x is rather tedious.[6] Weierstrasz's function is, in fact, the limit of a sequence of good functions (the partial sums S_k of the first k terms), but it is not a very well-behaved limit, and such functions are of no apparent use to us because they fail to satisfy condition (B.12). Nevertheless, functions like this do arise in applications; for example, in Chapter 7 our attempt to solve the integral equation (7.49) by Fourier transform methods ran up against this difficulty if the kernel was too broad. Then our conclusion was that the integral equation does not have any usable solution unless the kernel $\phi(x - y)$ is at least as sharp as the 'driving force' $f(x)$.

B.5.3 Bogus nondifferentiable functions

The case most often cited as an example of a nondifferentiable function is derived from a sequence $f_n(x)$, each of which is a string of isosceles right triangles whose hypotenuses lie on the real axis and have length $1/n$. As $n \to \infty$, the triangles shrink to zero size. For any finite n, the slope of $f_n(x)$ is ± 1 almost everywhere. Then what happens as $n \to \infty$? The limit $f_\infty(x)$ is often cited carelessly as a nondifferentiable function. Now it is clear that the limit of the derivative, $f_n'(x)$, does not exist; but it is the derivative of the limit that is in question here, $f_\infty(x) \equiv 0$, and this is certainly differentiable. Any number of such sequences $f_n(x)$ with discontinuous slope on a finer and finer scale may be defined. The error of calling the resulting limit $f_\infty(x)$ nondifferentiable, on the grounds that the limit of the derivative does not exist, is common in the literature. In many cases, the limit of such a sequence of bad functions is actually a well-behaved function (although awkwardly defined), and we have no reason to exclude it from our system.

Lebesgue defended himself against his critics thus: 'If one wished always to limit himself to the consideration of well-behaved functions, it would be necessary to renounce the solution of many problems which were proposed long ago and in simple terms.' The present writer is unable to cite any specific problem which was thus solved; but we can borrow Lebesgue's argument to defend our own position.

To reject limits of sequences of good functions is to renounce the solution of many current real problems. Those limits can and do serve many useful purposes, which much current mathematical education and practice still tries to stamp out. Indeed, the refusal to admit delta-functions as legitimate mathematical objects has led mathematicians into error. For example, H. Cramér (1946, Chap. 32) gives an inequality, which we derived in Chapter 17, placing a lower limit to the variance

[6] See Hardy (1911). Titchmarsh (1939, pp. 350–353) gives only a shorter proof valid when $ma > 1 + 3\pi/2$. Some authors state that $f(x)$ is nondifferentiable only in this case; but, to the best of our knowledge, nobody has ever claimed that Hardy's proof contains an error.

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of the sampling distribution for a parameter estimator θ^*:

$$\text{var}(\theta^*) \geq \frac{(1 + \mathrm{d}b/\mathrm{d}\theta)^2}{n \int \mathrm{d}x \, (\partial \log(f)/\partial\theta)^2 \, f(x|\theta)}, \tag{B.15}$$

where we have made n observations from a sampling distribution $f(x|\theta)$, and $b(\theta^*) \equiv E(\theta^* - \theta)$ is the bias of the estimator.

Then Cramér notes that, if $f(x|\theta)$ has discontinuities, then 'the conditions for the regular case are usually not satisfied. In such cases it is often possible to find unbiased estimates of 'abnormally high' precision, i.e. such that the variance is smaller than the lower limit [(B.15)] for regular estimates.' How could he have reached such a remarkable conclusion, since (B.15) is only the Schwartz inequality, which does not seem to admit of exceptions? We find that he has used the set-theory definition of a function, and concluded that the derivative $\partial \log(f)/\partial\theta$ does not exist at points of discontinuity. So he takes the integral in (B.15) only over those regions where $f(x|\theta)$ is continuous.

But the definition of a discontinuous function which is appropriate in analysis is our limit of a sequence of continuous functions. As we approach that limit, the derivative develops a higher and sharper spike. However close we are to that limit, the spike is part of the correct derivative of the function, and its contribution must be included in the exact integral. Thus the derivative of a discontinuous function $g(x)$ necessarily contains a delta-function $[g(y+) - g(y-)]\,\delta(x - y)$ at points y of discontinuity, *whose contribution is always present in the differentiated Fourier series for $g(x)$, and must be included in order to get the correct physical solution*. Had Cramér included this term, (B.15) would have reduced in the limit to $\text{var}(\theta^*) \geq 0$; hardly a useful statement, but at least there would have been no anomaly and no seeming violation of the Schwartz inequality.

In a similar way, the solution of an integral equation with finite limits, of the form

$$\int_a^b \mathrm{d}y K(x, y) f(y) = \lambda g(x), \tag{B.16}$$

generally involves delta-functions like $\delta(y - a)$ or $\delta'(y - b)$ at the end-points, and so those who do not believe in delta-functions consider such integral equations as not having solutions. But in real physical problems, exactly such integral equations occur repeatedly, and again the delta-functions must be included in order to get the correct physical solution. Some examples are given by D. Middleton (1960); they are virtually ubiquitous in the prediction of irreversible processes in statistical mechanics. It is astonishing that so few non-physicists have yet perceived this need to include delta-functions, but we think it only illustrates what we have observed independently; those who think of fundamentals in terms of set theory fail to see its limitations because they almost never get around to useful, substantive calculations.

So, bogus nondifferentiable functions are manufactured as limits of sequences of rows of tinier and tinier triangles, and this is accepted without complaint. Those who do this while looking askance at delta-functions are in the position of admitting limits of sequences of bad functions as legitimate mathematical objects, while refusing to admit limits of sequences of good functions! This seems to us a sick policy, for delta-functions serve many essential purposes in real, substantive calculations, but we are unable to conceive of any useful purpose that could be served by a nondifferentiable function. It seems that their only use is to provide trouble-makers with artificially contrived counter-examples to almost any sensible and useful mathematical statement one could make. Henri Poincaré (1909) noted this in his characteristically terse way:

In the old days when people invented a new function they had some useful purpose in mind: now they invent them deliberately just to invalidate our ancestors' reasoning, and that is all they are ever going to get out of them.

We would point out that those trouble-makers did not, after all, invalidate our ancestors' reasoning; their pathology appeared only because they adopted, surreptitiously, a different definition

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of the term 'function' than our ancestors used. Had this been pointed out, it would have been clear that there was no need to modify our ancestors' conclusions.

Today, this fad of artificially contrived mathematical pathology seems nearly to have run its course, and for just the reason that Poincaré foresaw; nothing useful can be done with it. While we still see exhortations not to assume differentiability of an unknown function, it is difficult to find even one specific example of a nondifferentiable function appearing – much less actually being used for anything – in the recent literature. One must go back to old works like Titchmarsh (1939) to see them at all.

Note, therefore, that we stamp out this plague too, simply by our defining the term 'function' in the way appropriate to our subject. The definition of a mathematical concept that is 'appropriate' to some field is the one that allows its theorems to have the greatest range of validity and useful applications, without the need for a long list of exceptions, special cases, and other anomalies. In our work the term 'function' includes good functions and well-behaved limits of sequences of good functions; but not nondifferentiable functions. We do not deny the existence of other definitions which do include nondifferentiable functions, any more than we deny the existence of fluorescent purple hair dye in England; in both cases, we simply have no use for them.[7]

B.6 Counting infinite sets?

It is well known that Lewis Carroll's children's books were really expositions of the principles of logic, conveyed by the device of stating the opposite in a form that would appear ludicrous even to small children. One of his poems ends thus:

> He thought he saw an Argument that proved he was the Pope:
> He looked again and found it was a Bar of Mottled Soap.
> 'A fact so dread,' he faintly said, 'Extinguishes all hope!'

Indeed, many of the arguments seriously proposed in probability theory are seen, on second glance, to be nothing but mottled soap. The idea was appropriated in a famous anecdote[8] about the Cambridge mathematician G. H. Hardy; J. E. McTaggart expressed doubt that from a false proposition all propositions can be deduced, by challenging him thus: 'Given $2 + 2 = 5$: prove that I am the Pope.' Whereupon Hardy replied: 'Subtract 3 from each side and we have $1 = 2$. Now we agree that the Pope and you are two; therefore the Pope and you are one!' But that was only a play on words; infinite-set theory gives us a superior grade of mottled soap, with which we can prove McTaggart's papacy much more convincingly.

We start from the premise that two sets have the same number of elements if they can be put into 1:1 correspondence with each other. Then by the association $(n \leftrightarrow 2n),\ n = 1, 2, \ldots$, we can put the positive integers into 1:1 correspondence with the positive even integers. And by the association $(2n \leftrightarrow 2n - 1),\ n = 1, 2, \ldots$, we can, equally well, put the positive even integers into 1:1 correspondence with the positive odd integers; so by such logic it seems that we would be driven to conclude that:

(A) (number of integers) = (number of even integers);
(B) (number of even integers) = (number of odd integers);
(C) (number of integers) = 2 × (number of even integers);

[7] On a different topic, in Chapter 17 (footnote 9 on p. 521) we follow the same policy by defining the term 'moving average' for a finite time series in such a way that our theorems are all exact, without any need for messy 'end effect' corrections. Of course, it then develops that this is the definition most directly useful in applications and that conserves information which would otherwise be lost.

[8] Cited by Jeffreys (1931; 1957 edn, p. 18).

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and from (A) and (C) it follows that $1 = 2$. The reasoning here is not very different from that in Eqs. (15.2)–(15.3).

Our view is that the 'set of all integers' is undefined except as a limit of finite sets, and if it is approached in that way, by introducing the explicit limiting process, no contradiction can be produced whatever limiting process we choose, even though the limiting ratio of (number of even integers)/(number of integers) can be made to be any x we please in $0 \leq x \leq 1$. That is, the limit of (number of odd integers)/(number of integers) will be $(1 - x)$, and our counting will remain consistent in the limit.

For example, every integer is included once and only once in the sequence $\{1, 3, 2, 5, 7, 4, \ldots\}$, in which we take alternately two odd and one even. Then counting elements only in the finite sets consisting of the first n elements of this sequence, and passing to the limit $n \to \infty$ after doing the counting, we would find in place of the inconsistent statements (A), (B), (C) above, the consistent set

(A′) (number of integers) = 3 × (number of even integers);
(B′) (number of even integers) = 1/2 × (number of odd integers);
(C′) (number of integers) = (number of even integers) + (number of odd integers).

These ideas are not as new as one might think. Galileo (1638), in his *Dialogues Concerning Two New Sciences*, notes two curious facts. On the one hand, each integer has one and only one square, and no two of them have the same square; from which it would seem that the number of integers and the number of squares must be the same. On the other hand, it is evident that there are many integers (in a certain sense, the 'great majority' of them) which are not squares. From this he draws the eminently sensible conclusion:

This is one of the difficulties which arise when we attempt, with our finite minds, to discuss the infinite, assigning to it those properties which we give to the finite and limited; but this I think is wrong, for we cannot speak of infinite quantities as being the one greater or less than or equal to another.

Hermann Weyl, 300 years later, expressed almost exactly the same judgment, as noted below. See, for example, Weyl (1949).

B.7 The Hausdorff sphere paradox and mathematical diseases

The inconsistent statements above are structurally almost identical with the Hausdorff paradox concerning congruent sets on a sphere, except for the promotion up to uncountable sets (here X, Y, Z are disjoint sets which nearly cover the sphere, and X is congruent to Y, in the sense that a rotation of the sphere makes X coincide with Y, and likewise Y is congruent to Z. But what is extraordinary is the claim that X is also congruent to the union of Y and Z, even though $Y \neq Z$). We are, like Poincaré and Weyl, puzzled by how mathematicians can accept and publish such results; why do they not see in this a blatant contradiction which invalidates the reasoning they are using?

Nevertheless, L. J. Savage (1962) accepted this antinomy as literal fact and, applying it to probability theory, said that someone may be so rash as to blurt out that he considers congruent sets on the sphere equally probable; but the Hausdorff result shows that his beliefs cannot actually have that property. The present writer, pondering this, has been forced to the opposite conclusion: my belief in the existence of a state of knowledge which considers congruent sets on a sphere equally probable, is vastly stronger than my belief in the soundness of the reasoning which led to the Hausdorff result.

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Presumably, the Hausdorff sphere paradox and the Russell Barber paradox have similar explanations: one is defining weird sets with self-contradictory properties, so, of course, from that mess it will be possible to deduce any absurd proposition we please. Hausdorff entitled his work '*Mengenlehre*', and Poincaré made the famous quip that 'Future generations will regard *Mengenlehre* as a disease from which one has recovered.' But he would be appalled to see this recovery not yet achieved 80 years later; nevertheless, Poincaré's views are alive and well today among users of applied mathematics.

For example, in 1983 the writer heard a talk by a very prominent statistician, reporting on an historical investigation. He remarked: 'I was surprised to learn that, before the days of Bourbaki, the French actually produced some useful mathematics.' More recently, the Nobel Laureate theoretical physicist Murray Gell-Mann (1992), discussed this situation. He opined that there is still much in modern mathematics of value to physics, and the divergence of pure mathematics from science is in part only an illusion produced by the obscurantist language of Bourbakists and their reluctance to write up any non-trivial example in explicit detail. He concludes: 'Pure mathematics and science are finally being reunited and, mercifully, the Bourbaki plague is dying out.'

We wish we could feel that optimistic. In our view, this plague is far more serious than mere obscure language; it infects the substantive content of pure mathematics. A sane person can have no confidence in any of it; rules of conduct must be found which prevent the appearance of these ridiculous paradoxes, and then our mathematics textbooks must be rewritten. As is well known, Russell's theory of types can dispose of a few paradoxes, but far from all of them. We fear that, even with the best of good will on both sides, it will require at least another generation to bring about the reconciliation of pure mathematics and science. For now, it is the responsibility of those who specialize in infinite-set theory to put their own house in order before trying to export their product to other fields. Until this is accomplished, those of us who work in probability theory or any other area of applied mathematics have a right to demand that this disease, for which we are not responsible, be quarantined and kept out of our field.

In this view, too, we are not alone; and indeed have the support of many non-Bourbakist mathematicians. In our Preface we quoted Morris Kline (1980) on the dangers of allowing infinite-set theory to get a foothold in applied mathematics. He in turn (on his p. 237) quotes Hermann Weyl. Both Brouwer and Weyl noted that classical logic had been developed for application to finite sets. The attempt to apply classical logic, without justification, to infinite sets is, in Weyl's words: '. . . the Fall and original sin of set theory, for which it is justly punished by the antinomies. It is not that such contradictions showed up that is surprising, but that they showed up at such a late stage of the game.'

But there is a simple explanation for this late appearance, noted with examples in Chapter 15: if an erroneous argument leads to an absurd result immediately, it will be abandoned and we shall never hear about it. If it yields a reasonable result on the first two or three tries, then there is some range of problems where it will succeed. One will continue using it, but at first conservatively – on problems that are quite similar, so it is likely to continue giving reasonable results. Only later, when one becomes over-confident and tries to extend the application to different kinds of problems, do the contradictions appear.[9]

Just the same phenomenon occurred in orthodox statistics, where the *ad hoc* inventions such as confidence intervals yielded acceptable results for a long time because they were used at first only on simple problems which were free of nuisance parameters, but sufficient statistics existed, and there was no very important prior information. Nobody took any note of the fact that the numerical

[9] The writer knew Hermann Weyl, took his course in group theory at Princeton, and admired him as the final authority on both group theory and variational principles for general relativity. But the Bourbakist mathematicians at Princeton sneered at him and called him 'Holy Hermann' behind his back, because of his Biblical exhortations to virtue like the one just quoted. They would have been better advised to listen to him.

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results were then the same as the Bayesian posterior probability intervals at the same level (based on the uninformative priors given by Jeffreys). Confidence intervals were widely held, by mathematicians such as Neyman, Cramér and Wilks, to be great advances over Bayesian methods, until their contradictions began to appear when one tried to apply them to more general problems.[10] Finally, we were able to show (Jaynes, 1976) that confidence intervals are satisfactory as inferences *only* in those special cases where they happen to agree with the Bayesian intervals after all.

Kline (1980, p. 285) also quotes J. Willard Gibbs on this subject: 'The pure mathematician can do what he pleases, but the applied mathematician must be at least partially sane.' In any event, no sane person would try to use such anomalies as the Hausdorff sphere paradox in a real application.

Finally, we offer a few more general comments on mathematical style.

B.8 What am I supposed to publish?

L. J. Savage (1962) asked this question to express his bemusement at the fact that, no matter what topic he chose to discuss, and no matter what style of writing he chose to adopt, he was sure to be criticized for not making a different choice. In this he was not alone. We would like to plead for a little more tolerance of our individual differences.

If anyone wants to concentrate his attention on infinite sets, measure theory, and mathematical pathology in general, he has every right to do so. And he need not justify this by pointing to useful applications or apologize for the lack of them; as was noted long ago, abstract mathematics is worth knowing for its own sake.

But others in turn have equal rights. If we choose to concentrate on those aspects of mathematics which *are* useful in real problems and which enable us to carry out the important substantive calculations correctly – but which the mathematical pathologists never get around to – we feel free to do so without apology.

Ultimately, the mathematical level and depth of this work were chosen with the aim of making it possible for all readers to extract what they want from it. Since those who approach a work with the sole purpose of finding fault with its style of presentation will always be able to do so no matter how it is presented, our aim was to ensure that those who approach it with sincere desire to understand its *content* will also be able to do so. Thus we try to give cogent reasons why the ideas we advocate are 'obvious', while those we deplore are not, when this can be done briefly enough not to interrupt the line of argument. This inevitably leaves some lacunae, in part filled in by the Comments sections at the end of most chapters.

In this connection, the question of what is and is not 'obvious' is a matter of gamesmanship that is played in two opposite directions. On the one hand, the standard way of introducing notions that do not stand up to critical examination – or to deprecate those that stand up too well to be safely opposed – is to call them 'obvious'. On the other hand, to express grave doubts about simple matters that *are* obvious is the equally standard technique for imputing to one's self deep critical faculties not possessed by others. We try to steer a middle course between these, but like Savage do so in the knowledge that, whatever our choice, it will receive opposite criticisms from the two types of gamesman.

But we avoid one common error: nothing could be more pathetically mistaken than the prefatory claim of one author in this field that mathematical rigor 'guarantees the correctness of the results'. On the contrary, much experience teaches us that the more one concentrates on the appearance of

[10] Confidence intervals are always correct as statements about sampling properties of estimators; yet they can be absurd as statements of inference about the values of parameters. For example, the entire confidence interval may lie in a region of the parameter space which we know, by deductive reasoning from the data, to be impossible.

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mathematical rigor, the less attention one pays to the validity of the premises in the real world, and the more likely one is to reach final conclusions that are absurdly wrong in the real world.

B.9 Mathematical courtesy

A few years ago the writer attended a seminar talk by a young mathematician who had just received his Ph.D. degree and, we understood, had a marvellous new limit theorem of probability theory. He started to define the sets he proposed to use, but three blackboards were not enough for them, and he never got through the list. At the end of the hour, having to give up the room, we walked out in puzzlement, not knowing even the statement of his theorem.

A '19th century mathematician' like Poincaré would have been into the meat of the calculation within a few minutes and would have completed the proof and pointed out its consequences in time for discussion.

The young man is not to be blamed; he was only doing what he had been taught a '20th century mathematician' must do. Although he has perhaps now learned to plan his talks a little better, he is surely still wasting much of his own time and that of others in reciting all the preliminary incantations that are demanded in 20th century mathematics before one is allowed to proceed to the actual problem. He is a victim of what we consider to be, not higher standards of rigor, but studied mathematical discourtesy.

Nowadays, if you introduce a variable x without repeating the incantation that it is in some set or 'space' X, you are accused of dealing with an undefined problem. If you differentiate a function $f(x)$ without first having stated that it is differentiable, you are accused of lack of rigor. If you note that your function $f(x)$ has some special property natural to the application, you are accused of lack of generality. In other words, every statement you make will receive the discourteous interpretation.

Obviously, mathematical results cannot be communicated without some decent standards of precision in our statements. But a fanatical insistence on one particular form of precision and generality can be carried so far that it defeats its own purpose; 20th century mathematics often degenerates into an idle adversary game instead of a communication process.

The fanatic is not trying to understand your substantive message at all, but only trying to find fault with your style of presentation. He will strive to read nonsense into what you are saying, if he can possibly find any way of doing so. In self-defense, writers are obliged to concentrate their attention on every tiny, irrelevant, nitpicking detail of how things are said rather on what is said. The length grows; the content shrinks.

Mathematical communication would be much more efficient and pleasant if we adopted a different attitude. For one who makes the courteous interpretation of what others write, the fact that x is introduced as a variable *already implies* that there is some set X of possible values. Why should it be necessary to repeat that incantation every time a variable is introduced, thus using up two symbols where one would do? (Indeed, the range of values is usually indicated more clearly at the point where it matters, by adding conditions such as $(0 < x < 1)$ after an equation.)

For a courteous reader, the fact that a writer differentiates $f(x)$ twice already implies that he considers it twice differentiable; why should he be required to say everything twice? If he proves proposition A in enough generality to cover his application, why should he be obliged to use additional space for irrelevancies about the most general possible conditions under which A would be true?

A scourge as annoying as the fanatic is his cousin, the compulsive mathematical nitpicker. We expect that an author will define his technical terms, and then use them in a way consistent with his definitions. But if any other author has ever used the term with a slightly different shade of meaning,

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the nitpicker will be right there accusing you of inconsistent terminology. The writer has been subjected to this many times; and colleagues report the same experience.

Nineteenth century mathematicians were not being nonrigorous by their style; they merely, as a matter of course, extended simple civilized courtesy to others, and expected to receive it in return. This will lead one to try to read sense into what others write, if it can possibly be done in view of the whole context; not to pervert our reading of every mathematical work into a witch-hunt for deviations from the Official Style.

Therefore, sympathizing with the young man's plight but not intending to be enslaved like him, we issue the following:

Emancipation Proclamation

Every variable x that we introduce is understood to have some set X of possible values. Every function $f(x)$ that we introduce is understood to be sufficiently well-behaved so that what we do with it makes sense. We undertake to make every proof general enough to cover the application we make of it. It is an assigned homework problem for the reader who is interested in the question to find the most general conditions under which the result would hold.

We could convert many 19th century mathematical works to 20th century standards by making a rubber stamp containing this Proclamation, with perhaps another sentence using the terms 'sigma-algebra, Borel field, Radon–Nikodym derivative', and stamping it on the first page.

Modern writers could shorten their works substantially, with improved readability and no decrease in content, by including such a Proclamation in the copyright message, and writing thereafter in 19th century style. Perhaps some publishers, seeing these words, may demand that they do this for economic reasons; it would be a service to science.

In this appendix we have presented many short quotations without the references. Supporting documentation and many further interesting details may be found in Bell (1937), Félix (1960), Kline (1980), and Rowe and McCleary (1989).

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