The Primary Pretenders

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Perhaps the most famous theorem in number theory is Fermat's theorem. Not Fermat's Last Theorem, of course, because that's now old hat, but Fermat's Little Theorem:

If p is a prime, and b is a positive integer prime to p, then $b^{p-1} \equiv 1 \pmod{p}$, which we prefer to write in the simpler form

$$b^p \equiv b \pmod{p}$$
.

If the converse of the theorem were true, then number theory would be a lot simpler than it is, but fortunately that is not the case. Counterexamples to the converse of the first (and, very occasionally, the second) form of Fermat's theorem are called **pseudoprimes**. A well-known example is $341 = 11 \times 31$, which is a pseudoprime to base 2:

$$2^{340} \equiv 1 \pmod{341}$$

The literature on pseudoprimes is extensive; for an introduction see section **A12** of the second author's *Unsolved Problems in Number Theory*, 2nd edition, Springer, 1994. D.H. Lehmer found the even pseudoprime $161038 = 2 \cdot 73 \cdot 1103$ and N.G.W.H. Beeger showed that there were infinitely many.

The **Carmichael numbers**, such as $561 = 3 \times 11 \times 17$, are counterexamples to the second form of Fermat's theorem to *any* base:

$$b^{561} \equiv b \pmod{561}$$
, $b = 1, 2, \dots$

The second form of the theorem admits a much wider class of counterexamples than the first, and to distinguish them from the pseudoprimes we will call any composite number q such that $b^q \equiv b \pmod{q}$ a **prime pretender** to base b.

We investigate q_b , the least prime pretender, or **primary pretender**, for the base b. We will see that there are only 132 distinct primary pretenders, and that q_b is a periodic function of b whose period is the 122-digit number

19 5685843334 6007258724 5340037736 2789820172 1382933760 4336734362-2947386477 7739548319 6097971852 9992599213 2923650684 2360439300

What is this number? Well, it's $p!_{59}p!_{9}$, where $p!_{k}$ is the product of the first k primes, $p_{1}p_{2}\cdots p_{k}$. And where do p_{59} and p_{9} come from? $p_{59}=277$ is the largest possible prime factor, and $p_{9}=23$ is the largest possible repeated prime factor, of a composite number less than the Carmichael number 561.

For what bases is 4 a prime pretender? If $b \equiv 0, 1, 2, 3 \pmod{4}$, then $b^4 \equiv 0, 1, 0, 1$, so 4 is a prime pretender just for $b \equiv 0, 1 \pmod{4}$.

The similar calculations mod 6 and 8 show that 6 is a prime pretender for bases $\equiv 0$ or 1 (mod 3) and that 8 is a prime pretender for bases $\equiv 0$ or 1 (mod 8). It follows that every number for which 8 is a prime pretender also has 4 as a prime pretender, so that 8 can never be the *primary* pretender. The calculations mod 9 show that 9 is a prime pretender for bases $\equiv 0$, 1 or 8 (mod 9), which may also be described as the square roots of 0 or 1 (mod 9).

These results can be recorded by saying that for q = 4 and 9,

"q is a prime pretender just for the bases that are kth roots of 0 or 1 (mod m)"

for a certain k and m. (It will turn out that such an assertion holds for all the primary pretenders — see Table 3.) They imply that we know the *primary* pretender q_b for all but the four residue classes 2, 11, 14, 23 (mod 36):

The values of q_b up to 21 for the residue classes mod 1260 missing from the last display are given in Table 1. In fact $q_b \geq 22$ for just the 32 residue classes mod 1260 indicated by ? in Table 1.

The number of distinct values of q_b is bounded, since the Carmichael number 561 will always serve if no smaller exponent has been found. The other numbers which occur

Table 1: $q_b = 10, 14, 15, 21$ for just 108 residue classes mod 1260.

b =	2	11	14	23	38	47	50	59	74	83	86	95	110	119	122	131	146	155	158	167
+0	?	10	14	?	?	?	10	15	15	21	10	10	10	14	?	10	10	10	?	21
+180	14	10	15	14	14	?	10	14	15	?	10	10	10	15	14	10	10	10	?	?
+360	?	10	15	?	21	14	10	15	14	?	10	10	10	15	21	10	10	10	14	?
+540	?	10	14	?	?	21	10	15	15	14	10	10	10	14	?	10	10	10	?	14
+720	14	10	15	14	?	?	10	15	15	?	10	10	10	15	?	10	10	10	?	?
+900																				
+1080	?	10	15	?	?	14	10	15	15	14	10	10	10	15	?	10	10	10	21	14

are products of just two prime factors: twice the primes from 2 to 277; thrice the primes from 3 to 181; five times those primes which are $\equiv 1 \pmod{4}$ from 5 to 109; seven times those primes which are $\equiv 1 \pmod{3}$ from 7 to 79; eleven times 11, 31 & 41; thirteen times 13 & 37; and the squares of 17, 19 & 23.

Computer calculations of the numbers in the missing residue classes for values of b up to 50000 appear in Table 2; the numbers at the left show the multiples of 1260 to be added. The programs used to calculate Tables 2 and 3 were straightforward, essentially using brute force.

Our final table, Table 3, shows how long it takes before any particular value of q_b appears; it can be summarized as follows. The value of q_b is

else
$$6$$
 if $b \equiv 0.1 \pmod{4}$
else 6 if $b \equiv 0.1 \pmod{3}$
else 9 if $b \equiv 8 \pmod{9}$
else $\dots \dots \dots$
else 561 if $b \equiv 0 \pmod{1}$

where the various statements can all be put into the form

"else
$$q$$
 if b is a k th root of 0 or 1 (mod m)"

for appropriate values of q, k and m. The table also gives the **first base**, that is the least b for which $q_b = q$, and the **rarity** r of q, meaning that q is the primary pretender for 1 in every r bases. For example

Table 2: $q_b \ge 22$ for 32 residue classes mod 1260, $2 \le b \le 51602$.

0	b =	2	23	38	47	122	158	227	263	338	347	362	383	443	527	542	563	578	662	698	758	767	803	842	878	887	947	983	1067	1082	1103	1118	1202
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means that 25 is the primary pretender for the bases that are 4th roots of 0 or 1 (mod 25) that have not already been coped with, that the first such base is 443, and that 1 in every 240.62 bases has 25 for its primary pretender (in fact 16 in every 3465 bases).

Another example is 'else 169 if $b^{12} \equiv 0$ or 1 (mod 169)', i.e., if $b \equiv \pm 19^e$ (mod 169), for $1 \le e \le 6$ where the cases e = 6 ($b \equiv \pm 1$), e = 3 ($b \equiv \pm 70$), and e = 2 or 4 ($b \equiv \pm 23$ or ± 22) have already been preempted by $q_b = 26$ or 39, by 65, and by 91 respectively.

The largest first base is 10009487, for q=453, while the greatest rarity is that of q=519.

Reference

The paper was prompted by the table of pseudoprimes to various bases given by Albert H. Beiler on p. 42 of his *Recreations in the Theory of Numbers*, Dover, New York, 1964.

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Table 3: The first base and rarity of the 132 primary pretenders.

$\begin{array}{c c c c c c c c c c c c c c c c c c c $	q roots	first	rarity	q roots	first	rarity	q roots	first	rarity
6 lst(3) 3 3 166 lst(83) 247838 69173.80 362 lst(181) 1050887 800429.64 9 2nd(9) 26 18 169 l2th(169) 1202 22203.93 365 4th(73) 822 313017.17 10 lst(5) 11 22.5 177 2nd(59) 111863 105468.69 381 2nd(127) 923162 1150798.45 14 lst(7) 14 52.5 178 lst(89) 48683 83809.94 382 lst(191) 383 886300.41 15 2nd(7) 83 157.5 185 4th(37) 1523 33318.02 393 2nd(131) 480638 1222539.12 12 lst(11) 23 216.56 194 lst(97) 58298 100995.26 394 lst(197) 384347 940782.12 25 4th(25) 443 240.62 201 2nd(67) 86027 138204.04 398 lst(199) 278402 960080.22 26 lst(13) 338 391.01 202 lst(101) 45047 109051.62 411 2nd(137) 786242 1315845.99 33 2nd(11) 263 639.84 205 4th(41) 14423 41858.20 417 2nd(139) 303158 1345305.23 41 st(17) 578 679.83 206 lst(103) 32342 119760.96 422 lst(211) 231467 1043600.74 438 lst(19) 38 861.12 213 2nd(71) 53462 163633.79 427 6th(61) 14958 139812.54 49 6th(49) 227 854.36 218 lst(109) 37823 155920.00 447 2nd(149) 141698 1633246.98 51 2nd(17) 3467 2135.92 219 2nd(73) 169067 206921.87 451 10th(41) 18302 50339.80 47 2nd(13) 983 930.58 254 lst(13) 3908 167015.51 453 2nd(151) 10009487 2143037.38 18t(19) 38 390.58 254 lst(13) 3908 167015.51 453 2nd(151) 10009487 2143037.38 18t(41) 2747 5293.84 265 4th(53) 98663 91000.38 478 lst(29) 24885.55 259 6th(37) 878 25091.09 469 6th(67) 473987 237840.01 41 st(37) 4847 4519.13 262 lst(131) 162047 234781.00 448 lst(227) 283523 1643477.99 262 lst(31) 4898 2698.68 249 2nd(83) 357563 246959.64 458 lst(423) 1567 6809.60 274 lst(137) 12478 2667 16791.76 418t(137) 44867 1679.69 2nd(23) 4622 4885.55 259 6th(37) 878 25091.09 469 6th(67) 473987 237840.01 41 st(37) 43667 27144.85 302 1st(151) 150698 360605.13 114 lst(37) 43667 27144.85 302 1st(151) 150698 360605.13 114 lst(47) 2867 1679.69 301 6th(43) 32987 42986.04 458 1st(241) 2252387 2262497.08 418 1st(67) 18523 351 10th(121) 5042 9990.30 305 4th(61) 287138 141802.12 519 2nd(167) 43667 231418.85 302 2367 lst(161) 485102 479193.40 514 lst(277) 3745622 4047604.68 133 6th(19) 2858 3954.76 326 lst(163) 296987 426312.06 554 5th(101) 2128262 967334.31 114 1	$k \mathrm{th}(m)$	base	one in	$k \operatorname{th}(m)$	base	one in			one in
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14 1st(7)	9 2nd(9)	26	18	169 12th(169) 1202	22203.93	3654 th(73)	8222	313017.17
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49 6th(49) 227 854.36				` /			` '		
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$146 \ 1 \mathrm{st}(73)^{\circ} \ 24602 \ 56543.84 \ \ 346 \ 1 \mathrm{st}(173)^{\circ} \ 846662 \ 708402.09 \ \ 554 \ 1 \mathrm{st}(277) \ \ 581423 \ 3497678.40$	` '			, ,			\ /		
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$158 \text{ 1st}(79) \qquad 158 62914.98 \mid 358 \text{ 1st}(179) 257402741543.71 \mid 561 \text{ 1st}(1) \qquad \qquad 10103 25437.66$				` /					
	158 Ist(79)	158	62914.98	358 1st (179)	257402	741543.71	$561 \operatorname{1st}(1)$	10103	25437.66