

REAL MATHEMATICS, RATIONAL COMPUTERS AND COMPLEX PEOPLE

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Introduction

In thinking about advanced mathematical notions – and even more in teaching these concepts to students – it is essential to be aware not only of the formal definitions and deductions of “real mathematics”, but also of the complex mental imagery that supports these ideas. Formal definitions of concepts, such as “real number”, “function”, “limit”, “continuity”, “completeness”, are based on experiences which invest them with all kinds of additional meaning. Examples given to “motivate” definitions invariably have specific properties that do not follow logically from the definition itself. For instance, examples of sequences are usually given by formulae which have the property that the sequence “gets closer and closer” to the limit, without actually reaching it. Consequently, many students believe that this is an essential property of the limit concept. Functions are nearly always given by formulae and their graphs look “smooth” so that students have difficulty imagining anything different. When discontinuities are exemplified, it is often as in figure 1 with a “smooth” curve except for a “jump” at the point under consideration. The result is a widespread belief that typical functions are given by a formula and are continuous except at occasional isolated points. In this way the individual builds up beliefs that do not hold true in the formal theory, leading to confusion and inherent barriers to comprehending formal subtleties.

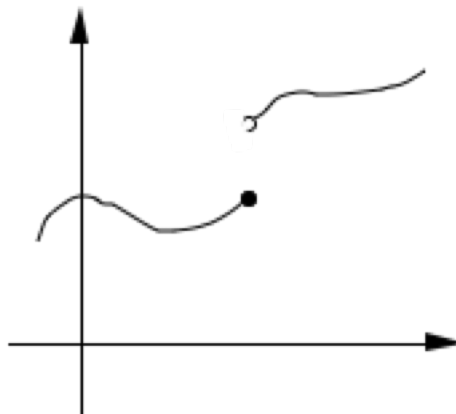


Figure 1 : a function with a discontinuity

The problem facing the teacher of mathematics at any level is to give appropriate experiences that help the student gain helpful images of “real” mathematics, which here means “real” in the sense of the mathematician, rather than the approximations of the outside world. A computer can provide a rich interactive source of possible imagery, both visual and computational. But the computer is essentially a *finite* machine which cannot encompass the actual infinity of the real line. Numbers are held within the machine as finite binary expansions and so are essentially *rational*. So how can we create an environment which gives helpful images of *real* mathematics on *rational* computers to *complex* people who will invest the examples with additional meanings of their own?

Paradoxically I suggest that we can use the very concept imagery – that research shows to causes confusion – *in a positive way to gain insight*. Instead of allowing the experiences to *implicitly* coerce the individual into conceiving properties which conflict with the

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theory, the strategy is to use *explicit* – even flawed – imagery to stimulate the imagination.

My own quest in recent years has been to use the computer to visualise mathematical concepts in helpful ways in calculus and analysis. Imaginative use of graph-plotters and graphic calculators has enabled students to cope more meaningfully with concepts such as differentiation through the notion of “local straightness”, integration through area summation, and solving (first order) differential equations by visually building up solution curves with given gradient. During this time I became increasingly aware of the limited concept imagery afforded by graph-plotters that only draw reasonably smooth graphs given by formulae. Some allow functions given by different formulae on different domains such as:

$$f(x) = \begin{cases} x & (x \leq 0) \\ 1-x & (x > 0) \end{cases}$$

I wanted to be able to draw more subtle graphs, such as

$$h(x) = \begin{cases} x & \text{if } x \text{ is rational} \\ 1-x & \text{if } x \text{ is irrational} \end{cases}$$

and use these to motivate deeper thoughts about continuity and more sophisticated ideas of integration, such as the Lebesgue theory that succeeds in defining the “area” under this curve.

Of course, I was bound to fail. With only rational computer numbers, it is clearly impossible to draw such curves. Or is it? To give up attempting something just because it is theoretically impossible ignores the capacity of the complex human mind to imagine concepts unachievable in finite time and space.

Instead I set about a more humble task – to use a computer to *simulate* the idea of rational and irrational numbers so that pictures can be drawn which stimulate the visual imagination. To do so requires some kind of distinction between rational and irrational that can be modelled in a computer algorithm. It is the development of such a model, and its use in visualising concepts in analysis that forms the basis of the remainder of this article.

Distinguishing rationals from irrationals

The Ancient Greeks used an algorithm to represent any (real) number x in terms of rational approximations. It begins by finding the integer part n , and decimal part d :

$$x = n + d \quad (\text{where } 0 \leq d < 1).$$

If $d=0$, then x is a (rational) integer. If not, the subtle part is to note that its reciprocal $1/d$ is greater than 1, so we can take the integer part again and write

$$1/d = n_2 + d_2 \quad (\text{where } 0 \leq d_2 < 1).$$

By continuing this process, the equations can be unravelled to give closer and closer rational approximations to any number x . For instance,

$$\pi = 3 + d \quad (\text{where } d = 0.14159\dots)$$

$$1/d = 7.0626...$$

and so a good approximation to π is

$$\pi = 3 \frac{1}{7} = \frac{22}{7}.$$

If the process is applied to a rational number such as $\frac{22}{7}$, then the remainder eventually becomes zero:

$$\begin{aligned} \frac{22}{7} &= 3 + \frac{1}{7} \\ 1 / (\frac{1}{7}) &= 7 + 0. \end{aligned}$$

and the process terminates.

This process gives a sequence of fractions, r_1, r_2, \dots which tend to the real number x . If x is rational, the sequence is eventually constant, equalling x expressed in lowest terms. If x is irrational, it is easy to see that the numerators and denominators of r_n must grow without limit. (For if the denominators were all less than an integer N , then the sequence $N!r_n$ would be a sequence of *integers* tending to $N!x$, so the terms must eventually be a fixed integer, implying $N!x$ is an integer, contradicting the fact that x is irrational.)

This gives a method of distinguishing between rationals and irrationals:

Compute the continued fraction expansion of a number x , and if the rational approximations have denominators which grow without limit, then x is irrational, otherwise it is rational.

Working in the practical world of computers there are technical difficulties. Since the process involves taking reciprocals, if d is small, then $1/d$ is huge. If d should be zero, but errors make it tiny, then taking the reciprocal causes the method to blow up. The practical way out is to cease when the process gives a decimal part smaller than a specified error e , and check if the size of the denominator of the approximating fraction is bigger than a specified (large) number K .

We will therefore make the following technical definition to simulate the notions of rational and irrational in a finite computer world:

Definition: A real number x is said to be (e,K) -rational if, on computing the continued fraction approximation to x , the first rational approximation within e of x has denominator less than K , otherwise x is said to be (e,K) -irrational.

This partitions numbers into two disjoint subsets. Different values of e and K will, of course, give different partitions, but we will work with specific values of e and K and use the terms *pseudo-rational* and *pseudo-irrational* numbers in this implicit context.

In practice it is important to choose e and K judiciously to make best use of the model. Most computers store numbers to at least 8-digit accuracy, so $e=10^{-9}$ is a suitable size. By experiment, $K=10\,000$ proves to be a suitable “large” number. With these values of e and K , we find that $\pi, \sqrt{2}, \sqrt{3}+1$ are all pseudo-irrational and $-1.5, 2/3, 22/7$ are all pseudo-rational.

The code to compute successive approximations $\frac{a_1}{b_1}, \frac{a_2}{b_2}, \dots$ is well-known (though a little technical) and can be programmed as follows:

```

r=x : a1=0 : b1=1 : a2=1 : b2=0
REPEAT
    n=INT(r) : d=r-n : a=n*a2+a1 : b=n*b2+b1
    IF d<>0 THEN r=1/d : a1=a2 : b1=b2 : a2=a : b2=b
UNTIL ABS(a/b-x)<e

```

It can be used to define a function $rational(x,e,k)$ which returns TRUE or FALSE depending on whether x is an (e,K) -rational or not:

```

DEFINITION rational(x,e,K)
r=x : a1=0 : b1=1 : a2=1 : b2=0
REPEAT
    n=INT(r) : d=r-n : a=n*a2+a1 : b=n*b2+b1
    IF d<>0 THEN r=1/d : a1=a2 : b1=b2 : a2=a : b2=b
UNTIL ABS(a/b-x)<e
IF b<K THEN return TRUE ELSE return FALSE

```

When specific values of e, K , are used (say $e=10^{-9}$, $K=10\,000$), one can define

$$rat(x) = rational(x, 10^{-9}, 10\,000).$$

The value of $rat(x)$ is TRUE if x is pseudo-rational and FALSE if it is pseudo-irrational.

The good news is that (for these values of e, K), $rat(\pi)$ is false and $rat(22/7)$ is true.

There is bad news as well. Before we started, we knew that we would be bound to fail, so this definition must have some peculiar side effects. For instance, working with (approximately) 8-digit arithmetic, clearly $10^8\pi$ is (almost) a whole number, and registers as a pseudo-rational. For $PI=3.14159265$, the number $1000*PI$ is also pseudo-rational. By the opposite token, $1/20\,000$ turns out to be pseudo-irrational (because its denominator exceeds $K=10\,000$).

Just because we have failed does not mean that all is lost. What is good about the model is that it partitions numbers into two disjoint sets – pseudo-rationals and pseudo-irrationals – which turn out to be intimately mixed up in a way which models rationals and irrationals in certain vital respects.

One useful property is the relative density of pseudo-rationals and pseudo-irrationals. In theory a likely random number is highly likely to be irrational, because it is highly unlikely for a decimal expansion with digits chosen at random to repeat in regular cycles. A little experiment can check what percentage of random numbers are pseudo-irrational.

The following generalised code:

```

number=0
FOR count=1 TO 100
    x=random: IF rat(x)=FALSE THEN number = number + 1
NEXT count
PRINT number

```

will generate a succession of 100 random numbers and print out the percentage of those that are pseudo-irrational. For the given choice of $e=10^{-9}$ and $K=10\,000$, this turns out to be about 94% pseudo-irrationals. By changing e and K , this percentage can be changed. In any given system it is best to choose e and K to maximise this percentage, providing a good model for the idea that the irrationals are far more numerous than the rationals.

Plotting graphs

We now come to the nub of the problem. The following function

$$f(x) = \text{if}(\text{rat}(x), x, 1-x)$$

represents the statement “if $\text{rat}(x)$ is true, then the value is x , else it is $1-x$ ”. How can the graph be drawn on a computer screen in a way which truly represents the function? Traditionally the graph is sometimes conceived to look like figure 2.

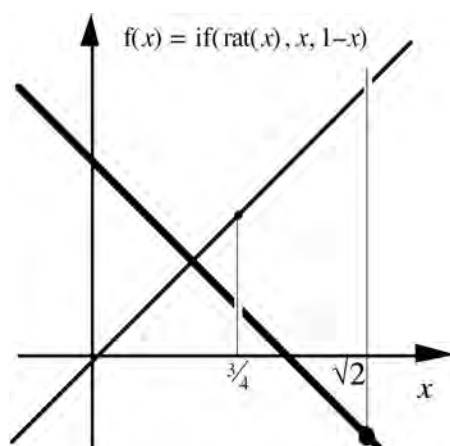


Figure 2 : the graph of a function defined differently on rationals and irrationals

There seem to be two distinct lines, one with points where x is rational, the other irrational. Perhaps the irrational part looks denser than the rational. But it seems a crazy thing to try to draw in any practical sense. Every point on the x -axis has a unique point on the graph, so every vertical line meets only one of the two lines. For instance, the points $x = \frac{3}{4}$ and $x = \sqrt{2}$ have corresponding points on the graph on different parts, as caricatured by figure 3.

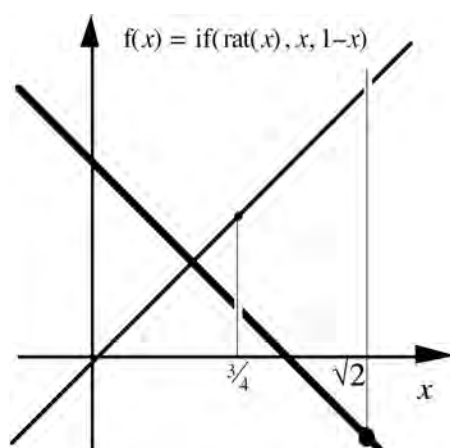


Figure 3 : plotting $(\frac{3}{4}, f(\frac{3}{4}))$ and $(\sqrt{2}, f(\sqrt{2}))$

How can the graph be adequately represented on the computer screen to give some kind of insight? Dynamic plotting would help, with the graph is built up from individual points, some (pseudo-) rational x , some (pseudo-) irrational. These can be done by separate procedures.

Binary Plot

One method is to make successive passes of the interval $[a,b]$ in which the first pass plots the mid-point, the second the quarters, the third the eighths, and so on, in such a way that points plotted on previous passes are not duplicated on successive passes. This can be done by the following general code.

```
s=(b-a) : x=a+s/2
repeat
  repeat
    plot (x, f(x)) : x=x+s
  until x > b
  s=s/2 : x= a+s/2
until satisfied
```

It starts with a step s equal to the interval width $w=b-a$ and a point x in the centre of the interval, plots the point $(x, f(x))$, then successively adds the step s to x and repeats the plot until the point x moves beyond the end of the interval. The process is repeated, with a new step $s=s/2$, starting at $x=a+s/2$. On the second pass, this starts at point $a+w/4$, step $s=w/2$ and plots the remaining quarter points $a+w/4, a+3w/4$. The next pass starts at $a+w/8$, step $s=w/4$ and plots the remaining eighth points $a+w/8, a+3w/8, a+5w/8, a+7w/8$, and so on.

The process is repeated until a pre-determined condition is satisfied (say a specified number of passes, or a specified time, or until a pre-determined key on the keyboard is pressed). Each pass doubles the density of the plot. Note, however, that the points plotted are all of the form $a+mw/2^n$ where m and n are positive integers with $m < 2^n$. In particular, when a and b are rational, the points plotted are all rational (figure 4).

In practice, if a computer plot is carried out with a rational x -range, say from $x=-2$ to 2 , then the first dozen or so passes give all rational points. If the plotting mechanism is left to run for a long time, the errors eventually produce pseudo-irrationals.

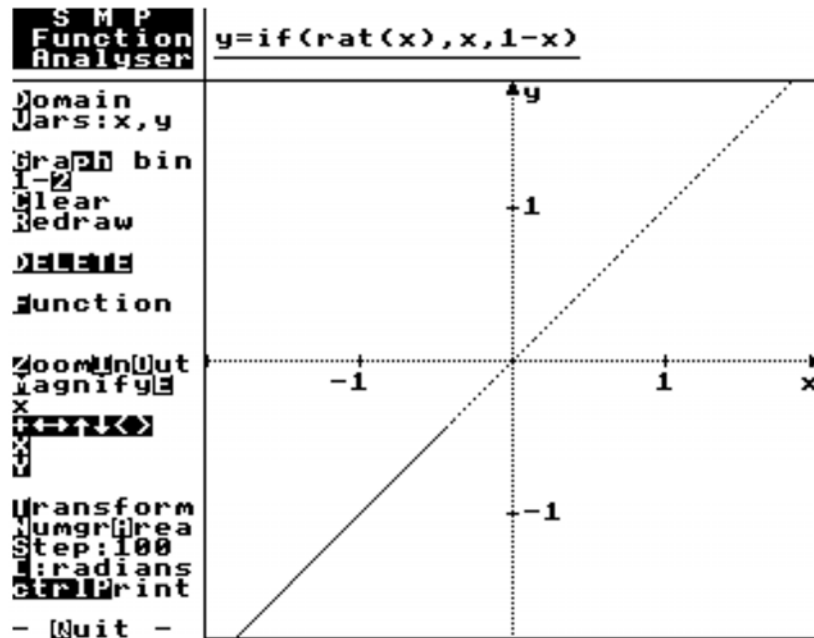


Figure 4 : a binary plot, initially producing only (pseudo-)rational points

Random Plot

Another method is to calculate (pseudo-)random numbers in the interval $[a,b]$ and plot the point $(x, f(x))$, until a pre-determined condition is satisfied (a certain number of points is plotted, a certain time has passed, or a selected key has been pressed).

```
repeat
  x=a+random*(b-a)
  plot(x,f(x))
until satisfied
```

This method simply sprays points on the graph where the x -value is calculated as $a+random*(b-a)$ where *random* is a random number between 0 and 1. *In theory*, such points have a high probability of having *irrational* values of x , based on the fact that a randomly chosen number has a low probability of having a repeating block of digits repeating in its decimal expansion.

In the context described, over 90% of the points plotted have pseudo-irrational x -values (figure 5).

To get only pseudo-irrationals, the code could be modified to

```
repeat
  x=a+random*(b-a)
  IF rat(x)=FALSE THEN plot(x,f(x))
until satisfied
```

to exclude pseudo-rationals. However, in using the program to stimulate the imagination, it is important that the student *sees* that the model is only an approximate one. The existence of rogue values helps to focus on the difference between theory and practice.

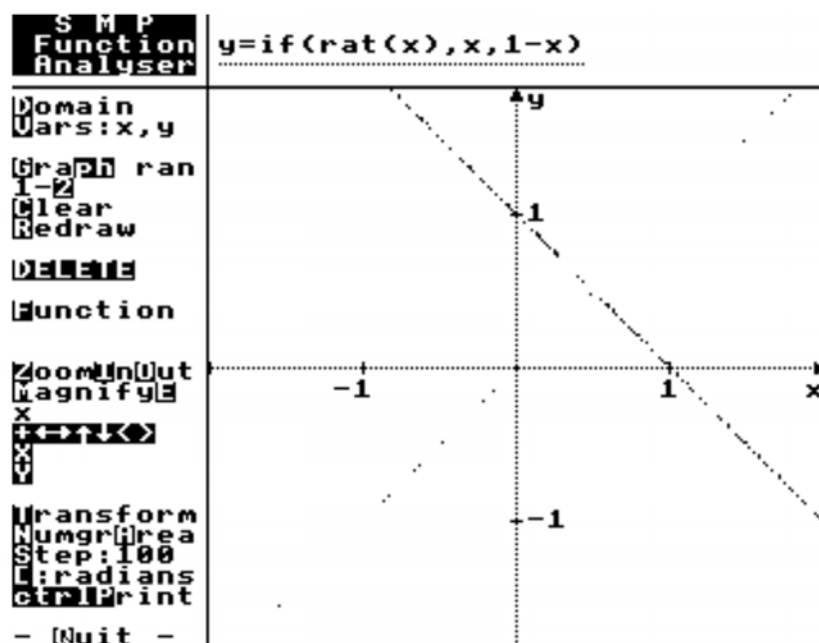


Figure 5 : a random plot producing mainly (pseudo-)irrational points

Mixing the plots

If the plotting program is set up with an easy switch between the two plot mechanisms then it is possible to draw points with both pseudo-rational and pseudo-irrational x . If it is then possible to specify x and plot $(x, f(x))$, then this shows for each value of x , there is just *one and only one* corresponding value on the graph. For instance, if $x=3/2$, then $y=0.75$, but if $x=\sqrt{2}$, then $y=-0.4142135$.

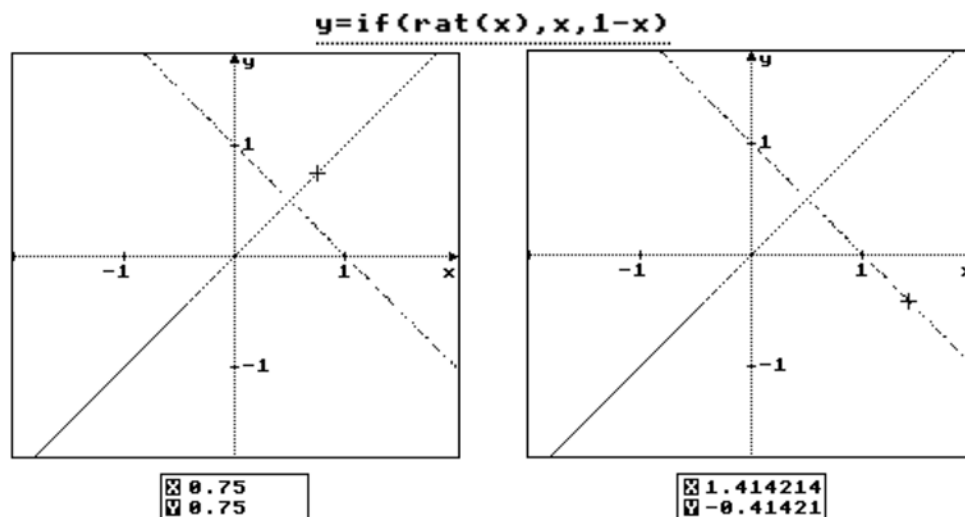


Figure 6 : plotting $(x, f(x))$ for $x=3/4$ and $x=\sqrt{2}$

Visual links between continuity, differentiability and integrability

There is much reference in the literature to the use of magnification to motivate the idea of gradient of a function through “local straightness”. An overview is given in the MAA Notes on *Visualization in Mathematics* [1]. What is less well understood is an appropriate intuitive notion of continuity (which tends to be linked with the connectedness of the graph with subtle inferences from the completeness of the reals). In the following sections I shall briefly recapitulate some of the central intuitive ideas from [1] and extend them to deal with the wider visualisations possible using the plotting routines discussed in this article.

Differentiability

The notion of differentiable function can be motivated simply by magnifying its graph, *retaining the same relative scales on the axes*. The graph of such a function magnifies to look straight and the gradient of this straight line segment is the gradient of the graph. This visual image proves to be a powerful gestalt for the notion of gradient function, though care should be taken to link graphical, numerical and symbolic representations. As a bonus, it stimulates the imagination by allowing the student to conceive of a *nowhere differentiable function*, which is one which remains wrinkled, no matter how much it is magnified. Again this is well-represented in the literature and fractal graphs such as the blancmange function can be plotted which illustrate this principle (figure 7). (See [1] for details.)

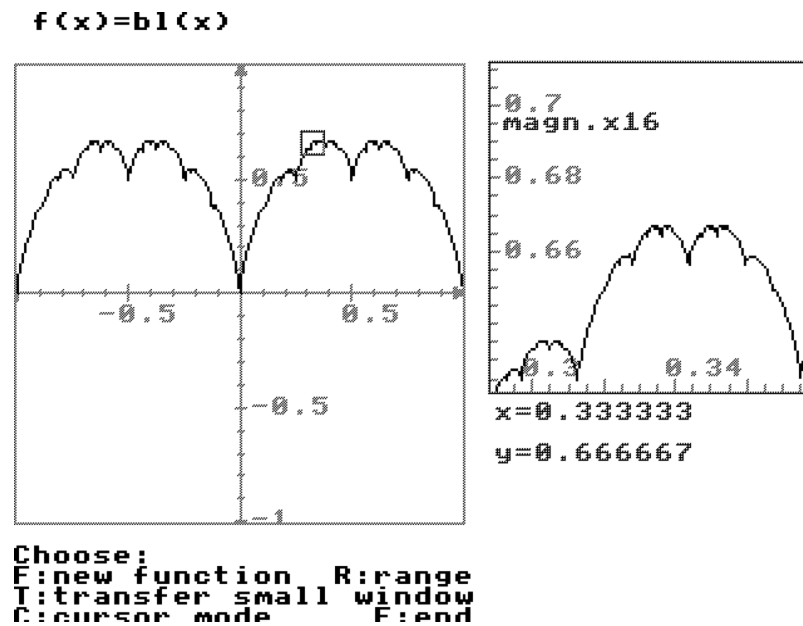


Figure 7: a highly wrinkled function, nowhere locally straight

It is also possible to motivate other strange looking graphs. For instance, figure 8 shows a graph whose derivative is 0 everywhere the derivative is defined except at one point where the derivative is 1. By magnifying the graph at $x=0$ it magnifies to look like a line of gradient 1 (despite the many jump discontinuities arbitrarily close to the origin). The veracity of this strange property, having been motivated visually, can, and should, be checked from first principles.

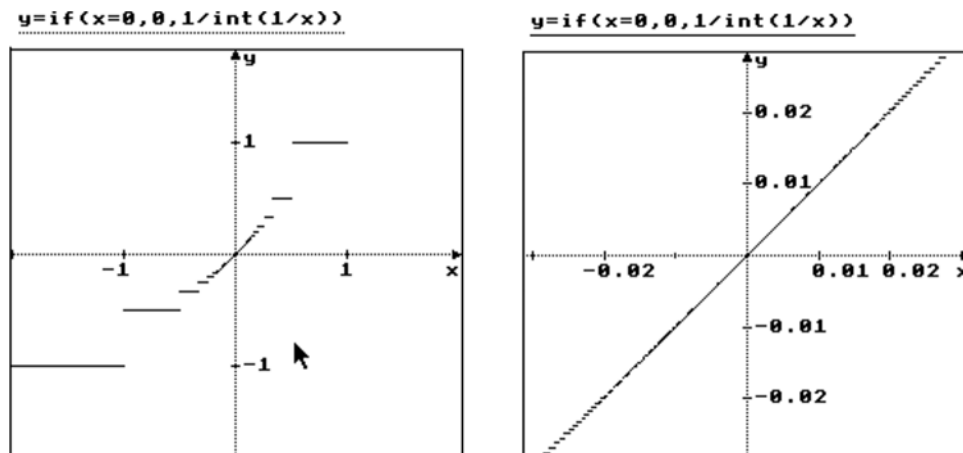


Figure 8 : A graph with derivative 1 at the origin, but zero everywhere else it is defined

Continuity

The intuitive idea (which proves to be flawed) that a continuous function is “one whose graph can be drawn *continuously* with a pencil, without taking the pencil off the paper” can be used to motivate the formal definition. Given a graph drawn “continuously” in this intuitive sense, simply by stretching it horizontally, keeping the vertical scale constant, pulls the picture of the graph in a window out flat (figure 9).

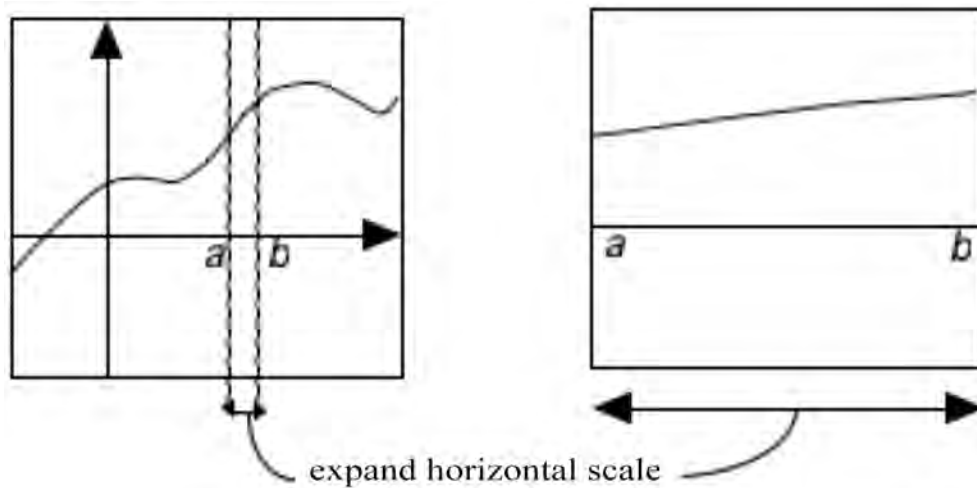


Figure 9 : stretching a graph horizontally

This can be performed on a computer to give a horizontal graph. (figure 10).

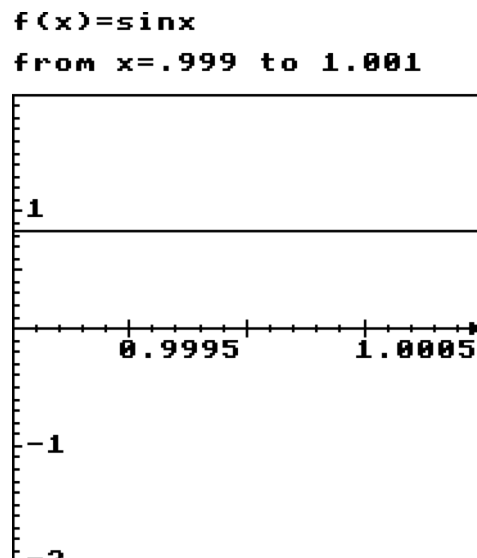


Figure 10 : horizontal stretching of the sine graph

The graph is captured in a horizontal line of pixels which can be thought of as being height $f(x_0) \pm \epsilon$ (figure 11).

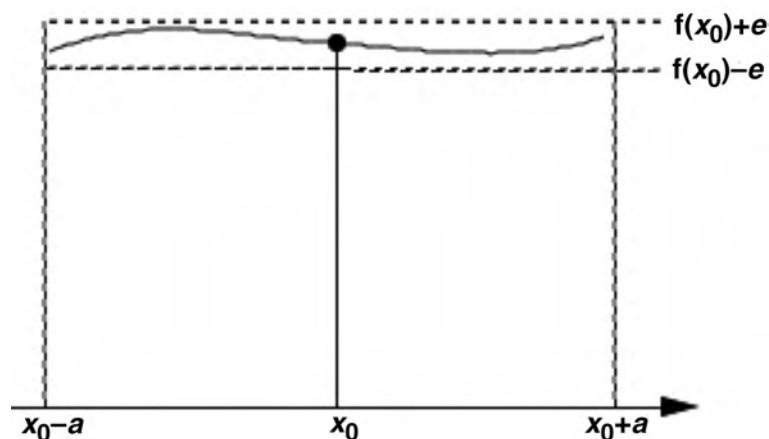


Figure 11 : the concept of continuity through horizontal stretching

So the fact that a small enough x -interval width $x_0 \pm \delta$ can be found to draw such a picture is enshrined in the property:

Given $\varepsilon > 0$, there exists $\delta > 0$ such that $x_0 - \delta < x < x_0 + \delta$ implies $f(x_0) - \varepsilon < f(x) < f(x_0) + \varepsilon$.

The relationship between (visual) continuity and (visual) differentiability is clearly that a graph which is locally straight can be stretched horizontally to look flat. So *continuity implies differentiability*. But the image of wrinkled graphs shows that *there are continuous functions which are not differentiable anywhere*.

It is also possible to motivate other seemingly strange ideas. The graph of the function $f(x) = \text{if}(\text{rat}(x), x, 1-x)$ seems highly discontinuous. Yet on keeping the y -range fixed and stretching a smaller and smaller x -range either side of $x = \frac{1}{2}$ to fit the fixed window eventually draws the graph flat. The graph is *continuous* at $x = \frac{1}{2}$, but *nowhere else*.

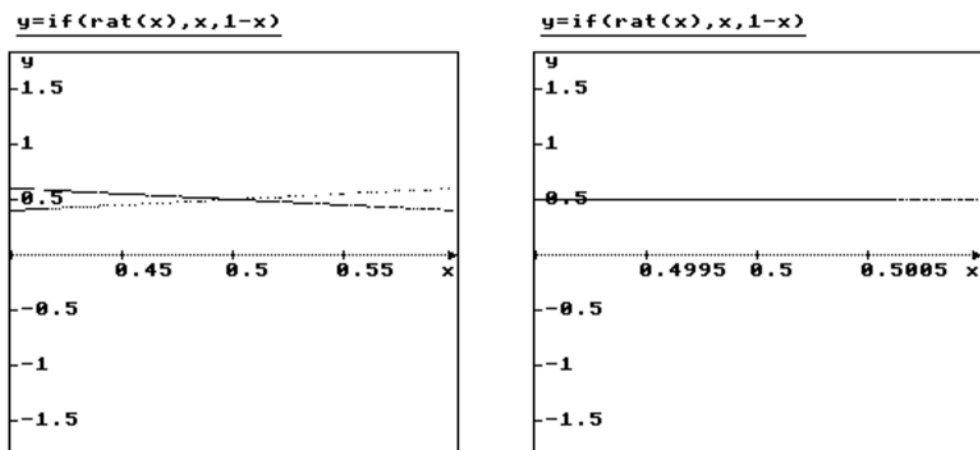


Figure 12 : stretching horizontally to see if(rat(x),x,1-x) is continuous at $x = \frac{1}{2}$

Figure 13 shows a graph whose domain is restricted to the pseudo-rationals which *appears* to have a discontinuity. But on inputting $x = \sqrt{2}$, the value is declared *not defined* because $\sqrt{2}$ is not a pseudo-rational. The graph is not defined on the very point where the jump occurs. On the other hand it *is* continuous at every point in the domain.

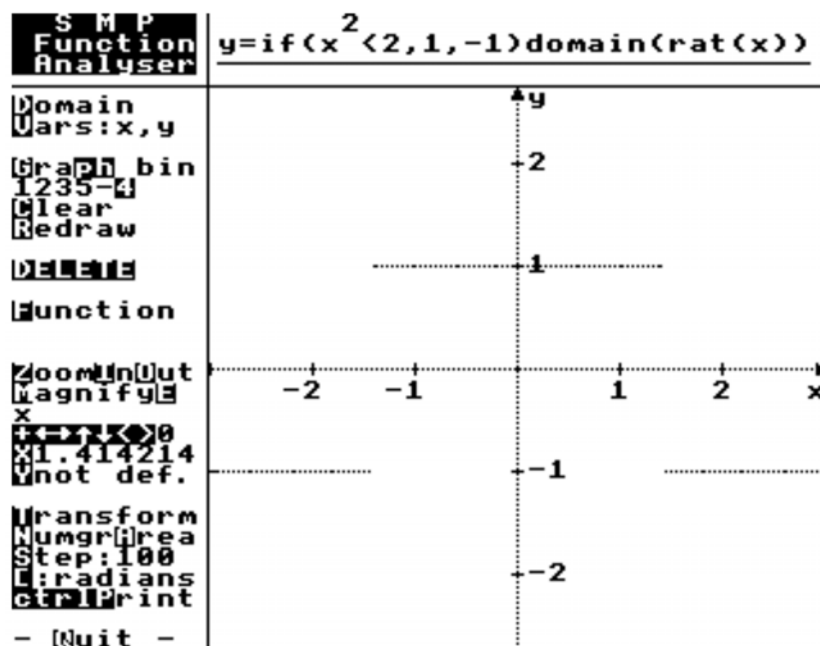


Figure 13: a graph defined on a (pseudo-) rational domain with an apparent discontinuity

With this latter graph the intuition is stimulated to focus on the notion of continuity as a pointwise definition *on the domain of the function concerned*. The pictures are now stretched to their practical limits and the human mind must take over to contemplate the underlying *real* mathematics.

Integrability

When integration is seen as the reverse of differentiation, the role of continuity becomes obscured. However, when integration is given an independent meaning through summation, the role of continuity becomes more focused. Calculating the area $A(x)$ from a fixed point x_0 to a variable point x under a continuous function $f(x)$ may be seen as giving an area function satisfying $A'(x)=f(x)$. This is because the area from x to $x+h$ is $A(x+h)-A(x)$ and, for small h , looking at a stretched picture which pulls the graph flat gives a visual approximation of $A(x+h)-A(x) \approx f(x)h$. So $\frac{A(x+h)-A(x)}{h}$ approximates to $f(x)$ and motivates the fundamental theorem $A'(x)=f(x)$ only on the assumption that $f(x)$ is *continuous*.

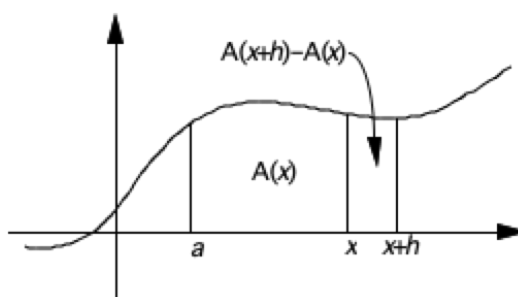


Figure 14 : the change in area

This means that if a function $f(x)$ is continuous but not differentiable, then its area function $A(x)$ is differentiable *once* (to get $f(x)$) *but not twice*. This can be illustrated by computing the area under the blancmange function. In figure 15 the increasing function is the numerical area under the blancmange calculated from the origin (for both positive and negative steps), using the mid-ordinate rule with steps width 0.1. See [1] for details.

It is even possible to compute the numerical gradient of the area function. The blancmange looking function in figure 15 is in fact the graph of this gradient, motivating the fact that $A'(x)$ is the original function.

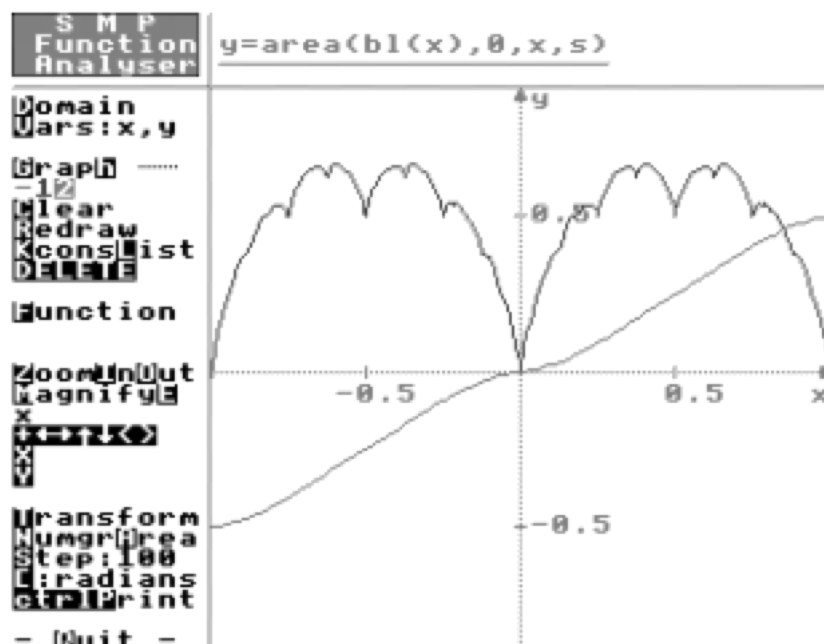


Figure 15 : the area function for the blancmange and its derivative

Integrating discontinuous functions

What happens when we attempt to compute the area under a function which is *not* continuous? The numerical calculations to compute the area approximations work in the usual way, but can produce insightful pictures. A graph with simple discontinuities such as $f(x)=x-\text{INT}(x)$ proves to have an area graph (the dotted curve in figure 16) which is locally straight, except at the points where f is discontinuous.



Figure 16 : The area under a curve with isolated jump discontinuities

Many early area plotters simply calculated the area and plotted the cumulative values *as a set of points*. In figure 17 the area is calculated *as a function* $\text{area}(f,a,b,h)$ of f from a to b with step h (using the mid-ordinate rule, here with $h=0.5$). It is then possible to zoom in on the graph at an appropriate points to see where it has different left and right gradients. Note that at $x=1$, the graph of $x-\text{int}(x)$ has left and right limits which are different (one and zero respectively); these are the gradients of the area graph to the left and right.

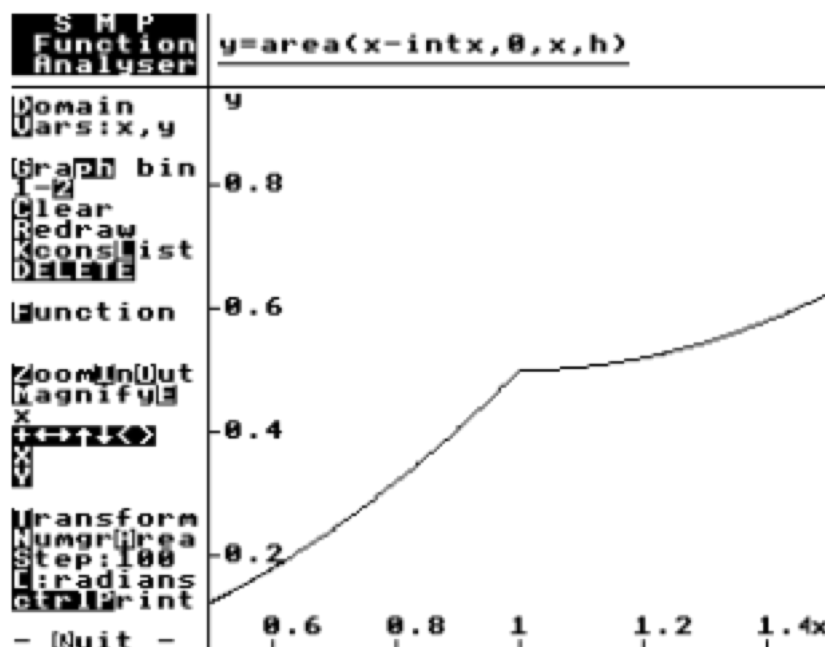


Figure 17 : zooming in on the area curve at $x=1$

What happens when we attempt to compute the integral under a highly discontinuous graph such as $f(x)=\text{if}(\text{rat}(x),x,1-x)$?

This proves to be highly interesting. Attempting to use a mid-ordinate rule to compute the area starting at a rational point with a rational step, clearly (mainly) pseudo-rationals will be encountered. Thus the area under $f(x)$ from 0 to 5 using this method is an upward facing parabola, of the approximate form $x^2/3$. The area under $y=x$ from 0 to 5 is $25/3 = 8\frac{1}{3}$. The difference between this and the result 7.51875 is due to errors in arithmetic giving a few pseudo-irrational points in the plot. Over a longer interval, such errors are likely to feature.

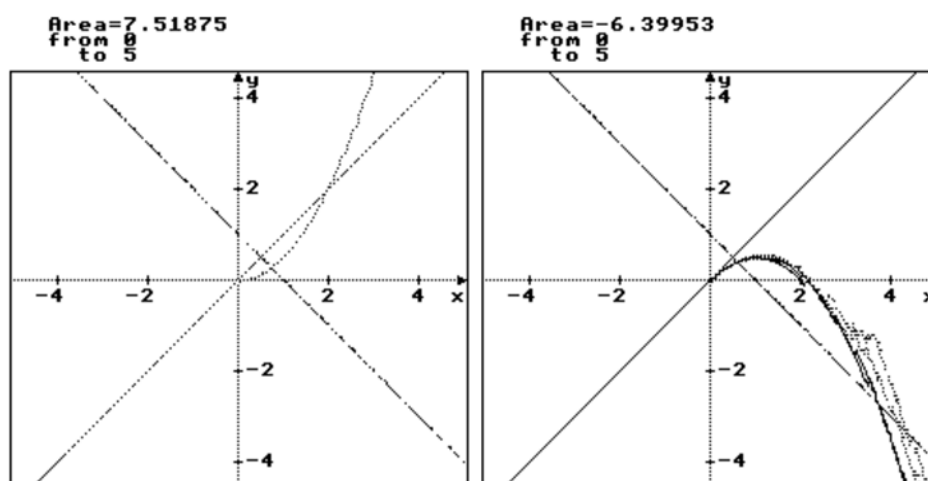


Figure 18 : calculating the area under the graph with rational and random steps

But a calculation with a *random* step-length, using strips whose height is computed at a *random* point within the strip produces a very different picture. The second picture shows the result after plotting the area from 0 to 5 several times over. There are several distinct but fairly close curves. A random value is highly likely (probability about 0.94) of being a pseudo-rational with the specific parameters for computation used in the program. Thus *most* of the values will lie on $f(x)=1-x$. Since $\int_0^t (1-x) dx = t - \frac{1}{2}t^2$, the graph will lie roughly on this curve but may diverge as the occasional pseudo-rational distorts the value. The given value -6.59953 compares approximately with the value of $5-12.5 = -7.5$. Some of the other computations were closer.

The interesting stimulus arising from the latter is that, in theory, irrationals are highly more likely to arise from random partitions than rationals. Using such a partition therefore may give an area which approximates to $x - \frac{1}{2}t^2$. This can motivate the possible development of a more powerful theory of integration in “real” mathematics – the theory of Lebesgue in which domains such as the irrationals inherently contribute more to an integral than the smaller domain of rationals. The step is, of course, a great one. It involves questions of cardinality and infinite series, which requires a leap in the imagination of a complex mind. But it is one which is better taken by a mind prepared for the journey.

Classroom experiences

The ideas in this article were piloted in a 60-hour analysis course for mathematics education students planning to be teachers. Traditionally such students have struggled with the subject. For instance, the previous year’s students were asked, after two weeks instruction in the ε - N definition of the limit of a sequence, to write down the definition. *None* of them were able to do so. Discussion on the mathematics was rare and there was sometimes a sense of alienation from the subject, as if it belonged to a different universe.

The decision was taken to revamp the course, using the ideas outlined here to make it more visual, and to encourage discussion techniques to build up the concepts. It was not expected that students would obtain greater facility with the formal aspects, but that they were more likely to be able to visualise and verbalise the concepts. This proved to be the case. Formal definitions (even if remembered!) are long and complex and usually need to be *written down* to be able to grasp them as a whole. Visual ideas prove to be easier to discuss in everyday language. The formal concepts were based on more meaningful conceptualizations.

The level of discussion was mature and often insightful. For example, on seeing the graph of the area function of the blancmange, a student observed that the area function must be “differentiable once but not twice”, before this was formally discussed. Few traditionally taught students have any idea what such a function might look like.

The discussions indicated a level of visualisation and verbalisation far greater than had been traditionally expected in earlier courses and they were by no means limited to a minority of the students.

Dealing with these visual concepts requires careful focusing and guidance to distinguish between the real mathematics and the rational images on the computer. Given a supportive environment, complex people can confront the conflict between real mathematics and rational images to produce a more meaningful foundation for the theory.

Reference

- [1] Tall, D. O., (1991), “Intuition and rigour: the role of visualization in the calculus”, *Visualization in Mathematics* (ed. Zimmermann & Cunningham), M.A.A., Notes No. 19, 105–119.