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20. We thank V. A. Novakovic for excellent technical assistance. Supported by the Heart and Stroke Foundation of Canada, Canadian Institutes of Health Research, and NIH. S.G. holds the Pitblado Chair in Cell Biology.

Supporting Online Material
www.sciencemag.org/cgi/content/full/319/5860/210/DC1
Materials and Methods
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23 October 2007; accepted 30 November 2007
10.1126/science.1152066

The Limits of Counting: Numerical Cognition Between Evolution and Culture

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Number words that, in principle, allow all kinds of objects to be counted ad infinitum are one basic requirement for complex numerical cognition. Accordingly, short or object-specific counting sequences in a language are often regarded as earlier steps in the evolution from premathematical conceptions to greater abstraction. We present some instances from Melanesia and Polynesia, whose short or object-specific sequences originated from the same extensive and abstract sequence. Furthermore, the object-specific sequences can be shown to be cognitively advantageous for calculations without notation because they use larger counting units, thereby abbreviating higher numbers, enhancing the counting process, and extending the limits of counting. These results expand our knowledge both regarding numerical cognition and regarding the evolution of numeration systems.

The discovery of the largely restricted (*1*) or probably even nonexistent (*2*) numeration system of the Pirahã in the Amazonian Basin contributed to the discussion of how numerical cognition depends on language. Numeration systems are cognitive tools for numerical cognition (*3*–*6*), and the experimental evidence gathered among the Pirahã provided a sound basis for an analysis of how such tools interact with the cognitive processing of numbers. Cognitive tools, like tools in general, may be more or less efficient, and respective differences in efficiency have been demonstrated both for notational (*7*, *8*) and for purely linguistic numeration systems (*9*–*12*). It should be noted, however, that the assessment of whether a feature is efficient always depends on the nature of the task and on the context of usage and that the efficiency of a specific numeration system does not say anything about the cognitive abilities of its users.

Apart from their efficiency, cognitive tools can also be ordered according to their presumed evolution. Because tools are typically developed in order to improve their efficiency, it is reasonable to assume that numeration systems evolve from being simpler to more sophisticated (*6*, *13*–*15*). But can one also conclude that the simpler a numeration system, the older it is? Although the authors of the recent studies on the Amazonian cases were careful not to draw this conclusion, the evolutionary status of the Pirahã system has become a matter of lively debate, both inside (*2*) and outside of academia. We propose that drawing conclusions on the cognitive and evolutionary status of specific numeration systems requires both diachronic and synchronic data. We set out to highlight the cognitive efficiency of some allegedly primitive systems in another part of the world and to show how they may have evolved from abstract to more specific as a result of cultural adaptation.

Among the properties commonly taken as indices for the simplicity of a numeration system are its extent and its degree of abstractness. The two are largely independent of each other, both on theoretical grounds as well as in practice, and they differ in terms of the attention they have attracted: Whereas the extent of numeration systems has been extensively addressed recently (*1*, *2*, *12*), the degree of abstractness has largely been neglected so far. We will illustrate these properties with two instances for each but will focus on the second feature.

One region where systems with limited extent abound is Papua New Guinea (*16*). Takia, a language in Madang Province, contains five numerals—*kaik*, *uraru*, *utol*, *iwaiwo*, and *kafe-n* (also denoting "his/her thumb"). Higher numbers may be composed by adding or multiplying numerals to the word for 5, but this seems to have been done rarely and for low numbers only (*17*). Adzera, a related language in the Markham River valley in Morobe Province, contains an even more restricted system. Its number words for 1 to 5 are composed of numerals for 1 and 2 only: *bits*, *iruˀ*, *iruˀ da bits* (= 2 + 1), *iruˀ da iruˀ* (= 2 + 2), and *iruˀ da iruˀ da bits* (= 2 + 2 + 1). Although because of its recursive character this system is in principle infinite, the inevitable difficulties in tallying the terms in higher-number words render it cumbersome. In such cases, people nowadays prefer to use loan words from Tok Pisin instead, a creole language based on English and used as lingua franca in New Guinea (*18*).

These two numeration systems are admittedly not as simple as the case of the Pirahã system, but their low bases and the lack of higher powers of their base restrict both of them. Although numerical cognition among the two Melanesian groups has not been studied experimentally, it can be inferred by analogy that, with such restricted systems, precise numerical operations should be laborious, if not impossible, for larger numbers (*1*, *12*, *19*).

The second property that is readily taken as evidence for restricted efficiency of a numeration system is its object specificity. Menninger inferred that the more object-specific counting sequences a language contains, the more antiquated the numeration system is (*14*). One of the languages referred to as having such object-specific counting sequences is Old High Fijian, a language in the eastern part of Fiji: Whereas it denotes 100 as *bola* when canoes are counted, for coconuts *koro* is used (*20*). Similar object-specific counting sequences can be found in the related Polynesian languages. On Mangareva, for instance, a volcanic island group in French Polynesia, tools, sugar cane, pandanus, breadfruit, and

Table 1. Numerals in traditional Mangarevan (abstract sequence).

Single numerals				Power numerals (quantities)			
1	tahi	6	ono	10^1	rogo'uru	$2 \cdot 10^5$	makiukiu
2	rua	7	hitu	$2 \cdot 10^1$	takau	$2 \cdot 10^6$	makore
3	toru	8	varu	$2 \cdot 10^2$	rau	$2 \cdot 10^7$	makorekore
4	hā	9	iva	$2 \cdot 10^3$	mano	$2 \cdot 10^8$	tini
5	rima			$2 \cdot 10^4$	makiu	$2 \cdot 10^9$	maeaea

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octopus were counted with different sequences (*21*). From an evolutionary point of view, it appears reasonable to regard such specific counting systems as predecessors of an abstract mathematical comprehension. But surprisingly, these same systems often also contained numerals for large powers—as far as 10^9 in Mangarevan—thus defining an extent not compatible with the conception of "primitive" numerical tools.

Why did we pick these particular instances? All four languages belong to the same linguistic cluster, namely, to the Oceanic subgroup of the Austronesian language family, and all inherited a regular and abstract decimal numeration system with (at least) two powers of base 10 from their common ancestor, Proto-Oceanic (*17*, *22*, *23*). Both the relative limitation of the two numeration systems in Papua New Guinea and the specific counting sequences in Fiji and Polynesia therefore constitute subsequent developments. Although the former might count as a case of regression in evolutionist terminology, the Polynesian cases are more complex and therefore require an elaborate analysis.

Traditional Mangarevan contained an abstract numeration system (Table 1) and three additional counting sequences for specific objects (*21*). As can be seen from Table 2, each of these sequences contained quantity terms different from the abstract power numerals and appears to have proceeded in diverging steps. However, this apparent divergence disappears when the value of the counting unit to which these sequences refer is extracted. For the first group of objects, the smallest unit *tauga* equals 2, for the second it equals 4, and for the third it equals 8 (for the polynomial composition and the sequence patterns, see Fig. 1C) (*24*).

Specific counting sequences were adopted in nearly every language in Polynesia and even beyond, and they all operated with counting units other than 1 (*25*–*27*). However, despite being based on the same construction principles, each of them was idiosyncratic with regard to the value of counting units, the objects of reference, and even to the numeration principles themselves. This indicates that each culture adapted its inherited system individually, in response to cultural needs. With only a few exceptions, the specific sequences regularly accompanied a general sequence that was purely decimal and abstract (*28*). Because this general sequence is constructed according to simple and coherent rules (Fig. 1A), it fulfills—unlike the English or German sequences (*4*, *5*, *9*–*11*)—all of the requirements of a well-designed and efficient numeration system. Why, then, the object-specific counting sequences?

One of the remarkable facts about numeration systems in Polynesian languages is their large extent. Clearly, Polynesians were interested in high numbers and had a need to operate with them (*25*). For instance, in precolonial times, Mangareva was home to a highly stratified society and was a junction for the long-distance exchange of goods. Accordingly, tributes and large shares for trade were regularly due (*29*–*31*). However, without notation, dealing with large numbers is difficult. In this context, specific counting sequences served practical reasons.

Their main effect was to abbreviate numbers by extracting from the absolute amount the factor inherent in the counting unit. This extraction has implications for critical factors for mental arithmetic: It directly affects the problem size effect in that it reduces calculation time (*3*), and it indirectly affects base size (*8*). Although large bases are more efficient for encoding large numbers and may, by virtue of compact internal representations, facilitate mental operations, they also require the memorization of larger addition and multiplication tables. Small bases, on the other hand, are cumbersome for the representation of large numbers but advantageous when it comes to simple calculations. This holds particularly for the binary system, as is well known since the work of Leibniz.

In Mangarevan, a preoccupation with 2 is apparent. Not only do the three specific sequences differ with regard to the value of their counting unit *tauga* by factor 2, but their general decimal pattern is also modulated with elements of a binary system. Because of its irregularities, the Mangarevan system gave rise to disadvantages not faced by other Polynesian languages with more-regular specific systems, but the disadvantages were compensated by a range of facilitation effects.

One of these effects was that counting specific objects was enhanced by counting them

Table 2. Different counting sequences in Mangarevan, ordered by number of single objects counted. Group 1 consisted of tools, pandanus, sugar cane, and breadfruit; group 2 of ripe breadfruits and octopus; and group 3 of the first breadfruits and octopus of a season. Ellipses indicate that parts of the counting sequence were omitted for reasons of space; dash entries indicate that a regular number word is lacking for this number in the respective sequence.

Objects	1…	2…	4…	8…	10…	20…	40…	80…	160…	200…	320…	640…
general	tahi	rua	hā …	varu	rogo'uru	takau				rau		
group 1	–	tauga	rua tauga	hā tauga		paua	tataua	varu	rua varu		hā varu	varu varu
group 2	–	–	tauga	rua tauga	–		paua	tataua	varu		rua varu	hā varu
group 3	–	–	–	tauga	–	–		paua	tataua		varu	rua varu

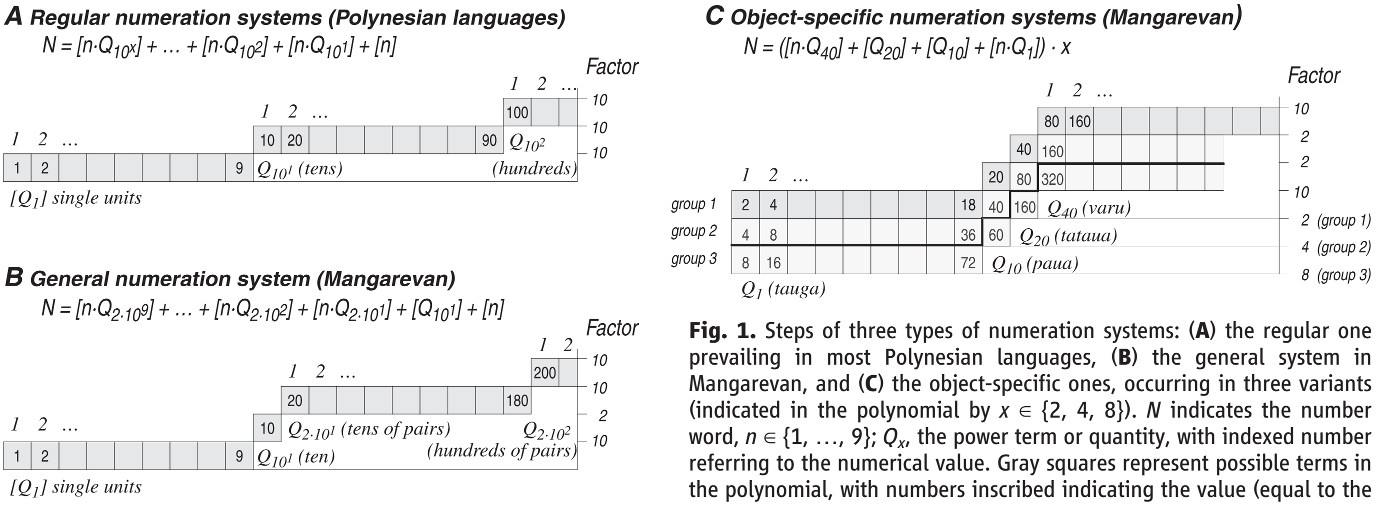

Fig. 1. Steps of three types of numeration systems: (**A**) the regular one prevailing in most Polynesian languages, (**B**) the general system in Mangarevan, and (**C**) the object-specific ones, occurring in three variants (indicated in the polynomial by $x \in \{2, 4, 8\}$). N indicates the number word, $n \in \{1, \ldots, 9\}$; Q_x, the power term or quantity, with indexed number referring to the numerical value. Gray squares represent possible terms in the polynomial, with numbers inscribed indicating the value (equal to the amount of single items referred to). Rows of squares (equal to quantities Q) are denoted by the words subscribed; numbers superscribed indicate the numeral n, multiplied by the respective quantity Q. The numbers on the right indicate the factor by which a level in the polynomial is multiplied to reach the next level.

in larger units (of pairs, quadruples, or eights). In addition, extracting the respective factor extended the limits of the counting sequence, but more importantly it also abbreviated higher numbers and consequently combined effects of large and small base sizes: Encoding produced compact number representations (e.g., 48 ripe breadfruits could be represented as 12 units = 1 *paua* + 2 *tauga*) as in a base 40 system; at the same time, calculating ensued with the addition and multiplication tables of the decimal base, supported by two binary steps.

To sum up, the linguistic analysis reveals that the specific counting systems in Mangareva did not precede an abstract system but were rather derived from it, despite their nonabstract nature (*32*). And the cognitive analysis suggests that this was done deliberately and for rational purposes. This justifies the conclusion that a feature of apparently little efficiency, once taken as indicator for an earlier evolutionary step in numerical cognition, can be used to overcome another such feature.

Not all cultures value numbers in the same way, even if they are concerned with mathematical topics (*33*). In some cultures in Papua New Guinea, for instance, large power numerals were given up together with decimal systems and replaced by quinary or body-counting sequences. In other cultures, the reverse of this took place: Not satisfied with the restrictions posed by their inherited numeration system, many Polynesian cultures not only extended its limits of counting but also designed efficient strategies to cope with the cognitive difficulties of mental arithmetic. Both lines of development started from the same regularly decimal and abstract numeration system inherited from Proto-Oceanic and therefore speak against a linear evolution of numerical cognition. Numeration systems do not always evolve from simple to more complex and from specific to abstract systems.

There may be no other domain in the field of cognitive sciences where it is so obvious that language (i.e., the verbal numeration system) affects cognition (i.e., mental arithmetic). One of the two core systems of number hinges on language (*6*, *34*). If one's language does not contain numerals beyond 1 and 2, calculating larger amounts is difficult, if not impossible. However, people are also very creative in adapting their cognitive and linguistic tools to cultural needs, and cases like those presented here add to our knowledge of how they achieve this.

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24. If *varu* was the principal counting unit of the specific sequences as indicated by cultural preferences, even the unusual steps (i.e., *paua* and *tataua*) could be explained, namely as short cuts to facilitate the representation of the incomplete units. The specific sequence would then be a modulo 40 system, in which units of 40 *tauga* were counted, and the remainder (if any occurred at all) was decomposed in $20 + 10 + n$. This may not be the most efficient method of decomposition, but—given the generally decimal nature of the system—it was surely the most preferable. The next possible decomposition ($20 + 10 + 5 + n$) would have arbitrarily restricted the single numerals to $n \in \{1, 2, 3, 4\}$.
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35. We are grateful to H. Spada for institutional support, to A. Rothe for assistance with the material, and to S. Mannion as well as two anonymous reviewers for discussion and valuable comments on earlier versions of this paper.

25 July 2007; accepted 29 November 2007
10.1126/science.1148345

Recognition of a Ubiquitous Self Antigen by Prostate Cancer–Infiltrating CD8$^+$ T Lymphocytes

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Substantial evidence exists that many tumors can be specifically recognized by CD8$^+$ T lymphocytes. The definition of antigens targeted by these cells is paramount for the development of effective immunotherapeutic strategies for treating human cancers. In a screen for endogenous tumor-associated T cell responses in a primary mouse model of prostatic adenocarcinoma, we identified a naturally arising CD8$^+$ T cell response that is reactive to a peptide derived from histone H4. Despite the ubiquitous nature of histones, T cell recognition of histone H4 peptide was specifically associated with the presence of prostate cancer in these mice. Thus, the repertoire of antigens recognized by tumor-infiltrating T cells is broader than previously thought and includes peptides derived from ubiquitous self antigens that are normally sequestered from immune detection.

T lymphocytes that are reactive to antigens expressed by tumor cells have been shown to modulate cancer development in animal models and human cancer patients (*1*, *2*). Thus, much effort has been devoted to the development of immunotherapeutic strategies aimed at