Minimal elements for the base *b* representations of the primes which are > *b*

Keywords

prime number, number theory, minimal element, partially ordered set, subsequence, formal language theory, positional notation, radix, algorithm, computer science, primality test, Miller–Rabin primality test, Baillie–PSW primality test, sieving, heuristic algorithm, conjecture, open problem, mathematical proof

Introduction

A string *x* is a subsequence of another string *y*, if *x* can be obtained from *y* by deleting zero or more of the characters (in this article, digits) in *y*. For example, 514 is a subsequence of 352148, "*string*" is a subsequence of "*Meistersinger*". In contrast, 758 is not a subsequence of 378259, since the characters (in this article, digits) must be in the same order. The empty string *λ* is a subsequence of every string. There are 2^n subsequences of a string with length *n*, e.g. the subsequences of 123456 are (totally $2^6 = 64$ subsequences):

λ, 1, 2, 3, 4, 5, 6, 12, 13, 14, 15, 16, 23, 24, 25, 26, 34, 35, 36, 45, 46, 56, 123, 124, 125, 126, 134, 135, 136, 145, 146, 156, 234, 235, 236, 245, 246, 256, 345, 346, 356, 456, 1234, 1235, 1236, 1245, 1246, 1256, 1345, 1346, 1356, 1456, 2345, 2346, 2356, 2456, 3456, 12345, 12346, 12356, 12456, 13456, 23456, 123456

(In this article, we only consider the subsequences with length ≥2, and not consider the subsequences beginning with 0 and/or ending with 0, e.g. for the string 123456, we have these subsequences: 12, 13, 14, 15, 16, 23, 24, 25, 26, 34, 35, 36, 45, 46, 56, 123, 124, 125, 126, 134, 135, 136, 145, 146, 156, 234, 235, 236, 245, 246, 256, 345, 346, 356, 456, 1234, 1235, 1236, 1245, 1246, 1256, 1345, 1346, 1356, 1456, 2345, 2346, 2356, 2456, 3456, 12345, 12346, 12356, 12456, 13456, 23456, 123456, totally 57 subsequences, and for a string with length *n* with no character 0, there are $2^n - n - 1$ subsequences)

Subsequence should not to be confused with substring, a substring is a contiguous sequence of characters within a string, they are related to two hard problems: longest common subsequence problem and longest common substring problem, respectively, e.g. 397 is a subsequence of 163975, "*string*" is a substring of "*substring*". In contrast, 514 is a subsequence of 352148, but not a substring. The empty string *λ* is a substring of every string. There are $n*(n+1)/2+1$ substrings of a string with length *n*, e.g. the substrings of 123456 are (totally $6*(6+1)/2+1 = 22$ substrings):

λ, 1, 2, 3, 4, 5, 6, 12, 23, 34, 45, 56, 123, 234, 345, 456, 1234, 2345, 3456, 12345, 23456, 123456

There are 64 − 22 = 42 subsequences of 123456 which are not substrings:

13, 14, 15, 16, 24, 25, 26, 35, 36, 46, 124, 125, 126, 134, 135, 136, 145, 146, 156, 235, 236, 245, 246, 256, 346, 356, 1235, 1236, 1245, 1246, 1256, 1345, 1346, 1356, 1456, 2346, 2356, 2456, 12346, 12356, 12456, 13456

(For the references of the difference of “subsequence” and “substring”, see this post and this post, and see the list below)

subsequence	substring
A071062	A033274
A130448	A238334
A039995	A039997
A039994	A039996
A094535	A093301

(In this article, we only research subsequence and not research substring, the reason is the minimal set of subsequence ordering must be finite even if the set is infinite (by the theorem that there are no infinite antichains for the subsequence ordering), and hence we may find this set, but the minimal set of substring ordering may be infinite, and it is highly possible that we cannot find this set, e.g. the minimal set of subsequence ordering of the set of prime number digit strings with length ≥2 in decimal (proofs for that this set is infinite) is known to be finite and contain exactly 77 elements, and the largest element is $50^{28}27$, where 0^{28} means the string with 28 0’s, but the minimal set of substring ordering of the set of prime number digit strings with length ≥2 in decimal is very likely to be infinite, since all primes of the form 1{0}3 (10^n+3, A159352) or 3{0}1 (3*10^n+1, A259866) are minimal elements of substring ordering of the set of prime number digit strings with length ≥2 in decimal, and there is likely infinitely many primes of the form 1{0}3 and infinitely many primes of the form 3{0}1 (see the “Proof” section of this article, also see this reference))

The set of all strings ordered by subsequence (i.e. under the binary relation “is a subsequence of”) is a partially ordered set (since this binary relation is reflexive, antisymmetric, and transitive), hence, any given (finite or infinite) set (e.g. the set of the “prime numbers > *b*” strings in base *b*, for 2 ≤ *b* ≤ 36), which is the target of this article) of strings ordered by subsequence is also a partially ordered set, and thus we can draw its Hasse diagram and find its greatest element, least element, maximal elements, and minimal elements, however, the greatest element and least element may not exist, and for an infinite set, the maximal elements also may not exist, thus we are only interested on finding the minimal elements of such sets, and we define *minimal set* of a set as the set of the minimal elements of this set, under a given partially ordered binary relation (this binary relation is "is a subsequence of" in this article), and we use *M*(*S*) to denote the minimal set of the set *S*.

A partially ordered set is a totally ordered set if the elements in this set are pairwise comparable, two elements *x* and *y* are comparable with respect to a binary relation "≤" if at least one of *x* ≤ *y* or *y* ≤ *x* is true, thus, under the binary relation "is a subsequence of", two strings *x* and *y* are comparable if either *x* is a subsequence of *y*, or *y* is a subsequence of *x*. A surprising result from formal language theory is that every set of pairwise incomparable (i.e. not comparable) strings is finite (note that this is not true for general partially ordered binary relations, e.g. the set of the positive integers, under the binary relation "is a divisor of", the infinite set of the prime numbers (proofs for that this set is infinite) is pairwise incomparable, in fact, this set is exactly the minimal set of the set of the positive integers >1 under this binary relation). This means that from any set of strings we can find its minimal elements. A string *x* in a set of strings *S* is a *minimal string* (minimal element of a set of strings ordered by subsequence) if whenever *y* (an element of *S*) is a subsequence of *x*, we have *y* = *x*.

The set of all minimal strings of *S* is denoted *M*(*S*), the set *M*(*S*) must be finite! Even if *S* is an infinite set, such as the set of prime number digit strings with length ≥2 in decimal (proofs for that this set is infinite) and the set of square number digit strings with length ≥2 in decimal, although the set of the minimal strings of the latter set is not known and extremely difficult to compute. The set of the minimal strings of the former set has exactly 77 elements, and it is {11, 13, 17, 19, 23, 29, 31, 37, 41, 43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97, 227, 251, 257, 277, 281, 349, 409, 449, 499, 521, 557, 577, 587, 727, 757, 787, 821, 827, 857, 877, 881, 887, 991, 2087, 2221, 5051, 5081, 5501, 5581, 5801, 5851, 6469, 6949, 8501, 9001, 9049, 9221, 9551, 9649, 9851, 9949, 20021, 20201, 50207, 60649, 80051, 666649, 946669, 5200007, 22000001, 60000049, 66000049, 66600049, 80555551, 555555555551, 5000000000000000000000000000027}, and we will prove that this set is complete, and the research of this set in other bases is exactly the target of this article. The set of the minimal strings of the latter set is {16, 25, 36, 49, 64, 81, 100, 121, 144, 289, 324, 400, 441, 484, 529, 576, 676, 729, 784, 900, 961, 1024, 1089, 2209, 2304, 2401, 2601, 2704, 3721, 3844, 4761, 5041, 5184, 6561, 6889, 7056, 7569, 7744, 7921, 21904, 22201, 28224, 29241, 29929, 31329, 35344, 38809, 46656, 47524, 55696, 62001, 63001, 69696, 79524, 80089, 80656, 82944, 88209, 88804, 91204, 91809, 97344, 97969, 98596, 99856, 138384, 139129, 173889, 182329, 199809, 300304, 301401, 304704, 305809, 332929, 339889, 345744, 374544, 393129, 473344, 505521, 515524, 558009, 559504, 567009, 589824, 595984, 657721, 660969, 665856, 683929, 695556, 702244, 719104, 743044, 777924, 779689, 842724, 850084, 876096, 877969, 896809, 898704, 929296, 935089, 1317904, 1557504, 1882384, 1898884, 2022084, 2027776, 2039184, 2070721, 2477476, 2802276, 2979076, 2999824, 3055504, 3073009, 3139984, 3323329, 3415104, 3794704, 4477456, 4545424, 4575321, 5053504, 5067001, 5071504, 5280804, 5303809, 5513104, 5527201, 5531904, 5574321, 5579044, 5707321, 5750404, 5755201, 5987809, 6517809, 6568969, 6620329, 6901129, 7006609, 7011904, 7033104, 7096896, 7177041, 7474756, 7551504, 7557001, 7573504, 7941124, 8020224, 8054244, 8282884, 8340544, 8508889, 8538084, 8620096, 8809024, 9229444, 9535744, 9809424, 9847044, 9935104, 9998244, 13118884, 13337104, 15038884, 15578809, 18939904, 19775809, 20903184, 20912329, 20994724, 23902321, 27709696, 29833444, 31102929, 31899904, 33039504, 33085504, 33315984, 33500944, 35533521, 35545444, 37797904, 38093584, 39980329, 40755456, 45535504, 47073321, 47444544, 50098084, 50566321, 50580544, 50608996, 50808384, 51151104, 53333809, 53993104, 55011889, 55517401, 55666521, 57501889, 57775201, 58247424, 58339044, 58859584, 59089969, 60575089, 60590656, 61199329, 65658609, 66650896, 66863329, 69072721, 69338929, 70006689, 70543201, 70997476, 71351809, 72233001, 73153809, 73994404, 74407876, 74632321, 75968656, 77668969, 77686596, 77757124, 77898276, 78907689, 78960996, 78978769, 79869969, 84052224, 85507009, 86992929, 88059456, 88096996, 88585744, 88868329, 89056969, 91833889, 94303521, ...}, although this set seems to be endless, but by the theorem that there are no infinite antichains for the subsequence ordering, this set must be finite, but this set is extremely difficult to found (reference), and it is also difficult to determine the number of elements in this set, and is much more difficult than that of the first set in every base $2 \le b \le 36$ (to find these two sets in bases $2 \le b \le 36$ (the prime or square = b (i.e. the prime or square "10") is also excluded when the base (b) is itself prime or square), we can use some theorems in number theory, e.g. a digit in base b can be the last digit of a prime number > b if and only if this digit is coprime to b (i.e. this digit is in the reduced residue system mod b, there are *eulerphi*(b) such digits), and a digit in base b can be the last digit of a square number > b if and only if this digit is a quadratic residue mod b). For example, it is not even known whether there is a square composed of digits 6, 7, 8 (except 676 = 26^2) (reference and reference and reference), also, it is not even known whether the non-simple family $3^m5^n9^r44$ contain a square or not, this situation usually not occur for primes in any base, i.e. every non-simple family which can not be ruled out as containing no primes > base usually contain a small prime > base, thus although the problem in this article (i.e. finding the minimal set of the primes > b in base b, for $2 \le b \le 36$) is hard, it is much easier than finding the minimal set of the squares > 10 in decimal (also finding the minimal set of the squares > b in base b for any base b > 4), thus the latter set is not discussed in this article.

In this article, we want to find the set of the minimal strings of the "prime number > b" digit strings in bases $2 \le b \le 36$, since decimal (base 10) is not special in mathematics, there is no reason to only find this set in decimal (base 10), also, finding this set in decimal (base 10) is too easy to be researched in an article (only harder than bases 2, 3, 4, 6), thus it is necessary to research this set in other bases b.

Equivalently, a string x in a set of strings S is a minimal string if and only if any proper subsequence of x (subsequence of x which is unequal to x, like proper subset) is not in S.

The minimal set $M(L)$ of a language L is interesting, this is because it allows us to compute two natural and related languages, defined as follows:

sub(*L*) := {*x* ∈ Σ* : there exists *y* ∈ *L* such that *x* is a subsequence of *y*};

sup(*L*) := {*x* ∈ Σ* : there exists *y* ∈ *L* such that *y* is a subsequence of *x*}.

An amazing fact is that *sub*(*L*) and *sup*(*L*) are always regular. This follows from the following classical theorem:

Theorem: For every language *L*, there are only finitely many minimal strings.

Indeed, we have *sup*(*L*) = *sup*(*M*(*L*)) and Σ* − *sub*(*L*) = *sup*(*M*(Σ* − *sub*(*L*))), and the superword language of a finite language is regular, since *sup*({w_1, ..., w_n}) = $\cup_{i=1}^{n} \quad \Sigma^* w_{i,1} \Sigma^* \ldots \Sigma^* w_{i,|w_i|} \Sigma^*$ where $w_i = w_{i,1} \ldots w_{i,|w\_i|}$ with $w_{i,j} \in \Sigma$.

Since there are no infinite antichains for the subsequence ordering of strings whose characters are in a fixed finite set (note that there can be infinite antichains for general ordering, e.g. the set of primes is an infinite antichain for the divisibility ordering (proofs for that this set is infinite), also, the set of strings {*abc*, *abbc*, *abbbc*, *abbbbc*, ...} is an infinite antichain for the substring ordering of strings whose characters are in a fixed finite set {*a*, *b*, *c*}), the set *M*(*S*) of minimal strings of any set *S* of strings must be finite.

Although the set *M*(*S*) of minimal strings is necessarily finite, determining it explicitly for a given *S* can be a difficult computational problem. We use some numbertheoretic heuristics to compute *M*(L_b), where L_b is the language of base-*b* representations of the prime numbers which are > *b*, for 2 ≤ *b* ≤ 16. (Also, I left as a challenge to readers the task of computing *M*(L_b) for 17 ≤ *b* ≤ 36) (we stop at base 36 since this base is a maximum base for which it is possible to write the numbers with the symbols 0, 1, ..., 9 (the 10 Arabic numerals) and A, B, ..., Z (the 26 Latin letters) of the Latin alphabet, references: http://www.tonymarston.net/php-mysql/converter.html https://www.dcode.fr/base-36-cipher https://docs.python.org/3/library/functions.html#int https://reference.wolfram.com/language/ref/BaseForm.html https://baseconvert.com/ https://www.calculand.com/unit-converter/zahlen.php?og=Base+2-36&ug=1, also see https://primes.utm.edu/notes/words.html for English words which are prime numbers when viewed as a number base 36)

This problem is very hard, since determining *M*(*L*) for arbitrary *L* is in general unsolvable and can be difficult even when *L* is relatively simple, the set *M*(*L*) is an antichain of *L* for the subsequence ordering (although may not be the "maximum antichain" (an antichain that has cardinality at least as large as every other antichain), which may not exist even for the subsequence ordering, although there cannot be an infinite antichains for the subsequence ordering), the problems in this article (i.e. determining *M*(L_b) for 2 ≤ *b* ≤ 36) are very hard open problems in number theory when *b* is large (say > 16) and may be NP-complete or an undecidable problem, or an example of Gödel's incompleteness theorems (like the continuum hypothesis and the halting problem, in fact, if the halting problem can be solved, then the problem in this article can also be solved (we only need to write a computer program for this problem, since this problem is discrete), however, the halting problem is known to be undecidable, i.e. a general algorithm to solve the halting problem for all possible program-input pairs cannot exist) (even in the weaker case that probable primes are allowed in place of proven primes, i.e. not including primality proving of the probable primes in $M(L_b)$), or as hard as the unsolved problems in mathematics, such as the Riemann hypothesis and the *abc* conjecture, determining $M(L_b)$ is much harder when $b > 24$ and/or *eulerphi*(b) is larger, since *eulerphi*(b) is the number of possible last digits of a prime number $> b$ in base b (these digits are exactly the base b digits coprime to b, all these bases are possible and for all such digits, there are infinitely many such primes (by Dirichlet's theorem), and for digits not coprime to b (let d be the greatest common divisor (GCD) of the digit and b), all such numbers are divisible by d and $d \le b$, thus cannot be primes $> b$). We can imagine an alien force, vastly more powerful than us, landing on Earth and demanding $M(L_b)$ for b = 17 (or 18, 19, 20, 21, 22, 23, 24, 28, 30, 36) (including primality proving of all primes in this set) or they will destroy our planet. In that case, I claim, we should marshal all our computers and all our mathematicians and attempt to find the set and to prove the primality of all numbers in this set. But suppose, instead, that they ask for $M(L_b)$ for b = 25 (or 26, 27, 29, 31, 32, 33, 34, 35). In that case, I believe, we should attempt to destroy the aliens.

Notation

In what follows, if x is a string of symbols over the alphabet $\Sigma_b := \{0, 1, ..., b - 1\}$ (the set of the base-b digits) we let $[x]_b$ denote the evaluation of x in the positional numeral system with base (or radix) b (starting with the most significant digit), and $[\lambda]_b := 0$ where λ is the empty string. This is extended to languages as follows: $[L]_b := \{ [x]_b : x \in L \}$. We use the convention that A := 10, B := 11, C := 12, ..., Z := 35, to conveniently represent strings of symbols in base $b > 10$. We let $(x)_b$ be the canonical representation of x in base b, that is, the representation without leading zeros. Finally, as usual, for a language L we let L^n := $LLL...LLL$ with n Ls and $L^* := \cup_{i\ge0} \; L^i$.

This is a list for L_b for bases $2 \le b \le 36$.

b	L_b (using A－Z to represent digit values 10 to 35)
2	11, 101, 111, 1011, 1101, 10001, 10011, 10111, 11101, 11111, 100101, 101001, 101011, 101111, 110101, 111011, 111101, 1000011, 1000111, 1001001, 1001111, 1010011, 1011001, 1100001, 1100101, 1100111, 1101011, 1101101, 1110001, 1111111, 10000011, 10001001, 10001011, 10010101, 10010111, 10011101, 10100011, 10100111, 10101101, 10110011, 10110101, 10111111, 11000001, 11000101, 11000111, 11010011, 11011111, 11100011, 11100101, 11101001, 11101111, 11110001, 11111011, 100000001, 100000111, 100001101, 100001111, 100010101, 100011001, 100011011, 100100101, 100110011, 100110111, 100111001, 100111101, 101001011, 101010001, 101011011, 101011101, 101100001, 101100111, 101101111, 101110101, 101111011, 101111111, 110000101, 110001101, 110010001, 110011001, 110100011, 110100101, 110101111, 110110001,

	110110111, 110111011, 111000001, 111001001, 111001101, 111001111, 111010011, 111011111, 111100111, 111101011, 111110011, 111110111, 111111101, 1000001001, 1000001011, 1000011101, 1000100011, ...
3	12, 21, 102, 111, 122, 201, 212, 1002, 1011, 1101, 1112, 1121, 1202, 1222, 2012, 2021, 2111, 2122, 2201, 2221, 10002, 10022, 10121, 10202, 10211, 10222, 11001, 11012, 11201, 11212, 12002, 12011, 12112, 12121, 12211, 20001, 20012, 20102, 20122, 20201, 21002, 21011, 21022, 21101, 21211, 22021, 22102, 22111, 22122, 22212, 22221, 100022, 100112, 100202, 100222, 101001, 101021, 101102, 101111, 101212, 102101, 102112, 102121, 102202, 110021, 110111, 110212, 110221, 111002, 111022, 111121, 111211, 112001, 112012, 112102, 112201, 112212, 120011, 120112, 120121, 120222, 121001, 121021, 121102, 121122, 121221, 122002, 122011, 122022, 122202, 200001, 200012, 200111, 200122, 200212, 201022, 201101, 202001, 202021, 202122, ...
4	11, 13, 23, 31, 101, 103, 113, 131, 133, 211, 221, 223, 233, 311, 323, 331, 1003, 1013, 1021, 1033, 1103, 1121, 1201, 1211, 1213, 1223, 1231, 1301, 1333, 2003, 2021, 2023, 2111, 2113, 2131, 2203, 2213, 2231, 2303, 2311, 2333, 3001, 3011, 3013, 3103, 3133, 3203, 3211, 3221, 3233, 3301, 3323, 10001, 10013, 10031, 10033, 10111, 10121, 10123, 10211, 10303, 10313, 10321, 10331, 11023, 11101, 11123, 11131, 11201, 11213, 11233, 11311, 11323, 11333, 12011, 12031, 12101, 12121, 12203, 12211, 12233, 12301, 12313, 12323, 13001, 13021, 13031, 13033, 13103, 13133, 13213, 13223, 13303, 13313, 13331, 20021, 20023, 20131, 20203, 20231, ...
5	12, 21, 23, 32, 34, 43, 104, 111, 122, 131, 133, 142, 203, 214, 221, 232, 241, 243, 304, 313, 324, 342, 401, 403, 412, 414, 423, 1002, 1011, 1022, 1024, 1044, 1101, 1112, 1123, 1132, 1143, 1204, 1211, 1231, 1233, 1242, 1244, 1321, 1343, 1402, 1404, 1413, 1424, 1431, 2001, 2012, 2023, 2034, 2041, 2102, 2111, 2113, 2133, 2212, 2221, 2223, 2232, 2311, 2322, 2342, 2344, 2403, 2414, 2432, 2443, 3004, 3013, 3024, 3042, 3101, 3114, 3134, 3141, 3211, 3213, 3224, 3233, 3244, 3312, 3321, 3323, 3332, 3404, 3422, 3431, 3444, 4003, 4014, 4041, 4043, 4131, 4142, 4212, 4223, ...
6	11, 15, 21, 25, 31, 35, 45, 51, 101, 105, 111, 115, 125, 135, 141, 151, 155, 201, 211, 215, 225, 241, 245, 251, 255, 301, 305, 331, 335, 345, 351, 405, 411, 421, 431, 435, 445, 455, 501, 515, 521, 525, 531, 551, 1011, 1015, 1021, 1025, 1035, 1041, 1055, 1105, 1115, 1125, 1131, 1141, 1145, 1151, 1205, 1231, 1235, 1241, 1245, 1311, 1321, 1335, 1341, 1345, 1355, 1411, 1421, 1431, 1435, 1445, 1501, 1505, 1521, 1535, 1541, 1555, 2001, 2011, 2015, 2025, 2041, 2045, 2051, 2055, 2115, 2131, 2135, 2151, 2155, 2205, 2225, 2231, 2301, 2311, 2325, 2335, ...
7	14, 16, 23, 25, 32, 41, 43, 52, 56, 61, 65, 104, 113, 115, 124, 131, 133, 142, 146, 155, 166, 203, 205, 212, 214, 221, 241, 245, 254, 256, 302, 304, 313, 322, 326, 335, 344, 346, 362, 364, 401, 403, 421, 436, 443, 445, 452, 461, 463, 506, 515, 524, 533, 535, 544, 551, 553, 566, 616, 623, 625, 632, 652, 661, 1004, 1006, 1013, 1022, 1033, 1042, 1051, 1055, 1064, 1105, 1112, 1123, 1136, 1141, 1154, 1156, 1165, 1202, 1211, 1222, 1226, 1231, 1235, 1253, 1264, 1301, 1312, 1316, 1325, 1343, 1345, 1402, 1411, 1424, 1433, 1442, ...
8	13, 15, 21, 23, 27, 35, 37, 45, 51, 53, 57, 65, 73, 75, 103, 107, 111, 117, 123,

	131, 141, 145, 147, 153, 155, 161, 177, 203, 211, 213, 225, 227, 235, 243, 247, 255, 263, 265, 277, 301, 305, 307, 323, 337, 343, 345, 351, 357, 361, 373, 401, 407, 415, 417, 425, 431, 433, 445, 463, 467, 471, 475, 513, 521, 533, 535, 541, 547, 557, 565, 573, 577, 605, 615, 621, 631, 643, 645, 657, 661, 667, 673, 701, 711, 715, 717, 723, 737, 747, 753, 763, 767, 775, 1011, 1013, 1035, 1043, 1055, 1063, 1071, ...
9	12, 14, 18, 21, 25, 32, 34, 41, 45, 47, 52, 58, 65, 67, 74, 78, 81, 87, 102, 108, 117, 122, 124, 128, 131, 135, 151, 155, 162, 164, 175, 177, 184, 201, 205, 212, 218, 221, 232, 234, 238, 241, 254, 267, 272, 274, 278, 285, 287, 308, 315, 322, 328, 331, 337, 342, 344, 355, 371, 375, 377, 382, 407, 414, 425, 427, 432, 438, 447, 454, 461, 465, 472, 481, 485, 504, 515, 517, 528, 531, 537, 542, 548, 557, 562, 564, 568, 582, 601, 605, 614, 618, 625, 638, 641, 661, 667, 678, 685, 702, ...
10	11, 13, 17, 19, 23, 29, 31, 37, 41, 43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97, 101, 103, 107, 109, 113, 127, 131, 137, 139, 149, 151, 157, 163, 167, 173, 179, 181, 191, 193, 197, 199, 211, 223, 227, 229, 233, 239, 241, 251, 257, 263, 269, 271, 277, 281, 283, 293, 307, 311, 313, 317, 331, 337, 347, 349, 353, 359, 367, 373, 379, 383, 389, 397, 401, 409, 419, 421, 431, 433, 439, 443, 449, 457, 461, 463, 467, 479, 487, 491, 499, 503, 509, 521, 523, 541, 547, 557, 563, 569, ...
11	12, 16, 18, 21, 27, 29, 34, 38, 3A, 43, 49, 54, 56, 61, 65, 67, 72, 76, 81, 89, 92, 94, 98, 9A, A3, 106, 10A, 115, 117, 126, 128, 133, 139, 142, 148, 153, 155, 164, 166, 16A, 171, 182, 193, 197, 199, 1A2, 1A8, 1AA, 209, 214, 21A, 225, 227, 232, 236, 238, 247, 25A, 263, 265, 269, 281, 287, 296, 298, 2A1, 2A7, 304, 30A, 315, 319, 324, 331, 335, 342, 351, 353, 362, 364, 36A, 373, 379, 386, 38A, 391, 395, 3A6, 403, 407, 414, 418, 423, 434, 436, 452, 458, 467, 472, 478, 47A, ...
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25	14, 16, 1C, 1G, 1I, 1M, 23, 29, 2B, 2H, 2L, 2N, 34, 38, 3E, 3M, 41, 43, 47, 49, 4D, 52, 56, 5C, 5E, 5O, 61, 67, 6D, 6H, 6N, 74, 76, 7G, 7I, 7M, 7O, 8B, 8N, 92, 94, 98, 9E, 9G, A1, A7, AD, AJ, AL, B2, B6, B8, BI, C7, CB, CD, CH, D6, DC, DM, DO, E3, E9, EH, EN, F4, F8, FE, FM, G1, G9, GJ, GL, H6, H8, HE, HI, HO, I7, IB, ID, IH, J4, JC, JG, JO, K3, K9, KL, KN, LG, LM, M7, MD, MJ, ML, N2, NC, NI, NO, ...
26	13, 15, 1B, 1F, 1H, 1L, 21, 27, 29, 2F, 2J, 2L, 31, 35, 3B, 3J, 3N, 3P, 43, 45, 49, 4N, 51, 57, 59, 5J, 5L, 61, 67, 6B, 6H, 6N, 6P, 79, 7B, 7F, 7H, 83, 8F, 8J, 8L, 8P, 95, 97, 9H, 9N, A3, A9, AB, AH, AL, AN, B7, BL, BP, C1, C5, CJ, CP, D9, DB, DF, DL, E3, E9, EF, EJ, EP, F7, FB, FJ, G3, G5, GF, GH, GN, H1, H7, HF, HJ, HL, HP, IB, IJ, IN, J5, J9, JF, K1, K3, KL, L1, LB, LH, LN, LP, M5, MF, ML, N1, ...
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28	11, 13, 19, 1D, 1F, 1J, 1P, 23, 25, 2B, 2F, 2H, 2N, 2R, 35, 3D, 3H, 3J, 3N, 3P, 41, 4F, 4J, 4P, 4R, 59, 5B, 5H, 5N, 5R, 65, 6B, 6D, 6N, 6P, 71, 73, 7F, 7R, 83, 85, 89, 8F, 8H, 8R, 95, 9B, 9H, 9J, 9P, A1, A3, AD, AR, B3, B5, B9, BN, C1, CB, CD, CH, CN, D3, D9, DF, DJ, DP, E5, E9, EH, ER, F1, FB, FD, FJ, FN, G1, G9, GD, GF, GJ, H3, HB, HF, HN, HR, I5, IH, IJ, J9, JF, JP, K3, K9, KB, KH, KR, L5, LB, ...
29	12, 18, 1C, 1E, 1I, 1O, 21, 23, 29, 2D, 2F, 2L, 2P, 32, 3A, 3E, 3G, 3K, 3M, 3Q, 4B, 4F, 4L, 4N, 54, 56, 5C, 5I, 5M, 5S, 65, 67, 6H, 6J, 6N, 6P, 78, 7K, 7O, 7Q, 81, 87, 89, 8J, 8P, 92, 98, 9A, 9G, 9K, 9M, A3, AH, AL, AN, AR, BC, BI, BS, C1, C5, CB, CJ, CP, D2, D6, DC, DK, DO, E3, ED, EF, EP, ER, F4, F8, FE, FM, FQ, FS, G3, GF, GN, GR, H6, HA, HG, HS, I1, IJ, IP, J6, JC, JI, JK, JQ, K7, KD, KJ, KL, ...
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32	15, 19, 1B, 1F, 1L, 1R, 1T, 23, 27, 29, 2F, 2J, 2P, 31, 35, 37, 3B, 3D, 3H, 3V, 43, 49, 4B, 4L, 4N, 4T, 53, 57, 5D, 5J, 5L, 5V, 61, 65, 67, 6J, 6V, 73, 75, 79, 7F, 7H, 7R, 81, 87, 8D, 8F, 8L, 8P, 8R, 95, 9J, 9N, 9P, 9T, AB, AH, AR, AT, B1, B7, BF, BL, BR, BV, C5, CD, CH, CP, D3, D5, DF, DH, DN, DR, E1, E9, ED, EF, EJ, EV, F7, FB, FJ, FN, FT, G9, GB, GT, H3, HD, HJ, HP, HR, I1, IB, IH, IN, IP, IV, ...
33	14, 18, 1A, 1E, 1K, 1Q, 1S, 21, 25, 27, 2D, 2H, 2N, 2V, 32, 34, 38, 3A, 3E, 3S, 3W, 45, 47, 4H, 4J, 4P, 4V, 52, 58, 5E, 5G, 5Q, 5S, 5W, 61, 6D, 6P, 6T, 6V, 72, 78, 7A, 7K, 7Q, 7W, 85, 87, 8D, 8H, 8J, 8T, 9A, 9E, 9G, 9K, A1, A7, AH, AJ, AN, AT, B4, BA, BG, BK, BQ, C1, C5, CD, CN, CP, D2, D4, DA, DE, DK, DS, DW, E1, E5, EH, EP, ET, F4, F8, FE, FQ, FS, GD, GJ, GT, H2, H8, HA, HG, HQ, HW, I5, I7, ID, ...
34	13, 17, 19, 1D, 1J, 1P, 1R, 1X, 23, 25, 2B, 2F, 2L, 2T, 2X, 31, 35, 37, 3B, 3P, 3T, 41, 43, 4D, 4F, 4L, 4R, 4V, 53, 59, 5B, 5L, 5N, 5R, 5T, 67, 6J, 6N, 6P, 6T, 71, 73, 7D, 7J, 7P, 7V, 7X, 85, 89, 8B, 8L, 91, 95, 97, 9B, 9P, 9V, A7, A9, AD, AJ, AR, AX, B5, B9, BF, BN, BR, C1, CB, CD, CN, CP, CV, D1, D7, DF, DJ, DL, DP, E3, EB, EF, EN, ER, EX, FB, FD, FV, G3, GD, GJ, GP, GR, GX, H9, HF, HL, HN, HT, ...
35	12, 16, 18, 1C, 1I, 1O, 1Q, 1W, 21, 23, 29, 2D, 2J, 2R, 2V, 2X, 32, 34, 38, 3M, 3Q, 3W, 3Y, 49, 4B, 4H, 4N, 4R, 4X, 54, 56, 5G, 5I, 5M, 5O, 61, 6D, 6H, 6J, 6N, 6T, 6V, 76, 7C, 7I, 7O, 7Q, 7W, 81, 83, 8D, 8R, 8V, 8X, 92, 9G, 9M, 9W, 9Y, A3, A9, AH, AN, AT, AX, B4, BC, BG, BO, BY, C1, CB, CD, CJ, CN, CT, D2, D6, D8, DC, DO, DW, E1, E9, ED, EJ, EV, EX, FG, FM, FW, G3, G9, GB, GH, GR, GX, H4, H6, HC, ...
36	11, 15, 17, 1B, 1H, 1N, 1P, 1V, 1Z, 21, 27, 2B, 2H, 2P, 2T, 2V, 2Z, 31, 35, 3J, 3N, 3T, 3V, 45, 47, 4D, 4J, 4N, 4T, 4Z, 51, 5B, 5D, 5H, 5J, 5V, 67, 6B, 6D, 6H, 6N, 6P, 6Z, 75, 7B, 7H, 7J, 7P, 7T, 7V, 85, 8J, 8N, 8P, 8T, 97, 9D, 9N, 9P, 9T, 9Z, A7, AD, AJ, AN, AT, B1, B5, BD, BN, BP, BZ, C1, C7, CB, CH, CP, CT, CV, CZ, DB, DJ, DN, DV, DZ, E5, EH, EJ, F1, F7, FH, FN, FT, FV, G1, GB, GH, GN, GP, GV, ...

The primes in $M(L_b)$ are called **minimal prime base *b*** in this article, although in fact this name should be used for L_b is the language of base-*b* representations of the prime numbers, where primes > *b* is not required (reference), this problem is an extension of the original minimal prime problem to include Conjectures 'R Us Sierpinski/Riesel conjectures base *b* with *k*-values < *b*, i.e. the smallest prime of the form $k*b^n+1$ and $k*b^n-1$ for all $k < b$. The original minimal prime base *b* puzzle does not cover CRUS Sierpinski/Riesel conjectures base *b* with CK < *b*, since in Riesel side, the prime is not minimal prime in original definition if either $k-1$ or $b-1$ (or both) is prime, and in Sierpinski side, the prime is not minimal prime in original definition if *k* is prime (e.g. $25*30^{34205}-1$ is not minimal prime in base 30 in original definition, since it is OT^{34205} in base 30, and T (= 29 in decimal) is prime, but it is minimal prime in base 30 if only primes > base are counted), but this extended version of minimal prime base *b* problem does, this requires a restriction of prime > *b*, and the primes ≤ *b* (including the $k-1$, $b-1$, *k*) are not allowed (i.e. only counting the primes > *b*, and we want to find the minimal set of “the primes > *b*” in base *b*), in fact, to include these conjectures, we only need to exclude the single-digit primes (i.e. the primes < *b*), also, in fact, I create this problem because I think that the single-digit primes are trivial (like strictly non-palindromic number, single-digit numbers are trivially palindromic, thus to test whether a number *n* is strictly non-palindromic, we do not consider the bases *b* > *n*, since in these bases, *n* is a single-digit number, thus trivially palindromic, note that all strictly non-palindromic numbers > 6 are primes), thus I do not count them (also see this forum post, there is someone else who also exclude the single-digit primes, but his research is about substring instead of subsequence), however, including the base (*b*) itself results in automatic elimination of all possible extension numbers with “0 after 1” from the set (when the base is prime, if the base is composite, then there is no difference to include the base (*b*) itself or not), which is quite restrictive (since when the base is prime, then the base (*b*) itself is the only prime ending with 0, i.e. having trailing zero, since in any base, all numbers ending with 0 (i.e. having trailing zero) are divisible by the base (*b*), thus cannot be prime unless it is equal the base (*b*), i.e. “10” in base *b*, note that the numbers cannot have leading zero, since typically this is not the way we write numbers (in any base), thus for all primes in our sets (i.e. all primes > base (*b*)), all zero digits must be “between” other digits) (see this forum post, there is someone else who also exclude the prime = base), thus, we also exclude the prime = *b* (i.e. the prime “10”) (you may ask me why we do not exclude the prime = *b*+1? Since *b*+1 is “11” in base *b*, this is a generalized repunit number base *b*, if we exclude it (“11” in base b), then we have the next question: should we exclude “111”, “1111”, “11111”, etc. in base *b*? This is hard to answer, and if we exclude them all, the result will not be “primes > *m*” for some integer *m*, thus we do not exclude “11” in base *b* but exclude “10” in base *b*, we also exclude the single-digit primes (i.e. the primes < *b*) in base *b*), besides, this problem is better than the original minimal prime problem since this problem is regardless whether 1 is considered as prime or not, i.e. no matter 1 is considered as prime or not prime (in the beginning of the 20th century, 1 is regarded as prime), the sets $M(L_b)$ in this problem are the same, while the sets $M(L_b)$ in the original minimal prime problem are different, e.g. in base 10, if 1 is considered as prime, then the set $M(L_b)$ in the original minimal prime problem is {1, 2, 3, 5, 7, 89, 409, 449, 499, 6469, 6949, 9049, 9649, 9949, 60649, 666649, 946669, 60000049, 66000049, 66600049}, while if 1 is not considered as prime, then the set $M(L_b)$ in the original minimal prime problem is {2, 3, 5, 7, 11, 19, 41, 61, 89, 409, 449, 499, 881, 991, 6469, 6949, 9001, 9049, 9649, 9949, 60649, 666649, 946669, 60000049, 66000049, 66600049}, however, in base 10, the set $M(L_b)$ in this problem is always {11, 13, 17, 19, 23, 29, 31, 37, 41, 43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97, 227, 251, 257, 277, 281, 349, 409, 449, 499, 521, 557, 577, 587, 727, 757, 787, 821, 827, 857, 877, 881, 887, 991, 2087, 2221, 5051, 5081, 5501, 5581, 5801, 5851, 6469, 6949, 8501, 9001, 9049, 9221, 9551, 9649, 9851, 9949, 20021, 20201, 50207, 60649, 80051, 666649, 946669, 5200007, 22000001, 60000049, 66000049, 66600049, 80555551, 555555555551, 5000000000000000000000000000027}, no matter 1 is considered as prime or not prime.

For example, 857 is a minimal prime in decimal because there is no prime > 10 among the shorter subsequences of the digits: 8, 5, 7, 85, 87, 57. The subsequence does not have to consist of consecutive digits, so 149 is not a minimal prime in decimal (because 19 is prime and 19 > 10). But it does have to be in the same order; so, for example, 991 is still a minimal prime in decimal even though a subset of the digits can form the shorter prime 19 > 10 by changing the order.

A summary of the results of our algorithm is presented in the table in the next section, I completely solved all bases up to 16 except for bases 14, 16, and the odd bases >6 (the proofs are at the end of this article), for bases 14, 16, and the odd bases >6, I only found all minimal primes up to certain limit (about 2^{32}) and some larger minimal primes (such as $3^{16}1$ in base 7 and 54^{11} in base 9). I left as a challenge to readers the task of solving (finding all minimal primes and proving that these are all such primes) bases 7, 9, 11, 13, 14, 15, 16, and bases 17 through 36 (this will be a hard problem, e.g. base 23 has a minimal prime $9E^{800873}$, and base 30 has a minimal prime OT^{34205}).

Prime numbers are central in number theory because of the fundamental theorem of arithmetic: every natural number greater than 1 is either a prime itself or can be factorized as a product of primes that is unique up to their order. Besides, “the sets in this article” to “the prime numbers (except *b* itself) digit strings with length > 1 in base *b*” to “the partially ordered binary relation by subsequence” is “the sets of prime numbers” to “the integers > 1” to “the partially ordered binary relation by divisibility” (and indeed, the “> 1” in “the prime numbers (except *b* itself) digit strings with length > 1 in base *b*” can be corresponded to the “> 1” in “the integers > 1”) (for the reason why *b* itself is excluded, see the sections above and this forum post), thus the problem in this article is very important and beautiful.

Recreations involving the decimal digits of primes have a long history. To give just a few examples, without trying to be exhaustive, Yates studied the “repunits”, which are primes of the form 111...111. Caldwell and Dubner studied the “near-repdigits”, which are primes with all like or repeated digits but one (e.g. 7877 and 333337). Card introduced prime numbers such as 37337999, in which every nonempty prefix is also a prime; he called them “snowball” primes. These were later studied by Angell & Godwin and Caldwell, who called them “right-truncatable” primes. They also studied the “left-truncatable” primes, such as 4632647, in which every nonempty suffix is prime (the left-truncatable primes are called “Russian doll primes” like that the right-truncatable primes are called “snowball primes”, see this page). Kahan and Weintraub gave a list of all the left-truncatable primes (The list of all left-truncatable primes and right-truncatable primes are in http://primerecords.dk/left-truncatable.txt and http://primerecords.dk/right-truncatable.txt, respectively, also see OEIS sequences A024785 and A024770). Huestis introduced the “recursively laminar primes”. In this note, I discuss an apparently new problem on the decimal digits of primes, but one inspired from a classical theorem in formal language theory, i.e. there are only finitely many minimal elements for the subsequence ordering of any given set of strings (in fact, every set of pairwise incomparable strings (for the subsequence ordering) is finite).

However, there is no reason to only study these classes of primes in decimal, since the number 10 is not special in mathematics, decimal (base 10) is not special in mathematics, thus, we had better study about the base *b* digits of primes for other bases *b*. For the repunit primes, there are a list of repunit primes or PRPs in all bases 2 ≤ *b* ≤ 160 and length ≤ 32803, and a list of repunit primes or PRPs in all bases 2 ≤ *b* ≤ 999 and length ≤ 3571, also see OEIS sequences A084740 and A084738 for the smallest repunit (probable) primes in base *b*; for the near-repdigit primes, there was no list of the smallest such primes (only a list of factorization of such numbers in decimal (base 10)), but recently I built a list of the smallest primes or PRPs in given near-repdigit form *x*{*y*} (i.e. *xyyy...yyy*) or {*x*}*y* (i.e. *xxx...xxxy*) (where *x* and *y* are digits in base *b*) in bases 2 ≤ *b* ≤ 36 (I stop at base 36 since this base is a maximum base for which it is possible to write the numbers with the symbols 0, 1, ..., 9 (the 10 Arabic numerals) and A, B, ..., Z (the 26 Latin letters) of the Latin alphabet, references: http://www.tonymarston.net/php-mysql/converter.html https://www.dcode.fr/base-36-cipher https://docs.python.org/3/library/functions.html#int https://reference.wolfram.com/language/ref/BaseForm.html https://baseconvert.com/ https://www.calculand.com/unit-converter/zahlen.php?og=Base+2-36&ug=1); for the left-truncatable primes, there is a graph of the actual values and estimation formulas for bases 3 ≤ *b* ≤ 120 (no such prime exists for *b* = 2), also see OEIS sequences A103443 and A103463 and A076623 for the largest left-truncatable primes in base *b* and the total number of left-truncatable primes in base *b*; for the right-truncatable primes, there is data for bases 3 ≤ *b* ≤ 90 (no such prime exists for *b* = 2), also see OEIS sequences A023107 and A103483 and A076586 for the largest right-truncatable primes in base *b* and the total number of right-truncatable primes in base *b*. Thus, this new problem on the digits of primes (i.e. the problem on the digits of primes inspired from a classical theorem in formal language theory) should also be generalized to other bases, and this problem in various bases is exactly the target of this article (in this article we aim to solve this problem in bases 2 ≤ *b* ≤ 36 (I stop at base 36 since this base is a maximum base for which it is possible to write the numbers with the symbols 0, 1, ..., 9 (the 10 Arabic numerals) and A, B, ..., Z (the 26 Latin letters) of the Latin alphabet, references: http://www.tonymarston.net/php-mysql/converter.html https://www.dcode.fr/base-36-cipher https://docs.python.org/3/library/functions.html#int https://reference.wolfram.com/language/ref/BaseForm.html https://baseconvert.com/ https://www.calculand.com/unit-converter/zahlen.php?og=Base+2-36&ug=1), but since this problem (finding all minimal primes) is much harder than finding all left-truncatable primes or all right-truncatable primes for the same base, in this article we only solve this problem in bases 2 ≤ *b* ≤ 16, and I left as a challenge to readers the task of solving this problem in bases 17 ≤ *b* ≤ 36, of course, you can also try to solve this problem in bases 2 ≤ *b* ≤ 120 as the same problem for the left-truncatable primes, but this will be extremely difficult).

There is a conjecture that there are infinitely many repunit primes in all bases *b* which are not perfect powers (if *b* is a perfect power, then it can be shown that there is at most one repunit prime in base *b*, since the numbers with all digits 1 in these bases can be factored algebraically (this strategy (algebraic factorization) will also be used in our problem, to show that some families (such as 10^n1 in base 8 and 38^n in base 9) contains no primes > base)), and it is also conjectured that there are also infinitely many primes in any given near-repdigit form *x*{*y*} (i.e. *xyyy...yyy*) or {*x*}*y* (i.e. *xxx...xxxy*) (where *x* and *y* are digits in base *b*) if this form cannot be proven as only contain composites or only contain finitely many primes, also, it is conjectured that there are finitely many left-truncatable primes and finitely many right-truncatable primes in any given base *b*, however, unlike minimal primes (which can be proven to be finite in any given base *b* by using the theorem that there are no infinite antichains for the subsequence ordering), none of these conjectures are proven.

These classes of primes are related to the class of primes in this article (i.e. minimal primes) and hence related to the problem in this article (i.e. finding $M(L_b)$ for bases $2 \le b \le 36$), since the smallest repunit prime (if exists) is always a minimal prime to the same base *b*, and the smallest near-repdigit prime with a given form *x*{*y*} (i.e. *xyyy...yyy*) or {*x*}*y* (i.e. *xxx...xxxy*) (where *x* and *y* are digits in base *b*) (if exists) is also always a minimal prime to the same base *b*, also, since all suffixes and all prefixes are also substrings, hence also subsequences, a left-truncatable prime or right-truncatable prime with length ≥ 3 cannot be a minimal prime to the same base *b*, and left-truncatable primes or right-truncatable primes can be regarded the opposite of minimal primes (reference).

Problems about the digits of prime numbers have a long history, and many of them are still unsolved. For example, are there infinitely many primes, all of whose base-10 digits are 1? Currently, there are only five such “repunits” known, corresponding to $(10^p - 1)/9$ for $p \in \{2, 19, 23, 317, 1031\}$. It seems likely that four more are given by $p \in \{49081, 86453, 109297, 270343, 5794777, 8177207\}$, but this has not yet been rigorously proven. This problem also exists for other bases, e.g. for base 12, there are only nine proven such numbers, corresponding to $(12^p - 1)/11$ for $p \in \{2, 3, 5, 19, 97, 109, 317, 353, 701\}$. It seems likely that five more are given by $p \in \{9739, 14951, 37573, 46889, 769543\}$, but this has not yet been rigorously proven. However, for some bases there exists no such primes, these bases are 9, 25, 32, 49, 64, 81, 121, 125, 144, ..., (https://oeis.org/A096059) this is because the numbers with all digits 1 in these bases can be factored algebraically (this strategy (algebraic factorization) will also be used in our problem, to show that some families (such as 10^n1 in base 8 and 38^n in base 9) contains no primes > base). Some positive integers *n* are repunit in some base $2 \le b \le n-2$ (every integer $n \ge 3$ are trivially repunit in base $b = n-1$ since *n* is written “11” in base $b = n-1$, but every integer $n \ge 2$ are not repunit in any base $b \ge n$ since *n* is written “10” in base $b = n$ and *n* is single-digit number (and this digit is not 1) in any base $b > n$), they are called Brazilian numbers, all integers >6 which are neither primes nor squares of primes are Brazilian numbers, but it is unknown whether there are infinitely many primes which are also Brazilian numbers (however, it is known that every squares of primes except 121 = “11111” in base 3 are not Brazilian numbers). Another unsolved problem about the digits of prime numbers is whether there are infinitely many palindromic primes (primes which remain the same when their digits are reversed, such as 151 and 94849) in base 10? So far, the largest known such prime is $10^{1234567} - 20342924302 * 10^{617278} - 1$, this number has 1234567 digits, can also be written as $9^{617278}796570756979^{617278}$, and the largest 20 known such primes are listed in this page. Of course, this problem also exists for other bases, there is no single bases for which it is known whether there are infinitely many palindromic primes. Some positive integers n are not palindromic in any base $2 \le b \le n-2$ (every integer $n \ge 3$ are trivially palindromic in base $b = n-1$ since n is written "11" in base $b = n-1$, also every positive integer n are trivially palindromic in any base $b > n$ since n is single-digit number in any base $b > n$, but every integer $n \ge 2$ are not palindromic in base $b = n$ since n is written "10" in base $b = n$), they are called strictly non-palindromic numbers, all such integers > 6 are primes, since all composites $n > 6$ is either "product of two numbers k and m with $m - k \ge 2$" (in this case, n is written "kk" in base $b = m-1$) or "square of prime p" (in this case, n is written "121" in base $b = p-1$ if $p > 3$, or written "1001" in base $b = 2$ if $p = 3$), it is also unknown whether there are infinitely many such integers, but it is known that in every base, almost all palindromic numbers are composite (neither 1 nor prime).

Table

$|x|$ is the length of x, and in the "$max(x, x \in L_b)$" column, xy^nz means $xyyy...yyyz$ with n y's (the n-value is written in decimal), not y to the nth power.

b	$\|M(L_b)\|$	$max(x, x \in M(L_b))$	$max(\|x\|, x \in M(L_b))$	Algebraic form of $max(x, x \in M(L_b))$
2	1	11	2	3
3	3	111	3	13
4	5	221	3	41
5	22	$10^{93}13$	96	$5^{95}+8$
6	11	40041	5	5209
7	71	$3^{16}1$	17	$\frac{7^{17}-5}{2}$
8	75	$4^{220}7$	221	$\frac{4 \cdot 8^{221}+17}{7}$
9[①]	≥149	$30^{1158}11$	1161	$3*9^{1160}+10$
10	77	$50^{28}27$	31	$5*10^{30}+27$

11①	≥914	557^{1011} or 57^n with n>50000	1013	$\frac{607\cdot 11^{1011}-7}{10}$
12	106	$40^{39}77$	42	$4*12^{41}+91$
13①②	≥2497	$80^{32017}111$ or 95^n with n>50000 or $A3^nA$ with n>50000	32021	$8*13^{32020}+183$
14①	≥606	$4D^{19698}$	19699	$5*14^{19698}-1$
15①	≥1212	$7^{155}97$	157	$\frac{15^{157}+59}{2}$
16①②	≥2045	DB^{32234}	32235	$\frac{206\cdot 16^{32234}-11}{15}$

Notes:

① I have not proved these bases, these are the largest elements in $M(L_b)$ known to me, and they are just the lower bounds.

② Data based on results of strong probable primality tests, i.e. at least one element in the set $M(L_b)$ is only strong probable prime (i.e. numbers which passed the Miller–Rabin primality tests to first few prime bases, for the smallest *composite* number which passed the Miller–Rabin primality test to first *n* prime bases, see https://oeis.org/A014233) and not provable prime, thus we cannot definitely say that the corresponding families can be removed from the list of unsolved families, and we cannot definitely compute this part of the set $M(L_b)$, e.g. since $80^{32017}111$ (base 13) is only strong probable prime and it is the smallest (probable) prime in family 8{0}111 in base 13, we cannot definitely say that the family 8{0}111 (base 13) can be removed from the list of unsolved families, and since DB^{32234} (base 16) is only strong probable prime and it is the smallest (probable) prime in family D{B} in base 16, we cannot definitely say that the family D{B} (base 16) can be removed from the list of unsolved families.

It is found that both $|M(L_b)|$ and $max(|x|, x \in M(L_b))$ are roughly $e^{\gamma*(b-1)*eulerphi(b)}$, the value $(b-1)*$*eulerphi*(b) is the number of possible (first digit,last digit) combos (ordered pair) of a minimal prime in base *b* (these (first digit,last digit) combos are also all possible (first digit,last digit) combos (ordered pair) of a prime > *b* in base *b*) (they are only all “possible” (first digit,last digit) combos (ordered pair) of a minimal prime in base *b*, this does not mean that they must be realized, e.g. there are no minimal primes with (first digit,last digit) = (2,2) in base 3), since the first digit has $b-1$ choices (all digits except 0 can be the first digit), and the last digit has *eulerphi*(b) choices (only digits coprime to *b* (i.e. the digits in the reduced residue system mod *b*) can be the last digit), by the rule of product, there are $(b-1)*$*eulerphi*(b) choices of the (first digit,last digit) combo. Thus, $(b-1)*$*eulerphi*(b) is also the relative hardness for (finding and proving the set $M(L_b)$ in) base *b*, there is exactly a sequence of $(b-1)*$*eulerphi*(b) in OEIS: A062955, for these $(b-1)*$*eulerphi*(b) possible (first digit,last digit) combos, we want to find all minimal primes with such (first digit,last digit) combo, if the string "first digit, last digit" represents a prime in base *b*, then this prime will be the only minimal prime with this (first digit,last digit) combo (since the string "first digit, last digit" is a subsequence of all numbers with this (first digit,last digit) combo), otherwise, we should find all digits which can be inserted to this (first digit,last digit) combo, i.e. the string "first digit, such digit, last digit" is neither prime nor have a subsequence which represents a prime, then do this repeatedly (find the possible (first digit,last digit) combos for the string which inserted to the starting (first digit,last digit) combo, etc.), then do program loops, these program loops must be finite by the theorem that there are no infinite antichains for the subsequence ordering, see the "proof" section and this forum post and this article.

The probability for a random prime to have a given (first digit,last digit) combo (ordered pair) which is a possible (first digit,last digit) combo (ordered pair) of a prime > *b* in base *b* (i.e. "first digit" is not 0, and "last digit" is coprime to *b*) are all the same, i.e. they are all $1/((b-1)*eulerphi(b))$ no matter which (first digit,last digit) combo (ordered pair) is given, the only condition is that "first digit" is not 0, and "last digit" is coprime to *b*, for the first digit, there is a reference about this, the primes do not follow the Benford's law (reference of Benford's law to other bases) (only the prime factors of the numbers with exponential growth (such as the repunits and the Fibonacci numbers) follow), instead, all nonzero digits have the same probability (i.e. probability $1/(b-1)$) for a random prime in base *b*, just like a positive integer in base *b*, for the last digit, by the prime number theorem (extended to arithmetic progression), all digits coprime to *b* have the same probability (i.e. probability $1/eulerphi(b)$) for a random prime in base *b*, however, according to Chebyshev's bias, if d_1 is a quadratic residue mod *b*, d_2 is a quadratic nonresidue mod *b* (i.e. d_1 can be the last digit of a square number, while d_2 cannot be), then for the primes $\le N$ for a random positive integer *N*, the probability for the number of primes end with d_2 in base *b* is more than the number of primes end with d_1 in base *b* is larger than 50%, e.g. the smallest *N* such that the number of primes end with 1 in base 4 is more than the number of primes end with 3 in base 4 is 12203231 (26861 in decimal), and the smallest *N* such that the number of primes end with 1 in base 3 is more than the number of primes end with 2 in base 3 is 2011012212222201102200001 (608981813029 in decimal), references: https://oeis.org/A007350 https://oeis.org/A007352 https://oeis.org/A199547 https://oeis.org/A306891 https://oeis.org/A038698 https://oeis.org/A112632 https://oeis.org/A275939 https://oeis.org/A306499 https://oeis.org/A306500, this is a classic example of the strong law of small numbers, another classic example is it appears that the sum of the Liouville function (which is an important function in number theory, defined as $(-1)^{bigomega(n)}$, which is A008836(n)) of the positive integers $\le N$ is ≤ 0 if $N > 1$, is it always true? (the Pólya conjecture), the smallest *N* such that this conjecture is false is 906150257 (this conjecture is important in number theory since if this conjecture is true, then the Riemann hypothesis can be proved, and hence many conjectures in number theory can also be proved), for more examples, see https://primes.utm.edu/glossary/xpage/LawOfSmall.html and https://oeis.org/A005165/a005165.pdf.

Excluding the primes $\le b$ (i.e. only counting the primes > *b*) makes the formula of the number of possible (first digit,last digit) combo of a minimal prime in base *b* more simple and smooth number, since if only excluding the primes < *b* (i.e. counting the primes ≥ *b*), then when *b* is prime, there is an additional possible (first digit,last digit) combo: (1,0), and hence the formula will be (*b* − 1)**eulerphi*(*b*)+1 if *b* is prime, or (*b* − 1)**eulerphi*(*b*) if *b* is composite (the fully formula will be (*b* − 1)**eulerphi*(*b*)+*isprime*(*b*) or (*b* − 1)**eulerphi*(*b*)+*floor*((*b* − *eulerphi*(*b*)) / (*b* − 1))), which is more complex, and if start with 1 (i.e. the original minimal prime problem), the formula is much more complex, since the prime digits (i.e. the single-digit primes) should be excluded (thus, e.g. for decimal (base *b*=10), the primes are limited in A034844), and (for such prime > *b*) the first digit has *b* − 1 − *pi*(*b*) (i.e. A065855(*b*)) choices, and the last digit has A048864(*b*) choices, by the rule of product, there are (*b* − 1 − *pi*(*b*))*(A048864(*b*)) choices of the (first digit,last digit) combo (if for such prime ≥ *b* instead of > *b*, then the formula will be (*b* − 1 − *pi*(*b*))*(A048864(*b*))+1 if *b* is prime, or (*b* − 1 − *pi*(*b*))*(A048864(*b*)) if *b* is composite), which is much more complex, (also, the possible (first digit,last digit) combo for a prime > *b* in base *b* are exactly the (first digit,last digit) combos which there are infinitely many primes have, while this is not true when the requiring of the prime is ≥ *b* or ≥ 2 instead of > *b*, since this will contain the prime factors of *b*, which are not coprime to *b* and hence there is only this prime (and not infinitely many primes) have this (first digit,last digit) combo), thus this problem is much better than the original minimal prime problem (another reason is that this problem is regardless whether 1 is considered as prime or not, i.e. no matter 1 is considered as prime or not prime (in the beginning of the 20th century, 1 is regarded as prime), the sets $M(L_b)$ in this problem are the same, while the sets $M(L_b)$ in the original minimal prime problem are different, e.g. in base 10, if 1 is considered as prime, then the set $M(L_b)$ in the original minimal prime problem is {1, 2, 3, 5, 7, 89, 409, 449, 499, 6469, 6949, 9049, 9649, 9949, 60649, 666649, 946669, 60000049, 66000049, 66600049}, while if 1 is not considered as prime, then the set $M(L_b)$ in the original minimal prime problem is {2, 3, 5, 7, 11, 19, 41, 61, 89, 409, 449, 499, 881, 991, 6469, 6949, 9001, 9049, 9649, 9949, 60649, 666649, 946669, 60000049, 66000049, 66600049}, however, in base 10, the set $M(L_b)$ in this problem is always {11, 13, 17, 19, 23, 29, 31, 37, 41, 43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97, 227, 251, 257, 277, 281, 349, 409, 449, 499, 521, 557, 577, 587, 727, 757, 787, 821, 827, 857, 877, 881, 887, 991, 2087, 2221, 5051, 5081, 5501, 5581, 5801, 5851, 6469, 6949, 8501, 9001, 9049, 9221, 9551, 9649, 9851, 9949, 20021, 20201, 50207, 60649, 80051, 666649, 946669, 5200007, 22000001, 60000049, 66000049, 66600049, 80555551, 555555555551, 5000000000000000000000000000027}, no matter 1 is considered as prime or not prime), reference: https://mersenneforum.org/showpost.php?p=562832&postcount=52.

Data

The data of bases 14, 16, and the odd bases >8 are possibly not complete, only tested to the test limit in the discussion of these bases and found the smallest (probable) prime in some unsolved families of these bases, but there may be more unsolved families not found by me.

Our results assume that a number which has passed Miller–Rabin primality tests to the first 13 prime bases (for the composite numbers which pass this test to the first n prime bases (i.e. numbers which are strong pseudoprimes to the first n prime bases), see https://oeis.org/A014233, we use $n = 13$ for the primality tests, i.e. test the prime bases $p \le 41$) and the strong Lucas primality test with parameters (P, Q) defined by Selfridge's Method A (for the composite numbers which pass this test (i.e. numbers which are strong Lucas pseudoprimes with parameters (P, Q) defined by Selfridge's Method A), see https://oeis.org/A217255) is in fact prime, since in some cases (e.g. $b = 13$ and $b = 16$) some candidate elements of $M(L_b)$ are too long to be proven prime rigorously (and neither $N-1$ nor $N+1$ can be ≥33.3333% factored), and the probability that such a number is in fact composite is very low, e.g. for such a number with 5000 decimal digits, the probability is less than $7.6 \cdot 10^{-680}$, and for such a number with 100000 decimal digits, the probability is less than $1.3 \cdot 10^{-10584}$, both of them are "almost" zero, i.e. we can "almost surely" (99.9999…% (with more than 10000 9's) surely, but not 100% surely) that they are primes, and the numbers which currently cannot be proven prime rigorously are usually very large (usually > 10^{5000}, see top 20 ECPP proving page and top 20 Primo proving page, the largest prime which is proven by ECPP is $p(1289844341)$, where $p(n)$ is the integer partition function, this number has 40000 decimal digits, and this number is the largest known ordinary prime, i.e. none of $p^n \pm 1$ (for small n) factor enough to make the number easily provable using the classical methods of primality proof), and if such a number is larger, then probability that this number is in fact composite is lower, thus the probability is much less than $7.6 \cdot 10^{-680}$, see this page, also, our tests (combine of the Miller–Rabin primality tests to the first 13 prime bases and the strong Lucas primality test with parameters (P, Q) defined by Selfridge's Method A) cover the Baillie–PSW primality test (which is only combine of the Miller–Rabin primality tests to base 2 and the strong Lucas primality test with parameters (P, Q) defined by Selfridge's Method A, i.e. (let D be the first number in the sequence 5, -7, 9, -11, 13, -15 ... such that $\left(\frac{D}{N}\right) = -1$ (N is the number which we want to test primality), where $\left(\frac{m}{n}\right)$ is the Jacobi symbol), set $P = 1$ and $Q = (1 - D)/4$), and no known composites which pass the Baillie–PSW test, and no composites < 2^{64} pass the Baillie–PSW test (reference and reference), although it is still conjectured that there exist infinitely many "Baillie–PSW pseudoprimes", i.e. composites which pass the Baillie–PSW test, thus if a such number is in fact composite, it will be a pseudoprime to the Baillie–PSW test, which currently no single example is known!

There are five unsolved families (families for which not even a probable prime is known nor can be ruled out as only contain composites (only count the numbers > b)) for bases $2 \le b \le 16$ found by me and searched to length 50000 with no (probable) prime found.

b	Unsolved family	Algebraic form
11	57^n	$\frac{57 \cdot 11^n - 7}{10}$

13	95^n	$\frac{113 \cdot 13^n - 5}{12}$
13	$A3^nA$	$\frac{41 \cdot 13^{n+1} + 27}{4}$
16	3^nAF	$\frac{16^{n+2} + 619}{5}$
16	4^nDD	$\frac{4 \cdot 16^{n+2} + 2291}{15}$

base 2

11

base 3

12, 21, 111

base 4

11, 13, 23, 31, 221

base 5

12, 21, 23, 32, 34, 43, 104, 111, 131, 133, 313, 401, 414, 3101, 10103, 14444, 30301, 33001, 33331, 44441, 300031, 1000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000013

base 6

11, 15, 21, 25, 31, 35, 45, 51, 4401, 4441, 40041

base 7

14, 16, 23, 25, 32, 41, 43, 52, 56, 61, 65, 113, 115, 131, 133, 155, 212, 221, 304, 313, 335, 344, 346, 364, 445, 515, 533, 535, 544, 551, 553, 1022, 1051, 1112, 1202, 1211, 1222, 2111, 3031, 3055, 3334, 3503, 3505, 3545, 4504, 4555, 5011, 5455, 5545, 5554, 6034, 6634, 11111, 11201, 30011, 30101, 31001, 31111, 33001, 33311, 35555, 40054, 100121, 150001, 300053, 351101, 531101, 1100021, 33333301, 5100000001, 33333333333333331

base 8

13, 15, 21, 23, 27, 35, 37, 45, 51, 53, 57, 65, 73, 75, 107, 111, 117, 141, 147, 161, 177, 225, 255, 301, 343, 361, 401, 407, 417, 431, 433, 463, 467, 471, 631, 643, 661, 667, 701, 711, 717, 747, 767, 3331, 3411, 4043, 4443, 4611, 5205, 6007, 6101, 6441, 6477, 6707, 6777, 7461, 7641, 47777, 60171, 60411, 60741, 444641, 500025, 505525, 3344441, 4444477, 5500525, 5550525, 55555025, 444444441, 744444441, 77774444441, 7777777777771, 555555555555525, 4447

base 9 (not proved, only checked to the prime 8333333335)

12, 14, 18, 21, 25, 32, 34, 41, 45, 47, 52, 58, 65, 67, 74, 78, 81, 87, 117, 131, 135, 151, 155, 175, 177, 238, 272, 308, 315, 331, 337, 355, 371, 375, 377, 438, 504, 515, 517, 531, 537, 557, 564, 601, 638, 661, 702, 711, 722, 735, 737, 751, 755, 757, 771, 805, 838, 1011, 1015, 1101, 1701, 2027, 2207, 3017, 3057, 3101, 3501, 3561, 3611, 3688, 3868, 5035, 5051, 5071, 5101, 5501, 5554, 5705, 5707, 7017, 7075, 7105, 7301, 8535, 8544, 8555, 8854, 20777, 22227, 22777, 30161, 33388, 50161, 50611, 53335, 55111, 55535, 55551, 57061, 57775, 70631, 71007, 77207, 100037, 100071, 100761, 105007, 270707, 301111, 305111, 333035, 333385, 333835, 338885, 350007, 500075, 530005, 555611, 631111, 720707, 2770007, 3030335, 7776662, 30300005, 30333335, 38333335, 51116111, 70000361, 300030005, 300033305, 351111111, 1300000007, 5161111111, 8333333335, ..., 300000000035, ..., 311111111161, ..., 544444444444, ..., 2000000000007, ..., 5700000000001, ..., 88888888833335, ..., 100000000000507, ..., 5111111111111161, ..., 88888888888888888335, ..., 30000000000000000000051, ..., 1000000000000000000000000057, ..., 56111111111111111111111111111111111111, ..., 7662, ..., 277707, ..., 300

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base 10

11, 13, 17, 19, 23, 29, 31, 37, 41, 43, 47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97, 227, 251, 257, 277, 281, 349, 409, 449, 499, 521, 557, 577, 587, 727, 757, 787, 821, 827, 857, 877, 881, 887, 991, 2087, 2221, 5051, 5081, 5501, 5581, 5801, 5851, 6469, 6949, 8501, 9001, 9049, 9221, 9551, 9649, 9851, 9949, 20021, 20201, 50207, 60649, 80051, 666649, 946669, 5200007, 22000001, 60000049, 66000049, 66600049, 80555551, 555555555551, 5000000000000000000000000000027

base 11 (not proved, only checked to the prime 1500000001)

12, 16, 18, 21, 27, 29, 34, 38, 3A, 43, 49, 54, 56, 61, 65, 67, 72, 76, 81, 89, 92, 94, 98, 9A, A3, 10A, 115, 117, 133, 139, 153, 155, 171, 193, 197, 199, 1AA, 225, 232, 236, 25A, 263, 315, 319, 331, 335, 351, 353, 362, 373, 379, 391, 395, 407, 414, 452, 458, 478, 47A, 485, 4A5, 4A7, 502, 508, 511, 513, 533, 535, 539, 551, 571, 579, 588, 595, 623, 632, 70A, 711, 715, 731, 733, 737, 755, 759, 775, 791, 797, 7AA, 803, 847, 858, 85A, 874, 885, 887, 913, 919, 931, 937, 957, 959, 975, 995, A07, A1A, A25, A45, A74, A7A, A85, AA1, AA7, 1101, 11A9, 1305, 1451, 1457, 15A7, 175A, 17A5, 17A9, 2023, 2045, 2052, 2083, 20A5, 2333, 2A05, 2A52, 3013, 3026, 3059, 3097, 3206, 3222, 3233, 3307, 3332, 3505, 4025, 4151, 4157, 4175, 4405, 4445, 4487, 450A, 4575, 5017, 5031, 5059, 5075, 5097, 5099, 5105, 515A, 517A, 520A, 5301, 5583, 5705, 577A, 5853, 5873, 5909, 5A17, 5A57, 5A77, 5A8A, 6683, 66A9, 7019, 7073, 7079, 7088, 7093, 7095, 7309, 7451, 7501, 7507, 7578, 757A, 75A7, 7787, 7804, 7844, 7848, 7853, 7877, 78A4, 7A04, 7A57, 7A79, 7A95, 8078, 8245, 8333, 8355, 8366, 8375, 8425, 8553, 8663, 8708, 8777, 878A, 8A05, 9053, 9101, 9107, 9305, 9505, 9703, A052, A119, A151, A175, A515, A517, A575, A577, A5A8, A719, A779, A911, AAA9, 10011, 10075, 10091, 10109, 10411, 10444, 10705, 10709, 10774, 10901, 11104, 11131, 11144, 11191, 1141A, 114A1, 13757, 1411A, 14477, 144A4, 14A04, 14A11, 17045, 17704, 1774A, 17777, 177A4, 17A47, 1A091, 1A109, 1A114, 1A404, 1A411, 1A709, 20005, 20555, 22203, 25228, 25282, 25552, 25822, 28522, 30037, 30701, 30707, 31113, 33777, 35009, 35757, 39997, 40045, 4041A, 40441, 4045A, 404A1, 4111A, 411A1, 42005, 44401, 44474, 444A1, 44555, 44577, 445AA, 44744, 44A01, 47471, 47477, 47701, 5057A, 50903, 5228A, 52A22, 52A55, 52A82, 55007, 550A9, 55205, 55522, 55557, 55593, 55805, 57007, 57573, 57773, 57807, 5822A, 58307, 58505, 58A22, 59773, 59917, 59973, 59977, 59999, 5A015, 5A2A2, 5AA99, 60836, 60863, 68636, 6A609, 6A669, 6A696, 6A906, 6A966, 70048, 70103, 70471, 70583, 70714, 71474, 717A4, 71A09, 74084, 74444, 74448, 74477, 744A8, 74747, 74774, 7488A, 74A48, 75773, 77144, 77401, 77447, 77799, 77A09, 78008, 78783, 7884A, 78888, 788A8, 79939, 79993, 79999, 7A051, 7A444, 7A471, 80005, 80252, 80405, 80522, 80757, 80AA5, 83002, 84045, 85307, 86883, 88863, 8A788, 90073, 90707, 90901, 95003, 97779, 97939, 99111, 99177, 99973, A0111, A0669, A0966, A0999, A0A09, A1404, A4177, A4401, A4717, A5228, A52AA, A5558, A580A, A5822, A58AA, A5A59, A5AA2, A6096, A6966, A6999, A7051, A7778, A7808, A9055, A9091, A9699, A9969, AA52A, AA58A, 100019, 100079, 101113, 101119, 101911, 107003, 140004, 144011, 144404, 1A0019, 1A0141, 1A5001, 1A7005, 1A9001, 222223, 222823, 300107, 300202, 300323, 303203, 307577, 310007, 332003, 370777, 400555, 401A11, 404001, 404111, 405AAA, 41A011, 440A41, 441011, 451777, 455555, 470051, 470444, 474404, 4A0401, 4A4041, 500015, 500053, 500077, 500507, 505577, 522A2A, 525223, 528A2A, 531707, 550777, 553707, 5555A9, 555A99, 557707, 55A559, 5807A7, 580A0A, 580A55, 58A0AA, 590007, 599907, 5A2228, 5A2822, 5A2AAA, 5A552A, 5AA22A, 5AAA22, 60A069, 683006, 6A0096, 6A0A96, 6A9099, 6A9909, 700778, 701074, 701777, 704408, 704417, 704457, 704484, 707041, 707441, 707708, 707744, 707784, 710777, 717044, 717077, 740008, 74484A, 770441, 770744, 770748, 770771, 777017, 777071, 777448, 777484, 777701, 7778A8, 777A19, 777A48, 778883, 78A808, 790003, 7A1009, 7A4408, 7A7708, 80A555, 828283, 828883, 840555, 850505, 868306, 873005, 883202, 900701, 909739, 909979, 909991, 970771, 977701, 979909, 990739, 990777, 990793, 997099, 999709, 999901, A00009, A00599, A01901, A05509, A0A058, A0A955, A10114, A555A2, A55999, A59991, A5A222, A5A22A, A60609, A66069, A66906, A69006, A79005, A87888, A90099, A90996, A96006, A96666, A97177, A97771, AA0A58, AA5A22, AAA522, 1000501, 1011141, 1030007, 1070047, 111114A, 1111A14, 1111A41, 1144441, 14A4444, 1700005, 1700474, 1A44444, 2555505, 2845055, 3030023, 3100003, 3333397, 4000111, 4011111, 41A1111, 4411111, 444441A, 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base 12

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base 13 (not proved, only checked to the prime 1010008001, also the numbers $B0^{6540}BBA$ and $80^{32017}111$ are only probable primes, i.e. not proven primes)

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base 15 (not proved, only checked to the prime 555555557)

12, 14, 18, 1E, 21, 27, 2B, 2D, 32, 38, 3E, 41, 47, 4B, 4D, 54, 58, 5E, 67, 6B, 6D, 72, 74, 78, 87, 8B, 92, 94, 9E, A1, A7, AD, B2, B8, BE, C1, CB, CD, D2, D4, E1, ED, 111, 11B, 131, 137, 13B, 13D, 157, 15B, 15D, 171, 177, 197, 19D, 1B7, 1BB, 1D1, 1DB, 1DD, 234, 298, 311, 31B, 337, 33D, 344, 351, 357, 35B, 364, 377, 391, 39B, 39D, 3A4, 3BD, 3C4, 3D7, 3DB, 3DD, 452, 51B, 51D, 531, 53B, 551, 55D, 562, 571, 577, 5A2, 5B1, 5B7, 5BB, 5BD, 5C2, 5D1, 5D7, 634, 652, 681, 698, 717, 71B, 731, 737, 757, 75D, 77D, 79B, 79D, 7B1, 7B7, 7BD, 7D7, 7DD, 801, 852, 88D, 8D8, 91D, 93B, 93D, 95B, 95D, 971, 977, 97B, 97D, 988, 991, 9BD, 9C8, 9D1, A98, AAB, B1D, B31, B3B, B44, B51, B57, B7B, B7D, B97, B9B, BB7, BC4, BD1, BD7, BDD, C07, C34, C52, C7E, C98, CC7, CE7, D0E, D1D, D31, D51, D5B, D68, D77, D7B, D91, D97, DA8, DAE, DCE, DD1, EB4, EEB, 107B, 1091, 10B1, 1107, 110D, 1561, 1651, 1691, 1B01, 2052, 2502, 2522, 303B, 307D, 3097, 30BB, 30D1, 3107, 3361, 3701, 3907, 3B01, 3B0B, 3C97, 4434, 4498, 4834, 4898, 49A8, 4E34, 5037, 507D, 5091, 509B, 5107, 5161, 5202, 53C7, 5552, 570B, 590B, 590D, 59C7, 5A5B, 5C97, 5D0D, 5DAB, 6061, 6151, 6191, 6511, 6601, 6911, 707B, 7091, 7097, 70AE, 70BB, 70CE, 70DB, 7561, 760E, 7691, 76CE, 7907, 7961, 7A0E, 7A3B, 7AEE, 7B0B, 7BAB, 7C0E, 7C77, 7CAE, 7D0B, 7D61, 7DAB, 7E5B, 7E6E, 7E7B, 7EBB, 8098, 811D, 8191, 835D, 853D, 8881, 8908, 8951, 8968, 899D, 8D3D, 8D5D, 8D6E, 8DDD, 8E98, 9011, 9037, 9097, 90D7, 9301, 93C7, 95C7, 9611, 9631, 96A8, 9811, 9851, 989D, 990B, 990D, 998D, 99AB, 99C7, 99D8, 9A08, 9A9B, 9AA8, 9ABB, 9B61, 9BC7, 9D0B, 9DAB, 9DC7, 9DD8, A052, A304, A502, A55B, A9BB, AB04, AB64, B09D, B107, B10B, B161, B1AB, B1C7, B30D, B3C7, B50B, B664, B691, B6A4, B707, B761, B90D, B961, BA5B, BABB, BBAB, BBB4, BC37, BC77, C777, C937, C997, D011, D03D, D05D, D09B, D0B1, D0BD, D101, D10B, D30D, D3AB, D507, D50D, D66E, D761, D7DE, D811, D85D, D86E, D89D, D8C8, D8E8, D9AB, D9D8, DA3B, DA9B, DABB, DB01, DB61, DBAB, DC88, DD07, DD0B, DD7E, DD8D, DDE7, DE6E, E252, E33B, E522, E57B, E7AE, E7CE, E898, E997, E9A8, E9BB, EA34, EB5B, EE98, EEC7, 10017, 10B0D, 170AB, 17A0B, 19001, 19601, 1A09B, 1D0C7, 22E52, 2EA52, 30017, 3001D, 300B1, 301C7, 30334, 30631, 307AB, 3300B, 3333B, 36031, 36301, 37A0B, 37BBB, 39997, 3A30B, 3B0C7, 3D001, 3D601, 40034, 40968, 43334, 49668, 49998, 50022, 5009D, 501C7, 50222, 50507, 505C7, 50611, 50C57, 53007, 53997, 55537, 5555B, 5557B, 5599B, 56101, 56691, 56961, 5700D, 5755B, 59001, 59557, 59997, 5999D, 599DB, 59DDD, 5D99B, 5DD3D, 5DD9D, 60931, 63031, 65691, 66951, 69031, 69361, 69561, 70011, 70051, 7005B, 7006E, 7030D, 703AB, 70501, 70701, 707C7, 71601, 71951, 7300D, 7333B, 75001, 7555B, 75911, 76011, 76051, 766EE, 76EEE, 7700B, 77191, 77661, 7776E, 77771, 777BB, 77911, 77BBB, 79001, 7A05B, 7A66E, 7AA6E, 7AAAE, 7ACCE, 7C6EE, 7CCEE, 7CECE, 7CEEE, 7D3BB, 7E7C7, 7EECE, 80034, 80304, 80434, 809DD, 80A34, 84A34, 850DD, 85961, 86661, 88151, 88331, 88511, 88591, 88898, 890DD, 89998, 89D0D, 8D90D, 8E434, 90017, 90051, 900A8, 900DB, 901C7, 90C57, 90D8D, 91007, 91061, 9199B, 95997, 96068, 96561, 99397, 99537, 9999B, 999B7, 999D7, 999DB, 999DD, 99BBB, 99DBB, 99DD7, 99DDD, 9B007, 9B00B, 9B0AB, 9BB11, 9BBBB, 9D007, 9D08D, 9D537, 9D9BB, 9D9DB, 9DD57, 9DDB7, 9DDDB, 9DDDD, A0A34, A0B5B, A0BBB, A0E34, A2E52, A330B, A8434, A8834, A8E34, A909B, AAA34, AAE52, AB0BB, AB334, ABB34, AE034, AE834, AE99B, AEA52, AEE52, B0011, B0071, B0077, B00B1, B0611, B0A64, B500D, B599D, B6101, B7771, B7911, BA064, BAAA4, BAB34, BB061, BB304, BB53D, BB601, BBB91, BBB9D, BBBBD, BDA0B, BDBBB, D0088, D00D7, D0307, D05C7, D070D, D0888, D0B07, D0BC7, D0C08, D0DC7, D0DD8, D1661, D59DD, D5D3D, D5DDD, D6611,

D700D, D8D0D, D900B, D9908, D999D, D9BBB, D9D9D, D9DDB, DB007, DB00D, DB1B1, DB53D, DB59D, DB99D, DBBB1, DD0D8, DD33B, DD3B7, DD3BB, DD57D, DD898, DD9DD, DDB37, DDBDB, DDD08, DDD3D, DDD5D, DDD7D, DDD88, DDD9D, DDDB7, DDDC8, DDDD7, DDE98, DE037, DE998, DEB07, E0098, E00C7, E0537, E0557, E077B, E0834, E0968, E3334, E37AB, E39C7, E4034, E5307, E55AB, E705B, E750B, E766E, E76EE, E8304, E8434, E9608, E9C37, EAE52, EBB0B, EC557, EC597, EC957, 1000BD, 1009AB, 10A90B, 1900AB, 190661, 19099B, 190A0B, 1A900B, 222A52, 2AAA52, 31000D, 330331, 333334, 3733AB, 373ABB, 3BBB61, 430004, 490068, 490608, 5000DB, 500D0B, 505557, 505A0B, 50D00B, 50DDDB, 50DDDD, 522222, 5500AB, 5500C7, 550957, 550A0B, 555A9B, 559057, 560011, 590661, 633331, 666331, 666591, 666661, 7050AB, 705A0B, 706101, 70A50B, 7300AB, 761661, 76666E, 777011, 777101, 77750B, 777A5B, 777CEE, 779051, 791501, 7E7797, 7ECCCE, 7EEE97, 800D9D, 808834, 836631, 83D661, 843004, 856611, 884034, 884304, 888E34, 88A434, 88AE34, 8A4034, 8AEE34, 8E8034, 8E8E34, 8EEE34, 9000BB, 9001AB, 900B07, 900D98, 903661, 905661, 906651, 9080DD, 9099A8, 909D9B, 90A668, 90DD9B, 90DDBB, 910001, 9100AB, 91A00B, 930007, 950001, 956661, 9909A8, 995907, 999068, 999507, 999907, 9B0B1B, 9B0BB1, 9BB01B, 9C5597, 9C5957, 9D09DD, 9D0D9D, 9D800D, 9DB307, 9DD09D, A00034, A0033B, A033B4, A2A252, AAAA52, ABBBBB, B00004, B0001B, B0003D, B00A04, B0555B, B07191, B07711, B07777, B0B911, B0BDBB, B77011, B777C7, BB0001, BB0034, BB035D, BB055B, BB0BDB, BB9101, BBB0DB, BBB50D, BBBB01, BBD0BB, C55397, C55557, C55597, D0003B, D00057, D0007D, D000B7, D000C8, D008DD, D00DAB, D0333B, D05537, D099DD, D09DDD, D0DDBB, D555C7, D5C537, D88008, D88088, D888EE, D909DD, D9D0DD, D9DD0D, DB0BBB, DBBB0B, DBBB0D, DC0008, DC5537, DDDDD8, DDDEBB, DDE99B, DE0808, DE0C57, DE300B, DE5537, DE8888, DEE088, DEE307, DEE888, DEEE37, DEEE57, DEEEC8, E0000B, E007BB, E00A52, E03BC7, E07ABB, E09B07, E0A99B, E0C397, E0E76E, E50057, E55007, E55597, E55937, E730AB, E73A0B, E80E34, E88834, E8E034, E90008, E95557, EA099B, EE4304, EE5057, EE5507, EE8E34, EE9307, EEE434, 100001D, 1000A9B, 1000DC7, 22AA252, 3000BC7, 3033301, 3076661, 333B304, 33B3034, 3B33304, 3D66661, 50007AB, 5005957, 5500597, 5550057, 5559007, 5559597, 5595007, 5966661, 5DDDDDB, 6366631, 7010001, 7066651, 7100061, 733BBBB, 766A6AE, 77505AB, 7776501, 777775B, 777AACE, 777ECCE, 777EEAE, 7CCCCCE, 7E30A0B, 7EEEEAE, 8300004, 8363331, 8693331, 880E834, 8833304, 8888034, 8888434, 888A034, 88A3334, 88E8834, 88EE034, 88EE304, 8AA3334, 8D0009D, 8EE8834, 9000361, 9000668, 9003331, 9005557, 9006008, 9008D0D, 9083331, 9090968, 90BBB01, 90D0908, 9500661, 9555597, 9555957, 9660008, 9900968, 9995597, 9996008, 9999557, 9999597, 9999908, 9A66668, A003B34, A003BB4, AA22252, B00B034, B00B35D, B033334, B0B6661, B0BB01B, B100001, B333304, B777777, B99999D, BA60004, BAA0334, BBB001B, BBB6611, BBBBB11, BBBD00B, BD000AB, D0000DB, D009098, D00CCC8, D00D908, D00D99D, D03000B, D0BB0BB, D0D9008, D0D9998, D1000C7, D800008, D8DDEEE, D90080D, DBBBBBB, DD09998, DDD5557, DDDDBBB, DDDDDBD, DDDE8EE, DECC008, DECCCC8, DEE0CC8, DEEC0C8, E000397, E0003BB, E000434, E00076E, E000937, E007A5B, E00909B, E0090B7, E009307, E00B077, E00E434, E00E797, E00E937, E05999B, E09009B, E0900B7, E0E0937, E0E7E97, E0EAA52, E0EEA52, E555057, E5555C7, E7777C7, E77E797, E88EE34, E999998, EA5999B, EB000BB, EB0BBBB, EE00434, EE0E797, EEE076E, EEE706E, EEE8834, EEEE557, EEEE797, 30333331, 30B66661, 33000034, 33030004, 33B33004, 500575AB, 55000007, 5500075B, 55500907, 55555057, 55555907, 55559507, 60003301, 60033001, 60330001, 7000003D, 70106661, 70666611, 77000001, 7777770B, 777777C7, 77777ACE, 77777EAE,

777E30AB, 777E3A0B, 7CCCC66E, 800005DD, 88AA0834, 90000008, 900008DD, 90099668, 90500557, 90555007, 90666668, 90909998, 90990998, 90996668, 9099999D, 90D00098, 90D90998, 95500057, 99099098, 99555057, 99900998, 99966608, 99966668, 99999668, 99999998, 9D009008, 9D090998, A0803334, A2222252, AAA52222, B00005AB, B000B55B, B0BBBB5B, B3330034, BB0BBB1B, BBAA3334, BBB0BB1B, BBB0BB5B, BBDB000B, D000BBBB, D00100C7, D8888888, D900008D, D9000098, DBB000BB, DC0CCCC8, DCC0CCC8, DCCCC008, DD000908, DD09009D, DDDDDDAB, DDDDDEEE, DDDEEE8E, DDDEEEE8, DEE80008, E0777E97, E0E0E397, E0E77797, E0EE0397, E7777797, E9066668, EE00E397, EE077797, EE0E0397, EEE00797, EEE07E97, EEE0AA52, EEE55397, EEE55557, EEEAAA52, EEEEE834, EEEEEA52, 300003331, 300007661, 300330031, 333000004, 333300001, 333B00034, 3700000AB, 3B3300034, 500000057, 555555007, 555555557, 5DDDDDDDD, 600000331, 7500000AB, 75000A00B, 75A00000B, 761000001, 77000E0C7, 777700EC7, 7777730AB, 7777777AE, 77777EE97, 7777E7E97, 777999997, 7A500000B, 7BBBBBB5B, 88888A834, 900000031, 900666608, 909990098, 90D009998, 950000557, 966666008, 990000007, 990555507, 999999997, A000000B4, A0005999B, AAEEEEE34, B000AA334, BBBBB005B, BBBBBBB5B, D09999998, D0D90009D, D800000DD, D90009998, DCCCC0CC8, DE88EEEEE, DEEEEEE88, E000B7777, E000BBBBB, E003ABBBB, EE0000797, EE0EEE397, EE5555557, EE777EE97, EEEEEE537, EEEEEE937, ..., 2222222252, ..., 3000000071, ..., 500000007B, ..., 7000000071, ..., 900000009B, ..., 900000009D, ..., 9000099998, ..., D300000007, ..., DDDDDDDDDE, ..., DDDEEEEEEE, ..., 9999999999D, ..., 5000000000DD, ..., 9000000000B7, ..., D000000001C7, ..., DCCCCCCCCCC8, ..., 3333333333331, ..., 3BBBBBBBBBBBB, ..., 71000000000001, ..., 77777777777777B, ..., DEEEEEEEEEEEEEE, ..., DDDDDDDDDDDDDDDDB, ..., E9666666666666668, ..., 3330000000000000031, ..., 7BBBBBBBBBBBBBBBBBBBB, ..., BBBBBBBBBBBBBBBBBBBBBB1, ..., B0000000000000000000000005B, ..., B7000000000000000000000000001, ..., 633000000000000000000000000001, ..., EBBBBBBBBBBBBBBBBBBBBBBBBBBBBBBB, ..., 5000000000000000000000000000000000017, ..., 966666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666666608, ..., EEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEEE397, ..., 77777777777777777777777777777777777777777777777777777777777777777777777777777777777777777777777777777777777777777777777777777777777777777777777777777777777797, ...

base 16 (not proved, only checked to 1000000000, also the number DB^{32234} is only a probable prime, i.e. not proven prime)

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Proof

There are lemmas, corollaries, theorems, proofs, conjectures, hypotheses, open problems, heuristic arguments, for this problem about the sets of the primes with no proper subsequence whose value is also prime in the positional numeral system with base (or radix) b for $2 \le b \le 36$.

Determining $M(L)$ for arbitrary L is in general unsolvable, and can be difficult even when L is relatively simple, also, determining $M(L)$ for arbitrary L may be an open problem or NP-complete or an undecidable problem, or an example of Gödel's incompleteness theorems (like the continuum hypothesis and the halting problem), or as hard as the unsolved problems in mathematics, such as the Riemann hypothesis and the *abc* conjecture.

The following is a “semi-algorithm” that is guaranteed to produce $M(L)$, but it is not so easy to implement:

(1) $M = \emptyset$

(2) while ($L \neq \emptyset$) do

(3) choose x, a shortest string in L

(4) $M = M \cup \{x\}$

(5) $L = L - \sup(\{x\})$

In practice, for arbitrary L, we cannot feasibly carry out step (5). Instead, we work with L', some regular overapproximation to L, until we can show $L' = \emptyset$ (which implies $L = \emptyset$). In practice, L' is usually chosen to be a finite union of sets of the form $L_1L_2{}^*L_3$, where each of L_1, L_2, L_3 is finite. In the case we consider in this paper, we then have to determine whether such a language contains a prime or not.

However, it is not even known if the following simpler decision problem is recursively solvable:

Problem: Given strings x, y, z, and a base b, does there exist a prime number whose base-b expansion is of the form xy^nz for some $n \geq 0$?

An algorithm to solve this problem, for example, would allow us to decide if there are any additional Fermat primes (of the form $2^{2^n}+1$) other than the known ones (corresponding to n = 0, 1, 2, 3, 4). To see this, take b = 2, x = 1, y = 0, and $z = 0^{16}1$. Since if 2^n+1 is prime then n must be a power of two, a prime of the form $(xy^*z)_b$ must be a new Fermat prime. Besides, it would allow us to decide if there are infinitely many Mersenne primes (of the form 2^p-1 with prime p). To see this, take b = 2, $x = \lambda$ (the empty string), y = 1, and $z = 1^{n+1}$, where n is the exponent of the Mersenne prime which we want to know whether it is the largest Mersenne prime or not. Since if 2^n-1 is prime then n must be a prime, a prime of the form $(xy^*z)_b$ must be a new Mersenne prime. Also, it would allow us to decide if 21181 is a Sierpinski number (take b = 2, x = 101001010111101, y = 0, and z = 1) and if 23669 is a Riesel number (take b = 2, x = 101110001110100, y = 1, and $z = \lambda$ (the empty string)).

Therefore, in practice, we are forced to try to rule out prime representations based on heuristics such as modular techniques and factorizations.

It will be necessary for our algorithm to determine if families of the form $(xy^*z)_b$ contain a prime > b or not. We use two different heuristic strategies to show that such families contain no primes > b.

In the first strategy, we mimic the well-known technique of "covering congruences", by finding some finite set S of primes p such that every number in a given family is divisible by some element of S (this is equivalent to finding an integer N such that all numbers in a given family are not coprime to N). In the second strategy, we attempt to find an algebraic factorization, such as difference-of-two-squares factorization, sum/difference-of-two-cubes factorization, and Aurifeuillian factorization for x^4+4y^4.

Examples of the first strategy: (we can show that the corresponding numbers are > all elements in S, if n makes corresponding numbers > b (i.e. $n \geq 1$ for 51^n in base 9 and 25^n in base 11 and 4^nD in base 16 and 8^nF in base 16, $n \geq 0$ for other examples), thus these factorizations are nontrivial)

* In base 10, all numbers of the form 46^n9 are divisible by 7
* In base 6, all numbers of the form 40^n1 are divisible by 5
* In base 15, all numbers of the form 96^n8 are divisible by 11

* In base 9, all numbers of the form 51^n are divisible by some element of {2,5} (note: the prime 5 is not allowed since the prime must be > base)
* In base 11, all numbers of the form 25^n are divisible by some element of {2,3} (note: the prime 2 is not allowed since the prime must be > base)
* In base 14, all numbers of the form $B0^n1$ are divisible by some element of {3,5}
* In base 8, all numbers of the form 64^n7 are divisible by some element of {3,5,13}
* In base 13, all numbers of the form 30^n95 are divisible by some element of {5,7,17}
* In base 16, all numbers of the form 4^nD are divisible by some element of {3,7,13} (note: the prime D is not allowed since the prime must be > base)
* In base 16, all numbers of the form 8^nF are divisible by some element of {3,7,13}

Examples of the second strategy: (we can show that both factors are > 1, if n makes corresponding numbers > b (i.e. $n \geq 2$ for 1^n in base 9, $n \geq 0$ for 10^n1 in base 8 and $B4^n1$ in base 16, $n \geq 1$ for other examples), thus these factorizations are nontrivial)

* In base 9, all numbers of the form 1^n factored as $(3^n-1) * (3^n+1) / 8$
* In base 8, all numbers of the form 10^n1 factored as $(2^{n+1}+1) * (4^{n+1}-2^{n+1}+1)$
* In base 9, all numbers of the form 38^n factored as $(2*3^n-1) * (2*3^n+1)$ (note: the prime 3 is not allowed since the prime must be > base)
* In base 16, all numbers of the form $8F^n$ factored as $(3*4^n-1) * (3*4^n+1)$
* In base 16, all numbers of the form F^n7 factored as $(4^{n+1}-3) * (4^{n+1}+3)$ (note: the prime 7 is not allowed since the prime must be > base)
* In base 9, all numbers of the form 31^n factored as $(5*3^n-1) * (5*3^n+1) / 8$ (note: the prime 3 is not allowed since the prime must be > base)
* In base 16, all numbers of the form 4^n1 factored as $(2*4^{n+1}-7) * (2*4^{n+1}+7) / 15$
* In base 16, all numbers of the form 15^n factored as $(2*4^n-1) * (2*4^n+1) / 3$
* In base 16, all numbers of the from C^nD factored as $(2*4^{n+1}-2*2^{n+1}+1) * (2*4^{n+1}+2*2^{n+1}+1) / 5$ (note: the prime D is not allowed since the prime must be > base)
* In base 16, all numbers of the form $B4^n1$ factored as $(13*4^{n+1}-7) * (13*4^{n+1}+7) / 15$

Examples of combine of the two strategies: (we can show that for the part of the first strategy, the corresponding numbers are > all elements in S, and for the part of the second strategy, both factors are > 1, if n makes corresponding numbers > b (i.e. $n \geq 0$ for B^n9B in base 12, $n \geq 1$ for other examples), thus these factorizations are nontrivial)

* In base 14, numbers of the form $8D^n$ are divisible by 5 if n is odd and factored as $(3*14^{n/2}-1) * (3*14^{n/2}+1)$ if n is even
* In base 12, numbers of the form B^n9B are divisible by 13 if n is odd and factored as $(12^{(n+2)/2}-5) * (12^{(n+2)/2}+5)$ if n is even

* In base 14, numbers of the form D^n5 are divisible by 5 if n is even and factored as $(14^{(n+1)/2} - 3) * (14^{(n+1)/2}+3)$ if n is odd (note: the prime 5 is not allowed since the prime must be > base)
* In base 17, numbers of the form 19^n are divisible by 2 if n is odd and factored as $(5*17^{n/2} - 3) * (5*17^{n/2}+3) / 16$ if n is even
* In base 19, numbers of the from 16^n are divisible by 5 if n is odd and factored as $(2*19^{n/2} - 1) * (2*19^{n/2}+1) / 3$ if n is even

As previously mentioned, in practice to compute $M(L_b)$ one works with an underapproximation M of $M(L_b)$ and an overapproximation L of $L_b - sup(M)$. One then refines such approximations until $L = \varnothing$ from which it follows that $M = M(L_b)$.

For the initial approximation, note that every minimal prime in base b with at least 4 digits is of the form xY^*z, where $x \in \{x \mid x$ is base-b digit, $x \neq 0\}$, $z \in \{z \mid z$ is base-b digit, $gcd(z,b) = 1\}$, and Y^* (for this (x,z) pair) = $\{y \mid xy, xz, yz, xyz$ are all composites$\}$. (Of course, if xz is prime, then the Y^* set for this (x,z) pair is $\varnothing$)

Making use of this, our algorithm sets M to be the set of base-b representations of the minimal primes with at most 3 digits (which can be found simply by brute force) and L to be $\cup_{x,z} (xY^*z)$ as described above.

All remaining minimal primes are members of L, so to find them we explore the families in L. During this process, each family will be decomposed into possibly multiple other families. For example, a simple way of exploring the family xY^*z where $Y = \{y_1, ..., y_n\}$ is to decompose it into the families $xY^*y_1z, ..., xY^*y_nz$. If the smallest member (say xy_iz) of any such family happens to be prime, it can be added to M and the family xY^*y_iz removed from consideration. Furthermore, once M has been updated it may be possible to simplify some families in L. In this case, xY^*y_jz (for $j \neq i$) can be simplified to $x(Y-y_i)^*y_jz$ since no minimal prime contains xy_iz as a proper subsequence.

We call families of the form xy^*z (where $x, z \in \Sigma_b^*$ and $y \in \Sigma_b$) *simple* families. Our algorithm then proceeds as follows:

1. Let

M := {minimal primes in base b of length ≤ 3}

$L := \cup_{x,z\in\Sigma b} (xY^*z)$

where $x \neq 0$ and Y is the set of digits y such that xyz has no subword in M.

2. While L contains non-simple families:

(a) Explore each family of L, and update L.

(b) Examine each family of *L*:

i. Let *w* be the shortest string in the family. If *w* has a subword in *M*, then remove the family from *L*. If *w* represents a prime, then add *w* to *M* and remove the family from *L*.
ii. If possible, simplify the family.
iii. Check if the family can be proven to contain no primes > base, and if so then remove the family from *L*.

(c) As much as possible and update *L*; after each split examine the new families as in (b).

At the conclusion of the algorithm described, *L* will consist of simple families (of the form *xy*z*) which have not yet yielded a prime, but for which there is no obvious reason why there can't be a prime of such a form. In such a case, the only way to proceed is to test the primality of larger and larger numbers of such form and hope a prime is eventually discovered (we usually conjecture that there must be a prime at some point if it cannot be proved that there can't be a prime, by covering congruence, algebra factorization, or combine of them, since there is a heuristic argument that there are infinitely many such primes (reference), since by the prime number theorem, the chance that a random *n*-digit base *b* number is prime is approximately 1/*n* (reference reference) (also see this page and this page, the chance is approximately $\frac{b-1}{ln(b)} \cdot \frac{b^{n-1}}{n}$, where *ln* is the natural logarithm). If one conjectures the numbers *xy*z* behave similarly (i.e. "*N* of the form *xy*z*" and "*N* is prime" are independent events) you would expect $\sum_{n=2}^{\infty} \frac{1}{n} = \infty$ (harmonic series is divergent) primes of the form *xy*z*, of course, this does not always happen, since some *xy*z* families can be proven to contain no primes > base, and every *xy*z* family has its own Nash weight (or difficulty), *xy*z* families which can be proven to contain no primes > base have Nash weight (or difficulty) 0, thus *xy*z* families are not "completely" random. They are random enough that the prime number theorem can be used to predict their primality, but divisibility by small primes is not as random and can easily be predicted: Once one candidate is found to be divisible by a prime *p* or to have an algebraic factorization (e.g. difference-of-two-squares factorization, sum/difference-of-two-cubes factorization, Aurifeuillian factorization for x^4+4y^4), another predictable candidate will also be divisible by *p* or also have the same algebraic factorization. This decreases the probability of expected primes. Sometimes though, the candidates will never be divisible by a prime *p*, which increases the probability of expected primes. However, it is at least a reasonable conjecture in the absence of evidence to the contrary, the numbers in simple families are of the form $\frac{a \cdot b^n + c}{gcd(a+c,b-1)}$ for some fixed integer triple (*a*, *b*, *c*), where *a*≥1, *b*≥2 (*b* is the base), *c*≠0, *gcd*(*a*,*c*)=1, *gcd*(*b*,*c*)=1, this is an exponential sequence, there is also a similar conjecture for polynomial sequence: the Bunyakovsky conjecture, the condition is similar to our conjecture in this article, both are the small prime factors and the algebraic factors, the main difference is that polynomial sequence cannot have a covering set with >1 primes, however, unlike our conjecture (the analog of Bunyakovsky conjecture for exponential sequences), the analog of Dickson's conjecture and Schinzel's hypothesis H for exponential sequences is widely believed to be false, e.g. for all integer *k* divisible by 3, it is widely believed that there are only finitely many integers *n*≥1 such that $k \cdot 2^n \pm 1$ are twin primes (see this page and this page, the conjecture that 237 is the smallest odd number divisible by 3 such that $k \cdot 2^n \pm 1$ are never twin primes will never be proven), another example is that it is widely believed that 127 is the largest number n such that the Mersenne number 2^n-1 and the Wagstaff number $(2^n+1)/3$ are both primes (see New Mersenne Conjecture and its status page, such primes are listed in https://oeis.org/A107360) (in fact, if n is even number, then $(2^n+1)/3$ is not integer, thus we only need to consider odd n, and for odd number n = 2*m+1, $(2^n+1)/3 = (2*4^m+1)/3$, thus it can be written as the form $\frac{a \cdot b^n+c}{gcd(a+c,b-1)}$, with ($a$, b, c) = (2, 4, 1), thus is included in this conjecture, also, if n is odd composite, then 2^n-1 and $(2^n+1)/3$ are both composites, thus we only need to consider odd prime n), another example is that it is widely believed that there are only finitely many integers n such that n and $n\pm1$ all have primitive roots, and $3^{541}-1$ may be the largest such n, since it is widely believed that there are only finitely many integers $n\geq1$ such that the given pair of exponential sequences both produce primes: $(2*3^n-1, 2*3^n+1)$, $((3^n+1)/2, 3^n+2)$, $((3^n-1)/2, 3^n-2)$, see https://oeis.org/A305237, also it is widely believed that for any polynomial sequence and any exponential sequence, there are only finitely many n such that both sequences produce primes, e.g. it is widely believed that only finitely many Mersenne exponents (i.e. primes p such that 2^p-1 is also prime) are Sophie Germain primes (such primes p are listed in https://oeis.org/A065406), i.e. the number of primes p such that 2*p+1 and 2^p-1 are both prime is expected to be finite, also it is widely believed that only finitely many Mersenne exponents (i.e. primes p such that 2^p-1 is also prime) are members of twin primes pair (such primes p are listed in https://oeis.org/A346645), see this post and this thread). For example, the base 11 family 57^n, this family have already been searched to length 50000 with no prime or PRP found, however the algebraic form of this family is $(57*11^n-7)/10$, and there is no n satisfying that $57*11^n$ and 7 are both r-th powers for some r>1 to make this number have difference-of-two-r-th powers factorization (since 7 is not perfect power), nor there is n satisfying that $57*11^n$ and -7 are (one is 4th power, another is of the form $4*m^4$) to make this number have Aurifeuillian factorization for x^4+4y^4 (since -7 is neither 4th power nor of the form 4*m^4), thus, base 11 family 57^n has no algebraic factorization for any n, thus 57^n eventually should yield a prime unless it can be proven to contain no primes > base using covering congruence, and we have:

57^n is divisible by 2 for n == 1 mod 2
57^n is divisible by 13 for n == 2 mod 12
57^n is divisible by 17 for n == 4 mod 16
57^n is divisible by 5 for n == 0 mod 5
57^n is divisible by 23 for n == 6 mod 22
57^n is divisible by 601 for n == 8 mod 600
57^n is divisible by 97 for n == 12 mod 48
57^n is divisible by 1279 for n == 16 mod 426
...

and it does not appear to be any covering set of primes (and its Nash weight (or difficulty) is positive, and it has prime candidate), so there must be a prime at some point.

The multiplicative order of *b* mod the primes is important in this problem, since if a prime *p* divides the number with *n* digits in a family in base *b*, then *p* also divides the number with *k**r+n* digits in the same family in base *b* for all nonnegative integer *k*, where *r* is the multiplicative order of *b* mod *p* (unless the multiplicative order of *b* mod *p* is 1, i.e. *p* divides $b-1$, in this case *p* also divides the number with *k**p+n* digits in the same family in base *b* for all nonnegative integer *k*), the primes *p* such that the multiplicative order of *b* mod *p* is *n* are exactly the primes *p* dividing *Zs*(*n*,*b*,1), where *Zs* is the Zsigmondy number, i.e. *Zs*(*n*,*b*,1) is the greatest divisor of b^n-1 that is coprime to b^m-1 for all positive integers $m < n$, with $b \geq 2$ and $n \geq 1$, if (and only if) there is only one such prime, then this prime is unique prime in base *b*, see list of the multiplicative order of *b* mod *p* for *b*≤128 and primes *p*≤4096, list of primes *p* such that the multiplicative order of *b* mod *p* is *n* for 2≤*b*≤64 and 1≤*n*≤64, smallest prime *p* such that znorder(Mod(*m*,*p*)) = (*p*−1)/*n* for 2≤*m*≤128 and 1≤*n*≤128, bases *b* such that Phi(*n*,*b*) (where Phi is cyclotomic polynomial) has algebra factors or small prime factors, bases *b* such that there is unique prime with period length *n*, unique period length in base *b*, also see factorization of $b^n\pm1$ (which is equivalent to factorization of *Zs*(*n*,*b*,1)) with *b*≤12 13≤*b*≤99 *b*=10 any *b* any *b*, also see this page.

The numbers in simple families are of the form $\frac{a \cdot b^n + c}{gcd(a+c,b-1)}$ for some fixed integers *a*, *b*, *c* where $a \geq 1$, $b \geq 2$ (*b* is the base), $c \neq 0$, *gcd*(*a*,*c*)=1, *gcd*(*b*,*c*)=1 (thus, all large minimal primes base *b* (but possible not all minimal primes base *b* if *b* is large, e.g. *b* = 25, 29, 31, 35) have a nice short algebraic description (see this page and this page, the prime numbers in these two pages do *not* have nice short algebraic descriptions, also see this page) and have simple expression (expression with ≤ 40 characters, all taken from “0” “1” “2” “3” “4” “5” “6” “7” “8” “9” “+” “-” “*” “/” “^” “(“ “)”), factorial (!), double factorial (!!), and primorial (#) are not allowed since they can be used to ensure many small factors, see this page). Except in the special case *c* = ±1 and *gcd*(*a*+*c*,$b-1$) = 1, when *n* is large the known primality tests for such a number are too inefficient to run (since this special case *c* = ±1 and *gcd*(*a*+*c*,$b-1$) = 1 is the only case which $N-1$ and/or *N*+1 is smooth, i.e. the case *c* = 1 and *gcd*(*a*+*c*,$b-1$) = 1 (corresponding to generalized Proth prime base *b*: $a \cdot b^n + 1$, they are related to generalized Sierpinski conjecture base *b*) can be easily proven prime using Pocklington *N*−1 method, and the case $c = -1$ and *gcd*(*a*+*c*,$b-1$) = 1 (corresponding to generalized Riesel prime base *b*: $a \cdot b^n - 1$, they are related to generalized Riesel conjecture base *b*) can be easily proven prime using Morrison *N*+1 method). In this case one must resort to a probable primality test such as a Miller–Rabin primality test or a Baillie–PSW primality test, unless a divisor of the number can be found, and thus these numbers cannot be proven primes and can only be probable primes, and we cannot definitely say that the corresponding families can be removed from the list of unsolved families, and we cannot definitely compute this part of the set $M(L_b)$. Since we are testing many numbers in an exponential sequence, it is possible to use a sieving process (such as *srsieve* software) to find divisors rather than using trial division, i.e. we will remove the integers *n* such that $\frac{a \cdot b^n + c}{gcd(a+c,b-1)}$ either has a prime factor less than certain limit (say 2^{32}) or has algebraic factorization, and test the primality of $\frac{a \cdot b^n + c}{gcd(a+c, b-1)}$ for other integers *n*.

To do this, we made use of Geoffrey Reynolds' *srsieve* software. This program uses the baby-step giant-step algorithm to find all primes *p* which divide $a \cdot b^n + c$ where *p* and *n* lie in a specified range. Since this program cannot handle the general case $\frac{a \cdot b^n + c}{gcd(a+c, b-1)}$ when $gcd(a+c, b-1) > 1$ we only used it to sieve the sequence $a \cdot b^n + c$ for primes *p* not dividing $gcd(a+c, b-1)$, and initialized the list of candidates to not include *n* for which there is some prime *p* dividing $gcd(a+c, b-1)$ for which *p* divides $\frac{a \cdot b^n + c}{gcd(a+c, b-1)}$. The program had to be modified slightly to remove a check which would prevent it from running in the case when *a*, *b*, and *c* were all odd (since then 2 divides $a \cdot b^n + c$, but 2 may not divide $\frac{a \cdot b^n + c}{gcd(a+c, b-1)}$).

Once the numbers with small divisors had been removed, it remained to test the remaining numbers using a probable primality test. For this we used the software *LLR* by Jean Penné. Although undocumented, it is possible to run this program on numbers of the form $\frac{a \cdot b^n + c}{gcd(a+c, b-1)}$ when $gcd(a+c, b-1) > 1$, so this program required no modifications (also, *LLR* can do a proven primality test (i.e. prove the primality) for numbers of the form $a \cdot b^n \pm 1$ (i.e. the special case $c = \pm 1$ and $gcd(a+c, b-1) = 1$) with $b^n > a$). A script was also written which allowed one to run *srsieve* while *LLR* was testing the remaining candidates, so that when a divisor was found by *srsieve* on a number which had not yet been tested by *LLR* it would be removed from the list of candidates. In the cases where the elements of $M(L_b)$ could be proven prime rigorously, we employed *PRIMO* by Marcel Martin, an elliptic curve primality proving implementation (for the primes of the form $\frac{a \cdot b^n + c}{gcd(a+c, b-1)}$, with $c \neq \pm 1$ and/or $gcd(a+c, b-1) \neq 1$, we cannot use the classical tests (including the tests of $N-1$, $N+1$, N^2+1, N^2+N+1, N^2-N+1 (all such polynomials are cyclotomic polynomials of *N*, and such tests are called cyclotomy proofs, see this page), and the combined tests), since for these primes, none of them is at least 1/3 factorable (Brillhart-Lehmer-Selfridge primality test) (see this page) (if we want to use the classical tests to prove the primality of *N*, then we must factor at least one of $N-1$, $N+1$, N^2+1, N^2+N+1, N^2-N+1 to the factored part ≥33.3333% (i.e. product of known prime factors ≥ the cube root of *N*), and except trial division with the primes up to certain limit (say 2^{64}) and the algebra factors (e.g. difference-of-two-squares factorization, sum/difference-of-two-cubes factorization, Aurifeuillian factorization, and algebra factors of the Cunningham number $b^n \pm 1$ (b^n-1 can be factored to product of $\Phi_d(b)$ with *d* dividing *n*, and b^n+1 can be factored to product of $\Phi_d(b)$ with *d* dividing 2*n* but not dividing *n*, where Φ is the cyclotomic polynomial), see this reference), we can use elliptic-curve factorization method (ECM), Pollard *P*−1 method, Williams *P*+1 method, special number field sieve (SNFS), general number field sieve (GNFS), etc. to factor the numbers, however, all these factorization algorithms take long time, i.e. they cannot be done in polynomial time (unlike primality proving, when the numbers are sufficiently large, no efficient, non-quantum integer factorization algorithm is known, i.e. integer factorization may be NP-complete. However, it has not been proven that no efficient algorithm exists. The presumed difficulty of this problem is at the heart of widely used algorithms in cryptography such as RSA. Many areas of mathematics and computer science have been brought to bear on the problem, including elliptic curves, algebraic number theory, and quantum computing), and hence to do this is impractically), i.e. they are ordinary primes, and if the prime is not large (say less than 10^{25000}), we can use elliptic curve primality proving (ECPP) to proof (see *PRIMO* top 20 records and elliptic curve primality proving top 20 records and top primes proven by Francois Morain's programs) and make primality certificate, but if the prime is very large (say > 10^{25000}), the known primality tests for such a number are too inefficient to run (although there is AKS primality test, which can prove the primality of any general prime in polynomial time, but since its time complexity is $O(ln(N)^{12})$, and if we can do 10^9 bitwise operations per second, use this test to prove the primality of a 5000-digit prime need $5.422859049 \times 10^{39}$ seconds, or $1.719577324 \times 10^{32}$ years, much longer than the age of the universe, thus to do this test is still impractically), thus we can only resort to a probable primality test such as Miller–Rabin primality test and Baillie–PSW primality test, unless a divisor of the number can be found, and hence we cannot prove the primality of this number, thus we cannot definitely say that the corresponding families can be removed from the list of unsolved families, and we cannot definitely compute this part of the sets $M(L_b)$.

Fermat pseudoprime (to base $b = 2$: https://oeis.org/A001567, and see this data)	Lucas pseudoprime (to parameters $(P, Q) = (1, -1)$: https://oeis.org/A081264 union https://oeis.org/A141137, and see this data) (to parameters (P, Q) defined by Selfridge's Method *A*: https://oeis.org/A217120, and see this data)
Strong Fermat pseudoprime (to base $b = 2$: https://oeis.org/A001262, and see this data)	Strong Lucas pseudoprime (to parameters (P, Q) defined by Selfridge's Method *A*: https://oeis.org/A217255, and see this data)
Over Fermat pseudoprime (to base $b = 2$: composite factors of A019320(n) / gcd(A019320(n), n) for some n, there is an OEIS sequence: https://oeis.org/A141232)	Over Lucas pseudoprime (to parameters $(P, Q) = (1, -1)$: composite factors of A061446(n) / gcd(A061446(n), n) for some n)
Baillie–PSW pseudoprime (none are known, none < 2^{64} exist)	
Carmichael number (https://oeis.org/A002997)	Lucas–Carmichael number (https://oeis.org/A006972)
Pépin primality test (for Fermat numbers, i.e. numbers of the form 2^n+1 (A000051), if 2^n+1 is prime, then n must be power of 2, such primes are https://oeis.org/A019434)	Lucas–Lehmer primality test (for Mersenne numbers, i.e. numbers of the form $2^n - 1$ (https://oeis.org/A000225), if $2^n - 1$ is prime, then n must be prime, such primes are https://oeis.org/A000668)
Proth primality test (for numbers of the form	Lucas–Lehmer–Riesel primality test (for

$k2^n+1$ with k odd and $k<2^n$, i.e. Proth numbers, https://oeis.org/A080075, such primes are https://oeis.org/A080076, also there is a list of such primes sorted by k)	numbers of the form $k2^n-1$ with k odd and $k<2^n$, i.e. Proth numbers of the second kind, https://oeis.org/A112714, such primes are https://oeis.org/A112715, also there is a list of such primes sorted by k)
Pocklington $N-1$ primality test (for numbers n such that $n-1$ can be trivially fully factored)	Morrison $N+1$ primality test (for numbers n such that $n+1$ can be trivially fully factored)
Combined $N-1$ / $N+1$ primality test (and other cyclotomy tests, i.e. $\Phi_r(N)$ for small r (where Φ is the cyclotomic polynomial), including N^2+1, N^2+N+1, N^2-N+1)	
Pollard $P-1$ integer factorization method	Williams $P+1$ integer factorization method

Some families *xy*z* could not be ruled out as containing no primes > base, but no primes > base could be found in the family, even after searching through numbers with over 50000 digits. Many *xy*z* families contain no small primes even though they do contain very large primes, for example:

* In base 5, the smallest prime in the family 10^n13 is $10^{93}13$
* In base 8, the smallest prime in the family 4^n7 is $4^{220}7$ (the prime 7 is not counted since the prime must be > base)
* In base 9, the smallest prime in the family 30^n11 is $30^{1158}11$
* In base 9, the smallest prime in the family 27^n07 is $27^{686}07$
* In base 11, family 57^n can not be ruled out as containing no primes > base but no primes > base found in the family after searching to length 50000 (the prime 5 is not counted since the prime must be > base)
* In base 13, the smallest prime in the family 80^n111 is $80^{32017}111$ (this prime is only a probable prime, i.e. not proven prime)
* In base 13, the smallest prime in the family $2B30^n1$ is $2B3^{15197}1$
* In base 13, the smallest prime in the family $B0^nBBA$ is $B0^{6540}BBA$ (this prime is only a probable prime, i.e. not proven prime)
* In base 13, the smallest prime in the family 390^n1 is $390^{6266}1$
* In base 13, the smallest prime in the family 720^n2 is $720^{2297}2$
* In base 13, family 95^n can not be ruled out as containing no primes > base but no primes > base found in the family after searching to length 50000
* In base 13, family $A3^nA$ can not be ruled out as containing no primes > base but no primes > base found in the family after searching to length 50000
* In base 14, the smallest prime in the family $4D^n$ is $4D^{19698}$
* In base 16, family 3^nAF can not be ruled out as containing no primes > base but no primes > base found in the family after searching to length 50000
* In base 16, family 4^nDD can not be ruled out as containing no primes > base but no primes > base found in the family after searching to length 50000
* In base 16, the smallest prime in the family DB^n is DB^{32234} (this prime is only a probable prime, i.e. not proven prime) (the prime D is not counted since the prime must be > base)

For any given base *b*, we find all (*x*,*z*) digits-pair such that $x \neq 0$ and *gcd*(*z*,*b*) = 1, and find the corresponding sets *Y**, see below.

Bold for minimal primes in base *b*, i.e. elements of the set $M(L_b)$

base 2

The possible (first digit,last digit) for an element with >=3 digits in the minimal set of the strings for primes with at least two digits are:

(1,1)

* Case (1,1):

** **11** is prime, and thus the only minimal prime in this family.

base 3

The possible (first digit,last digit) for an element with >=3 digits in the minimal set of the strings for primes with at least two digits are:

(1,1), (1,2), (2,1), (2,2)

* Case (1,1):

** Since 12, 21, **111** are primes, we only need to consider the family 1{0}1 (since any digits 1, 2 between them will produce smaller primes)

*** All numbers of the form 1{0}1 are divisible by 2, thus cannot be prime.

* Case (1,2):

** **12** is prime, and thus the only minimal prime in this family.

* Case (2,1):

** **21** is prime, and thus the only minimal prime in this family.

* Case (2,2):

** Since 21, 12 are primes, we only need to consider the family 2{0,2}2 (since any digits 1 between them will produce smaller primes)

*** All numbers of the form 2{0,2}2 are divisible by 2, thus cannot be prime.

base 4

The possible (first digit,last digit) for an element with >=3 digits in the minimal set of the strings for primes with at least two digits are:

(1,1), (1,3), (2,1), (2,3), (3,1), (3,3)

* Case (1,1):

** **11** is prime, and thus the only minimal prime in this family.

* Case (1,3):

** **13** is prime, and thus the only minimal prime in this family.

* Case (2,1):

** Since 23, 11, 31, **221** are primes, we only need to consider the family 2{0}1 (since any digits 1, 2, 3 between them will produce smaller primes)

*** All numbers of the form 2{0}1 are divisible by 3, thus cannot be prime.

* Case (2,3):

** **23** is prime, and thus the only minimal prime in this family.

* Case (3,1):

** **31** is prime, and thus the only minimal prime in this family.

* Case (3,3):

** Since 31, 13, 23 are primes, we only need to consider the family 3{0,3}3 (since any digits 1, 2 between them will produce smaller primes)

*** All numbers of the form 3{0,3}3 are divisible by 3, thus cannot be prime.

base 5

The possible (first digit,last digit) for an element with >=3 digits in the minimal set of the strings for primes with at least two digits are:

(1,1), (1,2), (1,3), (1,4), (2,1), (2,2), (2,3), (2,4), (3,1), (3,2), (3,3), (3,4), (4,1), (4,2), (4,3), (4,4)

* Case (1,1):

** Since 12, 21, **111**, **131** are primes, we only need to consider the family 1{0,4}1 (since any digits 1, 2, 3 between them will produce smaller primes)

*** All numbers of the form 1{0,4}1 are divisible by 2, thus cannot be prime.

* Case (1,2):

** **12** is prime, and thus the only minimal prime in this family.

* Case (1,3):

** Since 12, 23, 43, **133** are primes, we only need to consider the family 1{0,1}3 (since any digits 2, 3, 4 between them will produce smaller primes)

*** Since 111 is prime, we only need to consider the families 1{0}3 and 1{0}1{0}3 (since any digit combo 11 between (1,3) will produce smaller primes)

**** All numbers of the form 1{0}3 are divisible by 2, thus cannot be prime.

**** For the 1{0}1{0}3 family, since **10103** is prime, we only need to consider the families 1{0}13 and 11{0}3 (since any digit combo 010 between (1,3) will produce smaller primes)

***** The smallest prime of the form 1{0}13 is **100000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000013**, which can be written as $10_{93}13$ and equal the prime 5^95+8

***** All numbers of the form 11{0}3 are divisible by 3, thus cannot be prime.

* Case (1,4):

** Since 12, 34, **104** are primes, we only need to consider the families 1{1,4}4 (since any digits 0, 2, 3 between them will produce smaller primes)

*** Since 111, 414 are primes, we only need to consider the family 1{4}4 and 11{4}4 (since any digit combo 11 or 41 between them will produce smaller primes)

**** The smallest prime of the form 1{4}4 is **14444**.

**** All numbers of the form 11{4}4 are divisible by 2, thus cannot be prime.

* Case (2,1):

** **21** is prime, and thus the only minimal prime in this family.

* Case (2,2):

** Since 21, 23, 12, 32 are primes, we only need to consider the family 2{0,2,4}2 (since any digits 1, 3 between them will produce smaller primes)

*** All numbers of the form 2{0,2,4}2 are divisible by 2, thus cannot be prime.

* Case (2,3):

** **23** is prime, and thus the only minimal prime in this family.

* Case (2,4):

** Since 21, 23, 34 are primes, we only need to consider the family 2{0,2,4}4 (since any digits 1, 3 between them will produce smaller primes)

*** All numbers of the form 2{0,2,4}4 are divisible by 2, thus cannot be prime.

* Case (3,1):

** Since 32, 34, 21 are primes, we only need to consider the family 3{0,1,3}1 (since any digits 2, 4 between them will produce smaller primes)

*** Since 313, 111, 131, **3101** are primes, we only need to consider the families 3{0,3}1 and 3{0,3}11 (since any digit combo 10, 11, 13 between (3,1) will produce smaller primes)

**** For the 3{0,3}1 family, we can separate this family to four families:

***** For the 30{0,3}01 family, we have the prime **30301**, and the remain case is the family 30{0}01.

****** All numbers of the form 30{0}01 are divisible by 2, thus cannot be prime.

***** For the 30{0,3}31 family, note that there must be an even number of 3's between (30,31), or the result number will be divisible by 2 and cannot be prime.

****** Since 33331 is prime, any digit combo 33 between (30,31) will produce smaller primes.

******* Thus, the only possible prime is the smallest prime in the family 30{0}31, and this prime is **300031**.

***** For the 33{0,3}01 family, note that there must be an even number of 3's between (33,01), or the result number will be divisible by 2 and cannot be prime.

****** Since 33331 is prime, any digit combo 33 between (33,01) will produce smaller primes.

******* Thus, the only possible prime is the smallest prime in the family 33{0}01, and this prime is **33001**.

***** For the 33{0,3}31 family, we have the prime **33331**, and the remain case is the family 33{0}31.

****** All numbers of the form 33{0}31 are divisible by 2, thus cannot be prime.

**** All numbers of the form 3{0,3}11 are divisible by 3, thus cannot be prime.

* Case (3,2):

** **32** is prime, and thus the only minimal prime in this family.

* Case (3,3):

** Since 32, 34, 23, 43, **313** are primes, we only need to consider the family 3{0,3}3 (since any digits 1, 2, 4 between them will produce smaller primes)

*** All numbers of the form 3{0,3}3 are divisible by 3, thus cannot be prime.

* Case (3,4):

** **34** is prime, and thus the only minimal prime in this family.

* Case (4,1):

** Since 43, 21, **401** are primes, we only need to consider the family 4{1,4}1 (since any digits 0, 2, 3 between them will produce smaller primes)

*** Since 414, 111 are primes, we only need to consider the family 4{4}1 and 4{4}11 (since any digit combo 14 or 11 between them will produce smaller primes)

**** The smallest prime of the form 4{4}1 is **44441**.

**** All numbers of the form 4{4}11 are divisible by 2, thus cannot be prime.

* Case (4,2):

** Since 43, 12, 32 are primes, we only need to consider the family 4{0,2,4}2 (since any digits 1, 3 between them will produce smaller primes)

*** All numbers of the form 4{0,2,4}2 are divisible by 2, thus cannot be prime.

* Case (4,3):

** **43** is prime, and thus the only minimal prime in this family.

* Case (4,4):

** Since 43, 34, **414** are primes, we only need to consider the family 4{0,2,4}4 (since any digits 1, 3 between them will produce smaller primes)

*** All numbers of the form 4{0,2,4}4 are divisible by 2, thus cannot be prime.

base 6

The possible (first digit,last digit) for an element with >=3 digits in the minimal set of the strings for primes with at least two digits are:

(1,1), (1,5), (2,1), (2,5), (3,1), (3,5), (4,1), (4,5), (5,1), (5,5)

* Case (1,1):

** **11** is prime, and thus the only minimal prime in this family.

* Case (1,5):

** **15** is prime, and thus the only minimal prime in this family.

* Case (2,1):

** **21** is prime, and thus the only minimal prime in this family.

* Case (2,5):

** **25** is prime, and thus the only minimal prime in this family.

* Case (3,1):

** **31** is prime, and thus the only minimal prime in this family.

* Case (3,5):

** **35** is prime, and thus the only minimal prime in this family.

* Case (4,1):

** Since 45, 11, 21, 31, 51 are primes, we only need to consider the family 4{0,4}1 (since any digits 1, 2, 3, 5 between them will produce smaller primes)

*** Since **4401** and **4441** are primes, we only need to consider the families 4{0}1 and 4{0}41 (since any digits combo 40 and 44 between them will produce smaller primes)

**** All numbers of the form 4{0}1 are divisible by 5, thus cannot be prime.

**** The smallest prime of the form 4{0}41 is **40041**

* Case (4,5):

** **45** is prime, and thus the only minimal prime in this family.

* Case (5,1):

** **51** is prime, and thus the only minimal prime in this family.

* Case (5,5):

** Since 51, 15, 25, 35, 45 are primes, we only need to consider the family 5{0,5}5 (since any digits 1, 2, 3, 4 between them will produce smaller primes)

*** All numbers of the form 5{0,5}5 are divisible by 5, thus cannot be prime.

base 7

The possible (first digit,last digit) for an element with >=3 digits in the minimal set of the strings for primes with at least two digits are:

* Case (1,1):

** Since 14, 16, 41, 61, **131** are primes, we only need to consider the family 1{0,1,2,5}1 (since any digits 3, 4, 6 between them will produce smaller primes)

*** Since the digit sum of primes must be odd (otherwise the number will be divisible by 2, thus cannot be prime), there is an odd total number of 1 and 5 in the {}

**** If there are >=3 number of 1 and 5 in the {}:

***** If there is 111 in the {}, then we have the prime **11111**

***** If there is 115 in the {}, then the prime 115 is a subsequence

***** If there is 151 in the {}, then the prime 115 is a subsequence

***** If there is 155 in the {}, then the prime 155 is a subsequence

***** If there is 511 in the {}, then the current number is 15111, which has digit sum = 12, but digit sum divisible by 3 will cause the number divisible by 3 and cannot be prime, and we cannot add more 1 or 5 to this number (to avoid 11111, 155, 515, 551 as subsequence), thus we must add at least one 2 to this number, but then the number has both 2 and 5, and will have either 25 or 52 as subsequence, thus cannot be minimal prime

***** If there is 515 in the {}, then the prime 515 is a subsequence

***** If there is 551 in the {}, then the prime 551 is a subsequence

***** If there is 555 in the {}, then the prime 551 is a subsequence

**** Thus there is only one 1 (and no 5) or only one 5 (and no 1) in the {}, i.e. we only need to consider the families 1{0,2}1{0,2}1 and 1{0,2}5{0,2}1

***** For the 1{0,2}1{0,2}1 family, since **1211** is prime, we only need to consider the family 1{0}1{0,2}1

****** Since all numbers of the form 1{0}1{0}1 are divisible by 3 and cannot be prime, we only need to consider the family 1{0}1{0}2{0}1

******* Since **11201** is prime, we only need to consider the family 1{0}1{0}21

******** The smallest prime of the form 11{0}21 is **1100021**

******** All numbers of the form 101{0}21 are divisible by 5, thus cannot be prime

******** The smallest prime of the form 1001{0}21 is **100121**

********* Since this prime has no 0 between 1{0}1 and 21, we do not need to consider more families

***** For the 1{0,2}5{0,2}1 family, since 25 and 52 are primes, we only need to consider the family 1{0}5{0}1

****** Since **1051** is prime, we only need to consider the family 15{0}1

******* The smallest prime of the form 15{0}1 is **150001**

* Case (1,2):

** Since 14, 16, 32, 52 are primes, we only need to consider the family 1{0,1,2}2 (since any digits 3, 4, 5, 6 between them will produce smaller primes)

*** Since **1112** and **1222** are primes, there is at most one 1 and at most one 2 in {}

**** If there are one 1 and one 2 in {}, then the digit sum is 6, and the number will be divisible by 6 and cannot be prime.

**** If there is one 1 but no 2 in {}, then the digit sum is 4, and the number will be divisible by 2 and cannot be prime.

**** If there is no 1 but one 2 in {}, then the form is 1{0}2{0}2

***** Since **1022** and **1202** are primes, we only need to consider the number 122

****** 122 is not prime.

**** If there is no 1 and no 2 in {}, then the digit sum is 3, and the number will be divisible by 3 and cannot be prime.

* Case (1,3):

** Since 14, 16, 23, 43, **113**, **133** are primes, we only need to consider the family 1{0,5}3 (since any digits 1, 2, 3, 4, 6 between them will produce smaller primes)

*** Since 155 is prime, we only need to consider the family 1{0}3 and 1{0}5{0}3

**** All numbers of the form 1{0}3 are divisible by 2, thus cannot be prime.

**** All numbers of the form 1{0}5{0}3 are divisible by 3, thus cannot be prime.

* Case (1,4):

** **14** is prime, and thus the only minimal prime in this family.

* Case (1,5):

** Since 14, 16, 25, 65, **115**, **155** are primes, we only need to consider the family 1{0,3}5 (since any digits 1, 2, 4, 5, 6 between them will produce smaller primes)

*** All numbers of the form 1{0,3}5 are divisible by 3, thus cannot be prime.

* Case (1,6):

** **16** is prime, and thus the only minimal prime in this family.

* Case (2,1):

** Since 23, 25, 41, 61, **221** are primes, we only need to consider the family 2{0,1}1 (since any digits 2, 3, 4, 5, 6 between them will produce smaller primes)

*** Since **2111** is prime, we only need to consider the families 2{0}1 and 2{0}1{0}1

**** All numbers of the form 2{0}1 are divisible by 3, thus cannot be prime.

**** All numbers of the form 2{0}1{0}1 are divisible by 2, thus cannot be prime.

* Case (2,2):

** Since 23, 25, 32, 52, **212** are primes, we only need to consider the family 2{0,2,4,6}2 (since any digits 1, 3, 5 between them will produce smaller primes)

*** All numbers of the form 2{0,2,4,6}2 are divisible by 2, thus cannot be prime.

* Case (2,3):

** **23** is prime, and thus the only minimal prime in this family.

* Case (2,4):

** Since 23, 25, 14 are primes, we only need to consider the family 2{0,2,4,6}4 (since any digits 1, 3, 5 between them will produce smaller primes)

*** All numbers of the form 2{0,2,4,6}4 are divisible by 2, thus cannot be prime.

* Case (2,5):

** **25** is prime, and thus the only minimal prime in this family.

* Case (2,6):

** Since 23, 25, 16, 56 are primes, we only need to consider the family 2{0,2,4,6}6 (since any digits 1, 3, 5 between them will produce smaller primes)

*** All numbers of the form 2{0,2,4,6}6 are divisible by 2, thus cannot be prime.

* Case (3,1):

** Since 32, 41, 61 are primes, we only need to consider the family 3{0,1,3,5}1 (since any digits 2, 4, 6 between them will produce smaller primes)

*** Since 551 is prime, we only need to consider the family 3{0,1,3}1 and 3{0,1,3}5{0,1,3}1 (since any digits combo 55 between (3,1) will produce smaller primes)

**** For the 3{0,1,3}1 family, since **3031** and 131 are primes, we only need to consider the families 3{0,1}1 and 3{3}3{0,1}1 (since any digits combo 03, 13 between (3,1) will produce smaller primes, thus for the digits between (3,1), all 3's must be before all 0's and 1's, and thus we can let the red 3 in 3{3}3{0,1}1 be the rightmost 3 between (3,1), all digits before this 3 must be 3's, and all digits after this 3 must be either 0's or 1's)

***** For the 3{0,1}1 family:

****** If there are >=2 0's and >=1 1's between (3,1), then at least one of **30011**, **30101**, **31001** will be a subsequence.

****** If there are no 1's between (3,1), then the form will be 3{0}1

******* All numbers of the form 3{0}1 are divisible by 2, thus cannot be prime.

****** If there are no 0's between (3,1), then the form will be 3{1}1

******* The smallest prime of the form 3{1}1 is **31111**

****** If there are exactly 1 0's between (3,1), then there must be <3 1's between (3,1), or **31111** will be a subsequence.

******* If there are 2 1's between (3,1), then the digit sum is 6, thus the number is divisible by 6 and cannot be prime.

******* If there are 1 1's between (3,1), then the number can only be either 3101 or 3011

******** Neither 3101 nor 3011 is prime.

******* If there are no 1's between (3,1), then the number must be 301

******** 301 is not prime.

***** For the 3{3}3{0,1}1 family:

****** If there are at least one 3 between (3,3{0,1}1) and at least one 1 between (3{3}3,1), then **33311** will be a subsequence.

****** If there are no 3 between (3,3{0,1}1), then the form will be 33{0,1}1

******* If there are at least 3 1's between (33,1), then 31111 will be a subsequence.

******* If there are exactly 2 1's between (33,1), then the digit sum is 12, thus the number is divisible by 3 and cannot be prime.

******* If there are exactly 1 1's between (33,1), then the digit sum is 11, thus the number is divisible by 2 and cannot be prime.

******* If there are no 1's between (33,1), then the form will be 33{0}1

******** The smallest prime of the form 33{0}1 is **33001**

****** If there are no 1 between (3{3}3,1), then the form will be 3{3}3{0}1

******* If there are at least 2 0's between (3{3}3,1), then 33001 will be a subsequence.

******* If there are exactly 1 0's between (3{3}3,1), then the form is 3{3}301

******** The smallest prime of the form 3{3}301 is **33333301**

******* If there are no 0's between (3{3}3,1), then the form is 3{3}31

******** The smallest prime of the form 3{3}31 is **33333333333333331**

**** For the 3{0,1,3}5{0,1,3}1 family, since 335 is prime, we only need to consider the family 3{0,1}5{0,1,3}1

***** Numbers containing 3 between (3{0,1}5,1):

****** The form is 3{0,1}5{0,1,3}3{0,1,3}1

******* Since 3031 and 131 are primes, we only need to consider the family 35{3}3{0,1,3}1 (since any digits combo 03, 13 between (3,1) will produce smaller primes)

******** Since 533 is prime, we only need to consider the family 353{0,1}1 (since any digits combo 33 between (35,1) will produce smaller primes)

********* Since 5011 is prime, we only need to consider the family 353{1}{0}1 (since any digits combo 01 between (353,1) will produce smaller primes)

********** If there are at least 3 1's between (353,{0}1), then 31111 will be a subsequence.

********** If there are exactly 2 1's between (353,{0}1), then the digit sum is 20, thus the number is divisible by 2 and cannot be prime.

********** If there are exactly 1 1's between (353,{0}1), then the form is 3531{0}1

*********** The smallest prime of the form 3531{0}1 is 3531001, but it is not minimal prime since 31001 is prime.

********** If there are no 1's between (353,{0}1), then the digit sum is 15, thus the number is divisible by 6 and cannot be prime.

***** Numbers not containing 3 between (3{0,1}5,1):

****** The form is 3{0,1}5{0,1}1

******* If there are >=2 0's and >=1 1's between (3,1), then at least one of 30011, 30101, 31001 will be a subsequence.

******* If there are no 1's between (3,1), then the form will be 3{0}5{0}1

******** All numbers of the form 3{0}5{0}1 are divisible by 3, thus cannot be prime.

******* If there are no 0's between (3,1), then the form will be 3{1}5{1}1

******** If there are >=3 1's between (3,1), then 31111 will be a subsequence.

******** If there are exactly 2 1's between (3,1), then the number can only be 31151, 31511, 35111

********* None of 31151, 31511, 35111 are primes.

******** If there are exactly 1 1's between (3,1), then the digit sum is 13, thus the number is divisible by 2 and cannot be prime.

******** If there are no 1's between (3,1), then the number is 351

********* 351 is not prime.

******* If there are exactly 1 0's between (3,1), then the form will be 3{1}0{1}5{1}1 or 3{1}5{1}0{1}1

******** No matter 3{1}0{1}5{1}1 or 3{1}5{1}0{1}1, if there are >=3 1's between (3,1), then 31111 will be a subsequence.

******** If there are exactly 2 1's between (3,1), then the number can only be 311051, 310151, 310511, 301151, 301511, 305111, 311501, 315101, 315011, 351101, 351011, 350111

********* Of these numbers, 311051, 301151, 311501, 351101, 350111 are primes.

********** However, 311051, 301151, 311501 have 115 as subsequence, and 350111 has 5011 as subsequence, thus only **351101** is minimal prime.

******** No matter 3{1}0{1}5{1}1 or 3{1}5{1}0{1}1, if there are exactly 1 1's between (3,1), then the digit sum is 13, thus the number is divisible by 2 and cannot be prime.

******** If there are no 1's between (3,1), then the number is 3051 for 3{1}0{1}5{1}1 or 3501 for 3{1}5{1}0{1}1

********* Neither 3051 nor 3501 is prime.

* Case (3,2):

** **32** is prime, and thus the only minimal prime in this family.

* Case (3,3):

** Since 32, 23, 43, **313** are primes, we only need to consider the family 3{0,3,5,6}3 (since any digits 1, 2, 4 between them will produce smaller primes)

*** If there are >=2 5's in {}, then 553 will be a subsequence.

*** If there are no 5's in {}, then the family will be 3{0,3,6}3

**** All numbers of the form 3{0,3,6}3 are divisible by 3, thus cannot be prime.

*** If there are exactly 1 5's in {}, then the family will be 3{0,3,6}5{0,3,6}3

**** Since 335, 65, **3503**, 533, 56 are primes, we only need to consider the family 3{0}53 (since any digit 3, 6 between (3,5{0,3,6}3) and any digit 0, 3, 6 between (3{0,3,6}5,3) will produce smaller primes)

***** The smallest prime of the form 3{0}53 is **300053**

* Case (3,4):

** Since 32, 14, **304**, **344**, **364** are primes, we only need to consider the family 3{3,5}4 (since any digits 0, 1, 2, 4, 6 between them will produce smaller primes)

*** Since **3334** and 335 are primes, we only need to consider the family 3{5}4 and 3{5}34 (since any digits combo 33, 35 between them will produce smaller primes)

**** The smallest prime of the form 3{5}4 is 3(5^9234)4 (not minimal prime, since 35555 and 5554 are primes)

**** The smallest prime of the form 3{5}34 is 3555555555555555555555555555555555555555555555555555555555555555534 (not minimal prime, since 35555, 553, and 5554 are primes)

* Case (3,5):

** Since 32, 25, 65, **335** are primes, we only need to consider the family 3{0,1,4,5}5 (since any digits 2, 3, 6 between them will produce smaller primes)

*** If there are at least one 1's and at least one 5's in {}, then either 155 or 515 will be a subsequence.

*** If there are at least one 1's and at least one 4's in {}, then either 14 or 41 will be a subsequence.

*** If there are at least two 1's in {}, then 115 will be a subsequence.

*** If there are exactly one 1's and no 4's or 5's in {}, then the family will be 3{0}1{0}5

**** All numbers of the form 3{0}1{0}5 are divisible by 3, thus cannot be prime.

*** If there is no 1's in {}, then the family will be 3{0,4,5}5

**** If there are at least to 4's in {}, then 344 and 445 will be subsequences.

**** If there is no 4's in {}, then the family will be 3{0,5}5

***** Since **3055** and **3505** are primes, we only need to consider the families 3{0}5 and 3{5}5

****** All numbers of the form 3{0}5 are divisible by 2, thus cannot be prime.

****** The smallest prime of the form 3{5}5 is **35555**

**** If there is exactly one 4's in {}, then the family will be 3{0,5}4{0,5}5

***** Since 304, **3545** are primes, we only need to consider the families 34{0,5}5 (since any digits 0 or 5 between (3,4{0,5}5) will produce small primes)

****** All numbers of the form 34{0,5}5 are divisible by 5, thus cannot be prime.

* Case (3,6):

** Since 32, 16, 56, **346** are primes, we only need to consider the family 3{0,3,6}6 (since any digits 1, 2, 4, 5 between them will produce smaller primes)

*** All numbers of the form 3{0,3,6}6 are divisible by 3, thus cannot be prime.

* Case (4,1):

** **41** is prime, and thus the only minimal prime in this family.

* Case (4,2):

** Since 41, 43, 32, 52 are primes, we only need to consider the family 4{0,2,4,6}2 (since any digits 1, 3, 5 between them will produce smaller primes)

*** All numbers of the form 4{0,2,4,6}2 are divisible by 2, thus cannot be prime.

* Case (4,3):

** **43** is prime, and thus the only minimal prime in this family.

* Case (4,4):

** Since 41, 43, 14 are primes, we only need to consider the family 4{0,2,4,5,6}4 (since any digits 1, 3 between them will produce smaller primes)

*** If there is no 5's in {}, then the family will be 4{0,2,4,6}4

**** All numbers of the form 4{0,2,4,6}4 are divisible by 2, thus cannot be prime.

*** If there is at least one 5's in {}, then there cannot be 2 in {} (since if so, then either 25 or 52 will be a subsequence) and there cannot be 6 in {} (since if so, then either 65 or 56 will be a subsequence), thus the family is 4{0,4,5}5{0,4,5}4

**** Since 445, **4504**, 544 are primes, we only need to consider the family 4{0,5}5{5}4 (since any digit 4 between (4,5{0,4,5}4) and any digit 0, 4 between (4{0,4,5}5,4) will produce smaller primes)

***** If there are at least two 0's between (4,5{0,4,5}4), then **40054** will be a subsequence.

***** If there is no 0's between (4,5{0,4,5}4), then the family will be 4{5}5{5}4, which is equivalent to 4{5}4

****** The smallest prime of the form 4{5}4 is 45555555555555554 (not minimal prime, since 4555 and 5554 are primes)

***** If there is exactly one 0's between (4,5{0,4,5}4), then the family will be 4{5}0{5}5{5}4

****** Since 4504 is prime, we only need to consider the family 40{5}5{5}4 (since any digit 5 between (4,0{5}5{5}4) will produce small primes), which is equivalent to 40{5}4

******* The smallest prime of the form 40{5}4 is 405555555555555554 (not minimal prime, since 4555 and 5554 are primes)

* Case (4,5):

** Since 41, 43, 25, 65, **445** are primes, we only need to consider the family 4{0,5}5 (since any digits 1, 2, 3, 4, 6 between them will produce smaller primes)

*** If there are at least two 5's in {}, then **4555** will be a subsequence.

*** If there is exactly one 5's in {}, then the digit sum is 20, and the number will be divisible by 2 and cannot be prime.

*** If there is no 5's in {}, then the family will be 4{0}5

**** All numbers of the form 4{0}5 are divisible by 3, thus cannot be prime.

* Case (4,6):

** Since 41, 43, 16, 56 are primes, we only need to consider the family 4{0,2,4,6}6 (since any digits 1, 3, 5 between them will produce smaller primes)

*** All numbers of the form 4{0,2,4,6}6 are divisible by 2, thus cannot be prime.

* Case (5,1):

** Since 52, 56, 41, 61, **551** are primes, we only need to consider the family 5{0,1,3}1 (since any digits 2, 4, 5, 6 between them will produce smaller primes)

*** If there are at least two 3's in {}, then 533 will be a subsequence.

*** If there is no 3's in {}, then the family will be 5{0,1}1

**** Since **5011** is prime, we only need to consider the family 5{1}{0}1

***** Since 11111 is prime, we only need to consider the families 5{0}1, 51{0}1, 511{0}1, 5111{0}1 (since any digits combo 1111 between (5,1) will produce small primes)

****** All numbers of the form 5{0}1 are divisible by 6, thus cannot be prime.

****** The smallest prime of the form 51{0}1 is **5100000001**

****** All numbers of the form 511{0}1 are divisible by 2, thus cannot be prime.

****** All numbers of the form 5111{0}1 are divisible by 3, thus cannot be prime.

*** If there is exactly one 3's in {}, then the family will be 5{0,1}3{0,1}1

**** If there is at least one 1's between (5,3{0,1}1), then 131 will be a subsequence.

***** Thus we only need to consider the family 5{0}3{0,1}1

****** If there are no 1's between (5{0}3,1), then the digit sum is 12, and the number will be divisible by 3 and cannot be prime.

****** If there are exactly one 1's between (5{0}3,1), then the digit sum is 13, and the number will be divisible by 2 and cannot be prime.

****** If there are exactly three 1's between (5{0}3,1), then the digit sum is 15, and the number will be divisible by 6 and cannot be prime.

****** If there are at least four 1's between (5{0}3,1), then 11111 will be a subsequence.

****** If there are exactly two 1's between (5{0}3,1), then the family will be 5{0}3{0}1{0}1{0}1

******* Since 5011 is prime, we only need to consider the family 5311{0}1 (since any digit 0 between (5,1{0}1) will produce small primes, this includes the leftmost three {} in 5{0}3{0}1{0}1{0}1, and thus only the rightmost {} can contain 0)

******** The smallest prime of the form 5311{0}1 is **531101**

* Case (5,2):

** **52** is prime, and thus the only minimal prime in this family.

* Case (5,3):

** Since 52, 56, 23, 43, **533**, **553** are primes, we only need to consider the family 5{0,1}3 (since any digits 2, 3, 4, 5, 6 between them will produce smaller primes)

*** If there are at least two 1's in {}, then 113 will be a subsequence.

*** If there is exactly one 1's in {}, then the digit sum is 12, and the number will be divisible by 3 and cannot be prime.

*** If there is no 1's in {}, then the digit sum is 11, and the number will be divisible by 2 and cannot be prime.

* Case (5,4):

** Since 52, 56, 14, **544** are primes, we only need to consider the family 5{0,3,5}4 (since any digits 1, 2, 4, 6 between them will produce smaller primes)

*** If there are no 5's in {}, then the family will be 5{0,3}4

**** All numbers of the form 5{0,3}4 are divisible by 3, thus cannot be prime.

*** If there are at least one 5's and at least one 3's in {}, then either 535 or 553 will be a subsequence.

*** If there are exactly one 5's and no 3's in {}, then the digit sum is 20, and the number will be divisible by 2 and cannot be prime.

*** If there are at least two 5's in {}, then **5554** will be a subsequence.

* Case (5,5):

** Since 52, 56, 25, 65, **515**, **535** are primes, we only need to consider the family 5{0,4,5}5 (since any digits 1, 2, 3, 6 between them will produce smaller primes)

*** If there are no 4's in {}, then the family will be 5{0,5}5

**** All numbers of the form 5{0,5}5 are divisible by 5, thus cannot be prime.

*** If there are no 5's in {}, then the family will be 5{0,4}5

**** All numbers of the form 5{0,4}5 are divisible by 2, thus cannot be prime.

*** If there are at least one 4's and at least one 5's in {}, then either **5455** or **5545** will be a subsequence.

* Case (5,6):

** **56** is prime, and thus the only minimal prime in this family.

* Case (6,1):

** **61** is prime, and thus the only minimal prime in this family.

* Case (6,2):

** Since 61, 65, 32, 52 are primes, we only need to consider the family 6{0,2,4,6}2 (since any digits 1, 3, 5 between them will produce smaller primes)

*** All numbers of the form 6{0,2,4,6}2 are divisible by 2, thus cannot be prime.

* Case (6,3):

** Since 61, 65, 23, 43 are primes, we only need to consider the family 6{0,3,6}3 (since any digits 1, 2, 4, 5 between them will produce smaller primes)

*** All numbers of the form 6{0,3,6}3 are divisible by 3, thus cannot be prime.

* Case (6,4):

** Since 61, 65, 14 are primes, we only need to consider the family 6{0,2,3,4,6}4 (since any digits 1, 5 between them will produce smaller primes)

*** If there is no 3's in {}, then the family will be 6{0,2,4,6}4

**** All numbers of the form 6{0,2,4,6}4 are divisible by 2, thus cannot be prime.

*** If there are exactly two 3's in {}, then the family will be 6{0,2,4,6}3{0,2,4,6}3{0,2,4,6}4

**** All numbers of the form 6{0,2,4,6}3{0,2,4,6}3{0,2,4,6}4 are divisible by 2, thus cannot be prime.

*** If there are at least three 3's in {}, then 3334 will be a subsequence.

*** If there is exactly one 3's in {}, then the family will be 6{0,2,4,6}3{0,2,4,6}4

**** If there is 0 between (6,3{0,2,4,6}4), then **6034** will be a subsequence.

**** If there is 2 between (6,3{0,2,4,6}4), then 23 will be a subsequence.

**** If there is 4 between (6,3{0,2,4,6}4), then 43 will be a subsequence.

**** If there is 6 between (6,3{0,2,4,6}4), then **6634** will be a subsequence.

**** If there is 0 between (6{0,2,4,6}3,4), then 304 will be a subsequence.

**** If there is 2 between (6{0,2,4,6}3,4), then 32 will be a subsequence.

**** If there is 4 between (6{0,2,4,6}3,4), then 344 will be a subsequence.

**** If there is 6 between (6{0,2,4,6}3,4), then 364 will be a subsequence.

**** Thus the number can only be 634

***** 634 is not prime.

* Case (6,5):

** **65** is prime, and thus the only minimal prime in this family.

* Case (6,6):

** Since 61, 65, 16, 56 are primes, we only need to consider the family 6{0,2,3,4,6}6 (since any digits 1, 5 between them will produce smaller primes)

*** If there is no 3's in {}, then the family will be 6{0,2,4,6}6

**** All numbers of the form 6{0,2,4,6}6 are divisible by 2, thus cannot be prime.

*** If there is no 2's and no 4's in {}, then the family will be 6{0,3,6}6

**** All numbers of the form 6{0,3,6}6 are divisible by 3, thus cannot be prime.

*** If there is at least one 3's and at least one 2's in {}, then either 32 or 23 will be a subsequence.

*** If there is at least one 3's and at least one 4's in {}, then either 346 or 43 will be a subsequence.

base 8

The possible (first digit,last digit) for an element with >=3 digits in the minimal set of the strings for primes with at least two digits are:

(1,1), (1,3), (1,5), (1,7), (2,1), (2,3), (2,5), (2,7), (3,1), (3,3), (3,5), (3,7), (4,1), (4,3), (4,5), (4,7), (5,1), (5,3), (5,5), (5,7), (6,1), (6,3), (6,5), (6,7), (7,1), (7,3), (7,5), (7,7)

* Case (1,1):

** Since 13, 15, 21, 51, **111**, **141**, **161** are primes, we only need to consider the family 1{0,7}1 (since any digits 1, 2, 3, 4, 5, 6 between them will produce smaller primes)

*** Since 107, 177, 701 are primes, we only need to consider the number 171 and the family 1{0}1 (since any digits combo 07, 70, 77 between them will produce smaller primes)

**** 171 is not prime.

**** All numbers of the form 1{0}1 factored as 10^n+1 = (2^n+1) * (4^n-2^n+1), thus cannot be prime.

* Case (1,3):

** **13** is prime, and thus the only minimal prime in this family.

* Case (1,5):

** **15** is prime, and thus the only minimal prime in this family.

* Case (1,7):

** Since 13, 15, 27, 37, 57, **107**, **117**, **147**, **177** are primes, we only need to consider the family 1{6}7 (since any digits 0, 1, 2, 3, 4, 5, 7 between them will produce smaller primes)

*** The smallest prime of the form 1{6}7 is 16667 (not minimal prime, since 667 is prime)

* Case (2,1):

** **21** is prime, and thus the only minimal prime in this family.

* Case (2,3):

** **23** is prime, and thus the only minimal prime in this family.

* Case (2,5):

** Since 21, 23, 27, 15, 35, 45, 65, 75, **225**, **255** are primes, we only need to consider the family 2{0}5 (since any digits 1, 2, 3, 4, 5, 6, 7 between them will produce smaller primes)

*** All numbers of the form 2{0}5 are divisible by 7, thus cannot be prime.

* Case (2,7):

** **27** is prime, and thus the only minimal prime in this family.

* Case (3,1):

** Since 35, 37, 21, 51, **301**, **361** are primes, we only need to consider the family 3{1,3,4}1 (since any digits 0, 2, 5, 6, 7 between them will produce smaller primes)

*** Since 13, 343, 111, 131, 141, 431, **3331**, **3411** are primes, we only need to consider the families 3{3}11, 33{1,4}1, 3{3,4}4{4}1 (since any digits combo 11, 13, 14, 33, 41, 43 between them will produce smaller primes)

**** All numbers of the form 3{3}11 are divisible by 3, thus cannot be prime.

**** For the 33{1,4}1 family, since 111 and 141 are primes, we only need to consider the families 33{4}1 and 33{4}11 (since any digits combo 11, 14 between them will produce smaller primes)

***** The smallest prime of the form 33{4}1 is **3344441**

***** All numbers of the form 33{4}11 are divisible by 301, thus cannot be prime.

**** For the 3{3,4}4{4}1 family, since 3331 and 3344441 are primes, we only need to consider the families 3{4}1, 3{4}31, 3{4}341, 3{4}3441, 3{4}34441 (since any digits combo 33 or 34444 between (3,1) will produce smaller primes)

***** All numbers of the form 3{4}1 are divisible by 31, thus cannot be prime.

***** Since 4443 is prime, we only need to consider the numbers 3431, 34431, 34341, 344341, 343441, 3443441, 3434441, 34434441 (since any digit combo 444 between (3,3{4}1) will produce smaller primes)

****** None of 3431, 34431, 34341, 344341, 343441, 3443441, 3434441, 34434441 are primes.

* Case (3,3):

** Since 35, 37, 13, 23, 53, 73, **343** are primes, we only need to consider the family 3{0,3,6}3 (since any digits 1, 2, 4, 5, 7 between them will produce smaller primes)

*** All numbers of the form 3{0,3,6}3 are divisible by 3, thus cannot be prime.

* Case (3,5):

** **35** is prime, and thus the only minimal prime in this family.

* Case (3,7):

** **37** is prime, and thus the only minimal prime in this family.

* Case (4,1):

** Since 45, 21, 51, **401**, **431**, **471** are primes, we only need to consider the family 4{1,4,6}1 (since any digits 0, 2, 3, 5, 7 between them will produce smaller primes)

*** Since 111, 141, 161, 661, **4611** are primes, we only need to consider the families 4{4}11, 4{4,6}4{1,4,6}1, 4{4}6{4}1 (since any digits combo 11, 14, 16, 61, 66 between them will produce smaller primes)

**** The smallest prime of the form 4{4}11 is 44444444444444411 (not minimal prime, since 444444441 is prime)

**** For the 4{4,6}4{1,4,6}1 family, we can separate this family to 4{4,6}41, 4{4,6}411, 4{4,6}461

***** For the 4{4,6}41 family, since 661 and 6441 are primes, we only need to consider the families 4{4}41 and 4{4}641 (since any digits combo 64 or 66 between (4,41) will produce smaller primes)

****** The smallest prime of the form 4{4}41 is **444444441**

****** The smallest prime of the form 4{4}641 is **444641**

***** For the 4{4,6}411 family, since 661 and 6441 are primes, we only need to consider the families 4{4}411 and 4{4}6411 (since any digits combo 64 or 66 between (4,411) will produce smaller primes)

****** The smallest prime of the form 4{4}411 is **444444441**

****** The smallest prime of the form 4{4}6411 is 44444444444444446411 (not minimal prime, since 444444441 and 444641 are primes)

***** For the 4{4,6}461 family, since 661 is prime, we only need to consider the family 4{4}461

****** The smallest prime of the form 4{4}461 is 4444444461 (not minimal prime, since 444444441 is prime)

**** For the 4{4}6{4}1 family, since 6441 is prime, we only need to consider the families 4{4}61 and 4{4}641 (since any digits combo 44 between (4{4}6,1) will produce smaller primes)

***** The smallest prime of the form 4{4}61 is 4444444461 (not minimal prime, since 444444441 is prime)

***** The smallest prime of the form 4{4}641 is **444641**

* Case (4,3):

** Since 45, 13, 23, 53, 73, **433**, **463** are primes, we only need to consider the family 4{0,4}3 (since any digits 1, 2, 3, 5, 6, 7 between them will produce smaller primes)

*** Since **4043** and **4443** are primes, we only need to consider the families 4{0}3 and 44{0}3 (since any digits combo 04, 44 between them will produce smaller primes)

**** All numbers of the form 4{0}3 are divisible by 7, thus cannot be prime.

**** All numbers of the form 44{0}3 are divisible by 3, thus cannot be prime.

* Case (4,5):

** **45** is prime, and thus the only minimal prime in this family.

* Case (4,7):

** Since 45, 27, 37, 57, **407**, **417**, **467** are primes, we only need to consider the family 4{4,7}7 (since any digits 0, 1, 2, 3, 5, 6 between them will produce smaller primes)

*** Since 747 is prime, we only need to consider the families 4{4}7, 4{4}77, 4{7}7, 44{7}7 (since any digits combo 74 between (4,7) will produce smaller primes)

**** The smallest prime of the form 4{4}7 is **447**, with 220 4's, which can be written as $4_{220}7$ and equal the prime (2^665+17)/7

**** The smallest prime of the form 4{4}77 is **4444477**

**** The smallest prime of the form 4{7}7 is **47777**

**** The smallest prime of the form 44{7}7 is 4477, with 851 7's, which can be written as 447_{851} and equal the prime 37*2^2553-1 (not minimal prime, since 47777 is prime)

* Case (5,1):

** **51** is prime, and thus the only minimal prime in this family.

* Case (5,3):

** **53** is prime, and thus the only minimal prime in this family.

* Case (5,5):

** Since 51, 53, 57, 15, 35, 45, 65, 75 are primes, we only need to consider the family 5{0,2,5}5 (since any digits 1, 3, 4, 6, 7 between them will produce smaller primes)

*** Since 225, 255, **5205** are primes, we only need to consider the families 5{0,5}5 and 5{0,5}25 (since any digits combo 20, 22, 25 between them will produce smaller primes)

**** All numbers of the form 5{0,5}5 are divisible by 5, thus cannot be prime.

**** For the 5{0,5}25 family, since **500025** and **505525** are primes, we only need to consider the number 500525 the families 5{5}25, 5{5}025, 5{5}0025, 5{5}0525, 5{5}00525, 5{5}05025 (since any digits combo 000, 055 between (5,25) will produce smaller primes)

***** 500525 is not prime.

***** The smallest prime of the form 5{5}25 is **555555555555525**

***** The smallest prime of the form 5{5}025 is **55555025**

***** The smallest prime of the form 5{5}0025 is 555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555555550025, with 184 5's, which can be written as 51830025 and equal the prime (5*2^561-20333)/7 (not minimal prime, since 55555025 and 555555555555525 are primes)

***** The smallest prime of the form 5{5}0525 is **5550525**

***** The smallest prime of the form 5{5}00525 is **5500525**

***** The smallest prime of the form 5{5}05025 is 5555555555555555555555505025 (not minimal prime, since 5550525, 55555025, and 555555555555525 are primes)

* Case (5,7):

** **57** is prime, and thus the only minimal prime in this family.

* Case (6,1):

** Since 65, 21, 51, **631**, **661** are primes, we only need to consider the family 6{0,1,4,7}1 (since any digits 2, 3, 5, 6 between them will produce smaller primes)

*** Numbers containing 4: (note that the number cannot contain two or more 4's, or **6441** will be a subsequence)

**** The form is 6{0,1,7}4{0,1,7}1

***** Since 141, 401, 471 are primes, we only need to consider the family 6{0,7}4{1}1

****** Since 111 is prime, we only need to consider the families 6{0,7}41 and 6{0,7}411

******* For the 6{0,7}41 family, since **60741** is prime, we only need to consider the family 6{7}{0}41

******** Since 6777 is prime, we only need to consider the families 6{0}41, 67{0}41, 677{0}41

********* All numbers of the form 6{0}41 are divisible by 3, thus cannot be prime.

********* All numbers of the form 67{0}41 are divisible by 13, thus cannot be prime.

********* All numbers of the form 677{0}41 are divisible by 3, thus cannot be prime.

******* For the 6{0,7}411 family, since **60411** is prime, we only need to consider the family 6{7}411

******** The smallest prime of the form 6{7}411 is 67777411 (not minimal prime, since 6777 is prime)

*** Numbers not containing 4:

**** The form is 6{0,1,7}1

***** Since 111 is prime, we only need to consider the families 6{0,7}1 and 6{0,7}1{0,7}1

****** All numbers of the form 6{0,7}1 are divisible by 7, thus cannot be prime.

****** For the 6{0,7}1{0,7}1 family, since 711 and **6101** are primes, we only need to consider the family 6{0}1{7}1

******* Since **60171** is prime, we only need to consider the families 6{0}11 and 61{7}1

******** All numbers of the form 6{0}11 are divisible by 3, thus cannot be prime.

******** The smallest prime of the form 61{7}1 is 617771 (not minimal prime, since 6777 is prime)

* Case (6,3):

** Since 65, 13, 23, 53, 73, **643** are primes, we only need to consider the family 6{0,3,6}3 (since any digits 1, 2, 4, 5, 7 between them will produce smaller primes)

*** All numbers of the form 6{0,3,6}3 are divisible by 3, thus cannot be prime.

* Case (6,5):

** **65** is prime, and thus the only minimal prime in this family.

* Case (6,7):

** Since 65, 27, 37, 57, **667** are primes, we only need to consider the family 6{0,1,4,7}7 (since any digits 2, 3, 5, 6 between them will produce smaller primes)

*** Since 107, 117, 147, 177, 407, 417, 717, 747, **6007**, **6477**, **6707**, **6777** are primes, we only need to consider the families 60{1,4,7}7, 6{0}17, 6{0,4}4{4}7, 6{0}77 (since any digits combo 00, 10, 11, 14, 17, 40, 41, 47, 70, 71, 74, 77 between them will produce smaller primes)

**** All numbers of the form 6{0}17 or 6{0}77 are divisible by 3, thus cannot be prime.

**** For the 60{1,4,7}7 family, since 117, 147, 177, 417, 6477, 717, 747, 6777 are primes, we only need to consider the numbers 6017, 6047, 6077 and the family 60{4}7 (since any digit combo 11, 14, 17, 41, 47, 71, 74, 77 between (60,7) will produce smaller primes)

***** None of 6017, 6047, 6077 are primes.

**** All numbers of the form 60{4}7 are divisible by 21, thus cannot be prime.

**** For the 6{0,4}4{4}7 family, since 6007 and 407 are primes, we only need to consider the families 6{4}7 and 60{4}7 (since any digit combo 00, 40 between (6,4{4}7) will produce smaller primes)

***** All numbers of the form 6{4}7 are divisible by 3, 5, or 15, thus cannot be prime.

***** All numbers of the form 60{4}7 are divisible by 21, thus cannot be prime.

* Case (7,1):

** Since 73, 75, 21, 51, **701**, **711** are primes, we only need to consider the family 7{4,6,7}1 (since any digits 0, 1, 2, 3, 5 between them will produce smaller primes)

*** Since 747, 767, 471, 661, **7461**, **7641** are primes, we only need to consider the families 7{4,7}4{4}1, 7{7}61, 7{7}7{4,6,7}1 (since any digits combo 46, 47, 64, 66, 67 between them will produce smaller primes)

**** For the 7{4,7}4{4}1 family, since 747, 471 are primes, we only need to consider the family 7{7}{4}1 (since any digits combo 47 between (7,4{4}1) will produce smaller primes)

***** The smallest prime of the form 7{7}1 is **7777777777771**

***** The smallest prime of the form 7{7}41 is
777777777777777777777777777777777777777777777777777777777777777777777777777777741
, with 79 7's, which can be written as 77941 and equal the prime 2^243-31 (not minimal prime, since 7777777777771 is prime)

***** The smallest prime of the form 7{7}441 is
777777777777777777777777777777777777777777777777777777777777777777777777777777777
777441, with 84 7's, which can be written as 784441 and equal the prime 2^261-223 (not minimal prime, since 7777777777771 is prime)

***** The smallest prime of the form 7{7}4441 is
777777777777777777777777777777777777777777777777777777777777777777777777777777777
777777777777777777777777777777777777777777777777777777777777777777777777777777777
777777777777777777777777777777777777777777777777777777777777777777777774441, with 233 7's, which can be written as 72334441 and equal the prime 2^711-1759 (not minimal prime, since 7777777777771 is prime)

***** The smallest prime of the form 7{7}44441 is
7777777777777777777777777777777777777777777777777777777744441, with 56 7's, which can be written as 75644441 and equal the prime 2^183-14047 (not minimal prime, since 7777777777771 is prime)

***** All numbers of the form 7{7}444441 are divisible by 7, thus cannot be prime.

***** The smallest prime of the form 7{7}4444441 is **77774444441**

****** Since this prime has just 4 7's, we only need to consider the families with <=3 7's

******* The smallest prime of the form 7{4}1 is **744444441**

******* All numbers of the form 77{4}1 are divisible by 5, thus cannot be prime.

******* The smallest prime of the form 777{4}1 is 777444444444441 (not minimal prime, since 444444441 and 744444441 are primes)

* Case (7,3):

** **73** is prime, and thus the only minimal prime in this family.

* Case (7,5):

** **75** is prime, and thus the only minimal prime in this family.

* Case (7,7):

** Since 73, 75, 27, 37, 57, **717**, **747**, **767** are primes, we only need to consider the family 7{0,7}7 (since any digits 1, 2, 3, 4, 5, 6 between them will produce smaller primes)

*** All numbers of the form 7{0,7}7 are divisible by 7, thus cannot be prime.

base 10

The possible (first digit,last digit) for an element with >=3 digits in the minimal set of the strings for primes with at least two digits are:

(1,1), (1,3), (1,7), (1,9), (2,1), (2,3), (2,7), (2,9), (3,1), (3,3), (3,7), (3,9), (4,1), (4,3), (4,7), (4,9), (5,1), (5,3), (5,7), (5,9), (6,1), (6,3), (6,7), (6,9), (7,1), (7,3), (7,7), (7,9), (8,1), (8,3), (8,7), (8,9), (9,1), (9,3), (9,7), (9,9)

* Case (1,1):

** **11** is prime, and thus the only minimal prime in this family.

* Case (1,3):

** **13** is prime, and thus the only minimal prime in this family.

* Case (1,7):

** **17** is prime, and thus the only minimal prime in this family.

* Case (1,9):

** **19** is prime, and thus the only minimal prime in this family.

* Case (2,1):

** Since 23, 29, 11, 31, 41, 61, 71, **251**, **281** are primes, we only need to consider the family 2{0,2}1 (since any digits 1, 3, 4, 5, 6, 7, 8, 9 between them will produce smaller primes)

*** Since **2221** and **20201** are primes, we only need to consider the families 2{0}1, 2{0}21, 22{0}1 (since any digits combo 22 or 020 between them will produce smaller primes)

**** All numbers of the form 2{0}1 are divisible by 3, thus cannot be prime.

**** The smallest prime of the form 2{0}21 is **20021**

**** The smallest prime of the form 22{0}1 is **22000001**

* Case (2,3):

** **23** is prime, and thus the only minimal prime in this family.

* Case (2,7):

** Since 23, 29, 17, 37, 47, 67, 97, **227**, **257**, **277** are primes, we only need to consider the family 2{0,8}7 (since any digits 1, 2, 3, 4, 5, 6, 7, 9 between them will produce smaller primes)

*** Since 887 and **2087** are primes, we only need to consider the families 2{0}7 and 28{0}7 (since any digit combo 08 or 88 between them will produce smaller primes)

**** All numbers of the form 2{0}7 are divisible by 3, thus cannot be prime.

**** All numbers of the form 28{0}7 are divisible by 7, thus cannot be prime.

* Case (2,9):

** **29** is prime, and thus the only minimal prime in this family.

* Case (3,1):

** **31** is prime, and thus the only minimal prime in this family.

* Case (3,3):

** Since 31, 37, 13, 23, 43, 53, 73, 83 are primes, we only need to consider the family 3{0,3,6,9}3 (since any digits 1, 2, 4, 5, 7, 8 between them will produce smaller primes)

*** All numbers of the form 3{0,3,6,9}3 are divisible by 3, thus cannot be prime.

* Case (3,7):

** **37** is prime, and thus the only minimal prime in this family.

* Case (3,9):

** Since 31, 37, 19, 29, 59, 79, 89, **349** are primes, we only need to consider the family 3{0,3,6,9}9 (since any digits 1, 2, 4, 5, 7, 8 between them will produce smaller primes)

*** All numbers of the form 3{0,3,6,9}9 are divisible by 3, thus cannot be prime.

* Case (4,1):

** **41** is prime, and thus the only minimal prime in this family.

* Case (4,3):

** **43** is prime, and thus the only minimal prime in this family.

* Case (4,7):

** **47** is prime, and thus the only minimal prime in this family.

* Case (4,9):

** Since 41, 43, 47, 19, 29, 59, 79, 89, **409**, **449**, **499** are primes, we only need to consider the family 4{6}9 (since any digits 0, 1, 2, 3, 4, 5, 7, 8, 9 between them will produce smaller primes)

*** All numbers of the form 4{6}9 are divisible by 7, thus cannot be prime.

* Case (5,1):

** Since 53, 59, 11, 31, 41, 61, 71, **521** are primes, we only need to consider the family 5{0,5,8}1 (since any digits 1, 2, 3, 4, 6, 7, 9 between them will produce smaller primes)

*** Since 881 is prime, we only need to consider the families 5{0,5}1 and 5{0,5}8{0,5}1 (since any digit combo 88 between them will produce smaller primes)

**** For the 5{0,5}1 family, since **5051** and **5501** are primes, we only need to consider the families 5{0}1 and 5{5}1 (since any digit combo 05 or 50 between them will produce smaller primes)

***** All numbers of the form 5{0}1 are divisible by 3, thus cannot be prime.

***** The smallest prime of the form 5{5}1 is **555555555551**

**** For the 5{0,5}8{0,5}1 family, since **5081**, **5581**, **5801**, **5851** are primes, we only need to consider the number 581

***** 581 is not prime.

* Case (5,3):

** **53** is prime, and thus the only minimal prime in this family.

* Case (5,7):

** Since 53, 59, 17, 37, 47, 67, 97, **557**, **577**, **587** are primes, we only need to consider the family 5{0,2}7 (since any digits 1, 3, 4, 5, 6, 7, 8, 9 between them will produce smaller primes)

*** Since 227 and **50207** are primes, we only need to consider the families 5{0}7, 5{0}27, 52{0}7 (since any digits combo 22 or 020 between them will produce smaller primes)

**** All numbers of the form 5{0}7 are divisible by 3, thus cannot be prime.

**** The smallest prime of the form 5{0}27 is **5000000000000000000000000000027**

**** The smallest prime of the form 52{0}7 is **5200007**

* Case (5,9):

** **59** is prime, and thus the only minimal prime in this family.

* Case (6,1):

** **61** is prime, and thus the only minimal prime in this family.

* Case (6,3):

** Since 61, 67, 13, 23, 43, 53, 73, 83 are primes, we only need to consider the family 6{0,3,6,9}3 (since any digits 1, 2, 4, 5, 7, 8 between them will produce smaller primes)

*** All numbers of the form 6{0,3,6,9}3 are divisible by 3, thus cannot be prime.

* Case (6,7):

** **67** is prime, and thus the only minimal prime in this family.

* Case (6,9):

** Since 61, 67, 19, 29, 59, 79, 89 are primes, we only need to consider the family 6{0,3,4,6,9}9 (since any digits 1, 2, 5, 7, 8 between them will produce smaller primes)

*** Since 449 is prime, we only need to consider the families 6{0,3,6,9}9 and 6{0,3,6,9}4{0,3,6,9}9 (since any digit combo 44 between them will produce smaller primes)

**** All numbers of the form 6{0,3,6,9}9 are divisible by 3, thus cannot be prime.

**** For the 6{0,3,6,9}4{0,3,6,9}9 family, since 409, 43, **6469**, 499 are primes, we only need to consider the family 6{0,3,6,9}49

***** Since 349, **6949** are primes, we only need to consider the family 6{0,6}49

****** Since **60649** is prime, we only need to consider the family 6{6}{0}49 (since any digits combo 06 between {6,49} will produce smaller primes)

******* The smallest prime of the form 6{6}49 is **666649**

******** Since this prime has just 4 6's, we only need to consider the families with <=3 6's

********* The smallest prime of the form 6{0}49 is **60000049**

********* The smallest prime of the form 66{0}49 is **66000049**

********* The smallest prime of the form 666{0}49 is **66600049**

* Case (7,1):

** **71** is prime, and thus the only minimal prime in this family.

* Case (7,3):

** **73** is prime, and thus the only minimal prime in this family.

* Case (7,7):

** Since 71, 73, 79, 17, 37, 47, 67, 97, **727**, **757**, **787** are primes, we only need to consider the family 7{0,7}7 (since any digits 1, 2, 3, 4, 5, 6, 8, 9 between them will produce smaller primes)

*** All numbers of the form 7{0,7}7 are divisible by 7, thus cannot be prime.

* Case (7,9):

** **79** is prime, and thus the only minimal prime in this family.

* Case (8,1):

** Since 83, 89, 11, 31, 41, 61, 71, **821**, **881** are primes, we only need to consider the family 8{0,5}1 (since any digits 1, 2, 3, 4, 6, 7, 8, 9 between them will produce smaller primes)

*** Since **8501** is prime, we only need to consider the family 8{0}{5}1 (since any digits combo 50 between them will produce smaller primes)

**** Since **80051** is prime, we only need to consider the families 8{0}1, 8{5}1, 80{5}1 (since any digits combo 005 between them will produce smaller primes)

***** All numbers of the form 8{0}1 are divisible by 3, thus cannot be prime.

***** The smallest prime of the form 8{5}1 is 855555555555555555555551 (not minimal prime, since 555555555551 is prime)

***** The smallest prime of the form 80{5}1 is **80555551**

* Case (8,3):

** **83** is prime, and thus the only minimal prime in this family.

* Case (8,7):

** Since 83, 89, 17, 37, 47, 67, 97, **827**, **857**, **877**, **887** are primes, we only need to consider the family 8{0}7 (since any digits 1, 2, 3, 4, 5, 6, 7, 8, 9 between them will produce smaller primes)

*** All numbers of the form 8{0}7 are divisible by 3, thus cannot be prime.

* Case (8,9):

** **89** is prime, and thus the only minimal prime in this family.

* Case (9,1):

** Since 97, 11, 31, 41, 61, 71, **991** are primes, we only need to consider the family 9{0,2,5,8}1 (since any digits 1, 3, 4, 6, 7, 9 between them will produce smaller primes)

*** Since 251, 281, 521, 821, 881, **9001**, **9221**, **9551**, **9851** are primes, we only need to consider the families 9{2,5,8}0{2,5,8}1, 9{0}2{0}1, 9{0}5{0,8}1, 9{0,5}8{0}1 (since any digits combo 00, 22, 25, 28, 52, 55, 82, 85, 88 between them will produce smaller primes)

**** For the 9{2,5,8}0{2,5,8}1 family, since any digits combo 22, 25, 28, 52, 55, 82, 85, 88 between (9,1) will produce smaller primes, we only need to consider the numbers 901, 9021, 9051, 9081, 9201, 9501, 9801, 90581, 95081, 95801

***** 95801 is the only prime among 901, 9021, 9051, 9081, 9201, 9501, 9801, 90581, 95081, 95801, but it is not minimal prime since 5801 is prime.

**** For the 9{0}2{0}1 family, since 9001 is prime, we only need to consider the numbers 921, 9201, 9021

***** None of 921, 9201, 9021 are primes.

**** For the 9{0}5{0,8}1 family, since 9001 and 881 are primes, we only need to consider the numbers 951, 9051, 9501, 9581, 90581, 95081, 95801

***** 95801 is the only prime among 951, 9051, 9501, 9581, 90581, 95081, 95801, but it is not minimal prime since 5801 is prime.

**** For the 9{0,5}8{0}1 family, since 9001 and 5581 are primes, we only need to consider the numbers 981, 9081, 9581, 9801, 90581, 95081, 95801

***** 95801 is the only prime among 981, 9081, 9581, 9801, 90581, 95081, 95801, but it is not minimal prime since 5801 is prime.

* Case (9,3):

** Since 97, 13, 23, 43, 53, 73, 83 are primes, we only need to consider the family 9{0,3,6,9}3 (since any digits 1, 2, 4, 5, 7, 8 between them will produce smaller primes)

*** All numbers of the form 9{0,3,6,9}3 are divisible by 3, thus cannot be prime.

* Case (9,7):

** **97** is prime, and thus the only minimal prime in this family.

* Case (9,9):

** Since 97, 19, 29, 59, 79, 89 are primes, we only need to consider the family 9{0,3,4,6,9}9 (since any digits 1, 2, 5, 7, 8 between them will produce smaller primes)

*** Since 449 is prime, we only need to consider the families 9{0,3,6,9}9 and 9{0,3,6,9}4{0,3,6,9}9 (since any digit combo 44 between them will produce smaller primes)

**** All numbers of the form 9{0,3,6,9}9 are divisible by 3, thus cannot be prime.

**** For the 9{0,3,6,9}4{0,3,6,9}9 family, since **9049**, 349, **9649**, **9949** are primes, we only need to consider the family 94{0,3,6,9}9

***** Since 409, 43, 499 are primes, we only need to consider the family 94{6}9 (since any digits 0, 3, 9 between (94,9) will produce smaller primes)

****** The smallest prime of the form 94{6}9 is **946669**

base 12

The possible (first digit,last digit) for an element with >=3 digits in the minimal set of the strings for primes with at least two digits are:

(1,1), (1,5), (1,7), (1,B), (2,1), (2,5), (2,7), (2,B), (3,1), (3,5), (3,7), (3,B), (4,1), (4,5), (4,7), (4,B), (5,1), (5,5), (5,7), (5,B), (6,1), (6,5), (6,7), (6,B), (7,1), (7,5), (7,7), (7,B), (8,1), (8,5), (8,7), (8,B), (9,1), (9,5), (9,7), (9,B), (A,1), (A,5), (A,7), (A,B), (B,1), (B,5), (B,7), (B,B)

* Case (1,1):

** **11** is prime, and thus the only minimal prime in this family.

* Case (1,5):

** **15** is prime, and thus the only minimal prime in this family.

* Case (1,7):

** **17** is prime, and thus the only minimal prime in this family.

* Case (1,B):

** **1B** is prime, and thus the only minimal prime in this family.

* Case (2,1):

** Since 25, 27, 11, 31, 51, 61, 81, 91, **221**, **241**, **2A1**, **2B1** are primes, we only need to consider the family 2{0}1 (since any digits 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B between them will produce smaller primes)

*** The smallest prime of the form 2{0}1 is **2001**

* Case (2,5):

** **25** is prime, and thus the only minimal prime in this family.

* Case (2,7):

** **27** is prime, and thus the only minimal prime in this family.

* Case (2,B):

** Since 25, 27, 1B, 3B, 4B, 5B, 6B, 8B, AB, **2BB** are primes, we only need to consider the family 2{0,2,9}B (since any digits 1, 3, 4, 5, 6, 7, 8, A, B between them will produce smaller primes)

*** Since 90B, **200B**, **202B**, **222B**, **229B**, **292B**, **299B** are primes, we only need to consider the numbers 20B, 22B, 29B, 209B, 220B (since any digits combo 00, 02, 22, 29, 90, 92, 99 between them will produce smaller primes)

**** None of 20B, 22B, 29B, 209B, 220B are primes.

* Case (3,1):

** **31** is prime, and thus the only minimal prime in this family.

* Case (3,5):

** **35** is prime, and thus the only minimal prime in this family.

* Case (3,7):

** **37** is prime, and thus the only minimal prime in this family.

* Case (3,B):

** **3B** is prime, and thus the only minimal prime in this family.

* Case (4,1):

** Since 45, 4B, 11, 31, 51, 61, 81, 91, **401**, **421**, **471** are primes, we only need to consider the family 4{4,A}1 (since any digit 0, 1, 2, 3, 5, 6, 7, 8, 9, B between them will produce smaller primes)

*** Since A41 and **4441** are primes, we only need to consider the families 4{A}1 and 44{A}1 (since any digit combo 44, A4 between them will produce smaller primes)

**** All numbers of the form 4{A}1 are divisible by 5, thus cannot be prime.

**** The smallest prime of the form 44{A}1 is **44AAA1**

* Case (4,5):

** **45** is prime, and thus the only minimal prime in this family.

* Case (4,7):

** Since 45, 4B, 17, 27, 37, 57, 67, 87, A7, B7, **447**, **497** are primes, we only need to consider the family 4{0,7}7 (since any digit 1, 2, 3, 4, 5, 6, 8, 9, A, B between them will produce smaller primes)

*** Since **4707** and **4777** are primes, we only need to consider the families 4{0}7 and 4{0}77 (since any digit combo 70, 77 between them will produce smaller primes)

**** All numbers of the form 4{0}7 are divisible by B, thus cannot be prime.

**** The smallest prime of the form 4{0}77 is **400000000000000000000000000000000000000077**

* Case (4,B):

** **4B** is prime, and thus the only minimal prime in this family.

* Case (5,1):

** **51** is prime, and thus the only minimal prime in this family.

* Case (5,5):

** Since 51, 57, 5B, 15, 25, 35, 45, 75, 85, 95, B5, **565** are primes, we only need to consider the family 5{0,5,A}5 (since any digits 1, 2, 3, 4, 6, 7, 8, 9, B between them will produce smaller primes)

*** All numbers of the form 5{0,5,A}5 are divisible by 5, thus cannot be prime.

* Case (5,7):

** **57** is prime, and thus the only minimal prime in this family.

* Case (5,B):

** **5B** is prime, and thus the only minimal prime in this family.

* Case (6,1):

** **61** is prime, and thus the only minimal prime in this family.

* Case (6,5):

** Since 61, 67, 6B, 15, 25, 35, 45, 75, 85, 95, B5, **655**, **665** are primes, we only need to consider the family 6{0,A}5 (since any digits 1, 2, 3, 4, 5, 6, 7, 8, 9, B between them will produce smaller primes)

*** Since **6A05** and **6AA5** are primes, we only need to consider the families 6{0}5 and 6{0}A5 (since any digit combo A0, AA between them will produce smaller primes)

**** All numbers of the form 6{0}5 are divisible by B, thus cannot be prime.

**** The smallest prime of the form 6{0}A5 is **600A5**

* Case (6,7):

** **67** is prime, and thus the only minimal prime in this family.

* Case (6,B):

** **6B** is prime, and thus the only minimal prime in this family.

* Case (7,1):

** Since 75, 11, 31, 51, 61, 81, 91, **701**, **721**, **771**, **7A1** are primes, we only need to consider the family 7{4,B}1 (since any digits 0, 1, 2, 3, 5, 6, 7, 8, 9, A between them will produce smaller primes)

*** Since 7BB, **7441** and **7B41** are primes, we only need to consider the numbers 741, 7B1, 74B1

**** None of 741, 7B1, 74B1 are primes.

* Case (7,5):

** **75** is prime, and thus the only minimal prime in this family.

* Case (7,7):

** Since 75, 17, 27, 37, 57, 67, 87, A7, B7, **747**, **797** are primes, we only need to consider the family 7{0,7}7 (since any digits 1, 2, 3, 4, 5, 6, 8, 9, A, B between them will produce smaller primes)

*** All numbers of the form 7{0,7}7 are divisible by 7, thus cannot be prime.

* Case (7,B):

** Since 75, 1B, 3B, 4B, 5B, 6B, 8B, AB, **70B**, **77B**, **7BB** are primes, we only need to consider the family 7{2,9}B (since any digits 0, 1, 3, 4, 5, 6, 7, 8, A, B between them will produce smaller primes)

*** Since 222B, 729B is prime, we only need to consider the families 7{9}B, 7{9}2B, 7{9}22B (since any digits combo 222, 29 between them will produce smaller primes)

**** The smallest prime of the form 7{9}B is **7999B**

**** The smallest prime of the form 7{9}2B is 79992B (not minimal prime, since 992B and 7999B are primes)

**** The smallest prime of the form 7{9}22B is 79922B (not minimal prime, since 992B is prime)

* Case (8,1):

** **81** is prime, and thus the only minimal prime in this family.

* Case (8,5):

** **85** is prime, and thus the only minimal prime in this family.

* Case (8,7):

** **87** is prime, and thus the only minimal prime in this family.

* Case (8,B):

** **8B** is prime, and thus the only minimal prime in this family.

* Case (9,1):

** **91** is prime, and thus the only minimal prime in this family.

* Case (9,5):

** **95** is prime, and thus the only minimal prime in this family.

* Case (9,7):

** Since 91, 95, 17, 27, 37, 57, 67, 87, A7, B7, **907** are primes, we only need to consider the family 9{4,7,9}7 (since any digit 0, 1, 2, 3, 5, 6, 8, A, B between them will produce smaller primes)

*** Since 447, 497, 747, 797, **9777**, **9947**, **9997** are primes, we only need to consider the numbers 947, 977, 997, 9477, 9977 (since any digits combo 44, 49, 74, 77, 79, 94, 99 between them will produce smaller primes)

**** None of 947, 977, 997, 9477, 9977 are primes.

* Case (9,B):

** Since 91, 95, 1B, 3B, 4B, 5B, 6B, 8B, AB, **90B**, **9BB** are primes, we only need to consider the family 9{2,7,9}B (since any digit 0, 1, 3, 4, 5, 6, 8, A, B between them will produce smaller primes)

*** Since 27, 77B, **929B**, **992B**, **997B** are primes, we only need to consider the families 9{2,7}2{2}B, 97{2,9}B, 9{7,9}9{9}B (since any digits combo 27, 29, 77, 92, 97 between them will produce smaller primes)

**** For the 9{2,7}2{2}B family, since 27 and 77B are primes, we only need to consider the families 9{2}2{2}B and 97{2}2{2}B (since any digits combo 27, 77 between (9,2{2}B) will produce smaller primes)

***** The smallest prime of the form 9{2}2{2}B is 9222B (not minimal prime, since 222B is prime)

***** The smallest prime of the form 97{2}2{2}B is 9722222222222B (not minimal prime, since 222B is prime)

**** For the 97{2,9}B family, since 729B and 929B are primes, we only need to consider the family 97{9}{2}B (since any digits combo 29 between (97,B) will produce smaller primes)

***** Since 222B is prime, we only need to consider the families 97{9}B, 97{9}2B, 97{9}22B (since any digit combo 222 between (97,B) will produce smaller primes)

****** All numbers of the form 97{9}B are divisible by 11, thus cannot be prime.

****** The smallest prime of the form 97{9}2B is 979999992B (not minimal prime, since 9999B is prime)

****** All numbers of the form 97{9}22B are divisible by 11, thus cannot be prime.

**** For the 9{7,9}9{9}B family, since 77B and 9999B are primes, we only need to consider the numbers 99B, 999B, 979B, 9799B, 9979B

***** None of 99B, 999B, 979B, 9799B, 9979B are primes.

* Case (A,1):

** Since A7, AB, 11, 31, 51, 61, 81, 91, **A41** are primes, we only need to consider the family A{0,2,A}1 (since any digits 1, 3, 4, 5, 6, 7, 8, 9, B between them will produce smaller primes)

*** Since 221, 2A1, **A0A1**, **A201** are primes, we only need to consider the families A{A}{0}1 and A{A}{0}21 (since any digits combo 0A, 20, 22, 2A between them will produce smaller primes)

**** For the A{A}{0}1 family:

***** All numbers of the form A{0}1 are divisible by B, thus cannot be prime.

***** The smallest prime of the form AA{0}1 is **AA000001**

***** The smallest prime of the form AAA{0}1 is **AAA0001**

***** The smallest prime of the form AAAA{0}1 is **AAAA1**

****** Since this prime has no 0's, we do not need to consider the families {A}1, {A}01, {A}001, etc.

**** All numbers of the form A{A}{0}21 are divisible by 5, thus cannot be prime.

* Case (A,5):

** Since A7, AB, 15, 25, 35, 45, 75, 85, 95, B5 are primes, we only need to consider the family A{0,5,6,A}5 (since any digits 1, 2, 3, 4, 7, 8, 9, B between them will produce smaller primes)

*** Since 565, 655, 665, **A605**, **A6A5**, **AA65** are primes, we only need to consider the families A{0,5,A}5 and A{0}65 (since any digits combo 56, 60, 65, 66, 6A, A6 between them will produce smaller primes)

**** All numbers of the form A{0,5,A}5 are divisible by 5, thus cannot be prime.

**** The smallest prime of the form A{0}65 is **A00065**

* Case (A,7):

** **A7** is prime, and thus the only minimal prime in this family.

* Case (A,B):

** **AB** is prime, and thus the only minimal prime in this family.

* Case (B,1):

** Since B5, B7, 11, 31, 51, 61, 81, 91, **B21** are primes, we only need to consider the family B{0,4,A,B}1 (since any digits 1, 2, 3, 5, 6, 7, 8, 9 between them will produce smaller primes)

*** Since 4B, AB, 401, A41, **B001**, **B0B1**, **BB01**, **BB41** are primes, we only need to consider the families B{A}0{4,A}1, B{0,4}4{4,A}1, B{0,4,A,B}A{0,A}1, B{B}B{A,B}1 (since any digits combo 00, 0B, 40, 4B, A4, AB, B0, B4 between them will produce smaller primes)

**** For the B{A}0{4,A}1 family, since A41 is prime, we only need consider the families B0{4}{A}1 and B{A}0{A}1

***** For the B0{4}{A}1 family, since **B04A1** is prime, we only need to consider the families B0{4}1 and B0{A}1

****** The smallest prime of the form B0{4}1 is B04441 (not minimal prime, since 4441 is prime)

****** The smallest prime of the form B0{A}1 is B0AAAA1 (not minimal prime, since AAAA1 is prime)

***** For the B{A}0{A}1 family, since A0A1 is prime, we only need to consider the families B{A}01 and B0{A}1

****** The smallest prime of the form B{A}01 is **BAA01**

****** The smallest prime of the form B0{A}1 is B0AAAAA1 (not minimal prime, since AAAA1 is prime)

**** For the B{0,4}4{4,A}1 family, since 4441 is prime, we only need to consider the families B{0}4{4,A}1 and B{0,4}4{A}1

***** For the B{0}4{4,A}1 family, since B001 is prime, we only need to consider the families B4{4,A}1 and B04{4,A}1

****** For the B4{4,A}1 family, since A41 is prime, we only need to consider the family B4{4}{A}1

******* Since 4441 and BAAA1 are primes, we only need to consider the numbers B41, B441, B4A1, B44A1, B4AA1, B44AA1

******** None of B41, B441, B4A1, B44A1, B4AA1, B44AA1 are primes.

****** For the B04{4,A}1 family, since **B04A1** is prime, we only need to consider the family B04{4}1

******* The smallest prime of the form B04{4}1 is B04441 (not minimal prime, since 4441 is prime)

***** For the B{0,4}4{A}1 family, since 401, 4441, B001 are primes, we only need to consider the families B4{A}1, B04{A}1, B44{A}1, B044{A}1 (since any digits combo 00, 40, 44 between (B,4{A}1) will produce smaller primes)

****** The smallest prime of the form B4{A}1 is B4AAA1 (not minimal prime, since BAAA1 is prime)

****** The smallest prime of the form B04{A}1 is **B04A1**

****** The smallest prime of the form B44{A}1 is B44AAAAAAA1 (not minimal prime, since BAAA1 is prime)

****** The smallest prime of the form B044{A}1 is B044A1 (not minimal prime, since B04A1 is prime)

**** For the B{0,4,A,B}A{0,A}1 family, since all numbers in this family with 0 between (B,1) are in the B{A}0{4,A}1 family, and all numbers in this family with 4 between (B,1) are in the B{0,4}4{4,A}1 family, we only need to consider the family B{A,B}A{A}1

***** Since **BAAA1** is prime, we only need to consider the families B{A,B}A1 and B{A,B}AA1

****** For the B{A,B}A1 family, since AB and **BAAA1** are primes, we only need to consider the families B{B}A1 and B{B}AA1

******* All numbers of the form B{B}A1 are divisible by B, thus cannot be prime.

******* The smallest prime of the form B{B}AA1 is **BBBAA1**

****** For the B{A,B}AA1 family, since **BAAA1** is prime, we only need to consider the families B{B}AA1

******* The smallest prime of the form B{B}AA1 is **BBBAA1**

**** For the B{B}B{A,B}1 family, since AB and BAAA1 are primes, we only need to consider the families B{B}B1, B{B}BA1, B{B}BAA1 (since any digits combo AB or AAA between (B{B}B,1) will produce smaller primes)

***** The smallest prime of the form B{B}B1 is **BBBB1**

***** All numbers of the form B{B}BA1 are divisible by B, thus cannot be prime.

***** The smallest prime of the form B{B}BAA1 is **BBBAA1**

* Case (B,5):

** **B5** is prime, and thus the only minimal prime in this family.

* Case (B,7):

** **B7** is prime, and thus the only minimal prime in this family.

* Case (B,B):

** Since B5, B7, 1B, 3B, 4B, 5B, 6B, 8B, AB, **B2B** are primes, we only need to consider the family B{0,9,B}B (since any digits 1, 2, 3, 4, 5, 6, 7, 8, A between them will produce smaller primes)

*** Since 90B and 9BB are primes, we only need to consider the families B{0,B}{9}B

**** Since 9999B is prime, we only need to consider the families B{0,B}B, B{0,B}9B, B{0,B}99B, B{0,B}999B

***** All numbers of the form B{0,B}B are divisible by B, thus cannot be prime.

***** For the B{0,B}9B family:

****** Since **B0B9B** and **BB09B** are primes, we only need to consider the families B{0}9B and B{B}9B (since any digits combo 0B, B0 between (B,9B) will produce smaller primes)

******* The smallest prime of the form B{0}9B is **B0000000000000000000000000009B**

******* All numbers of the from B{B}9B is either divisible by 11 (if totally number of B's is even) or factored as 10^(2*n)-21 = (10^n-5) * (10^n+5) (if totally number of B's is odd number 2*n-1), thus cannot be prime.

***** For the B{0,B}99B family:

****** Since B0B9B and BB09B are primes, we only need to consider the families B{0}99B and B{B}99B (since any digits combo 0B, B0 between (B,99B) will produce smaller primes)

******* The smallest prime of the form B{0}99B is **B00099B**

******* The smallest prime of the form B{B}99B is **BBBBBB99B**

***** For the B{0,B}999B family:

****** Since B0B9B and BB09B are primes, we only need to consider the families B{0}999B and B{B}999B (since any digits combo 0B, B0 between (B,999B) will produce smaller primes)

******* The smallest prime of the form B{0}999B is B00999B, with 1765 0's, which can be written as B01765999B and equal the prime 11*12^1769+16967 (not minimal prime, since B00099B and B0000000000000000000000000009B are primes)

******* The smallest prime of the form B{B}999B is BBB999B, with 245 B's, which can be written as B244999B and equal the prime 12^248-3769 (not minimal prime, since BBBBBB99B is prime)

References

Main reference for this article: The mersenneforum thread https://mersenneforum.org/showthread.php?t=24972

Other references:

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[2] https://en.wikipedia.org/wiki/Minimal_prime_(recreational_mathematics) (article “minimal prime” in Wikipedia)

[3] https://www.primepuzzles.net/puzzles/puzz_178.htm (the puzzle of minimal primes (when the restriction of prime>base is not required) in The Prime Puzzles & Problems Connection)

[4] https://www.primepuzzles.net/problems/prob_083.htm (the problem of minimal primes in The Prime Puzzles & Problems Connection)

[5] https://github.com/xayahrainie4793/non-single-digit-primes (my data for these $M(L_b)$ sets for $2 \le b \le 16$)

[6] http://recursed.blogspot.com/2006/12/prime-game.html (Shallit’s The Prime Game page)

[7] http://www.cs.uwaterloo.ca/~shallit/Papers/minimal5.pdf (Shallit’s proof of base 10 minimal primes, when the restriction of prime>base is not required)

[8] https://archive.ph/lGZE1 (proofs of minimal primes in bases $b \le 10$, when the restriction of prime>base is not required, warning: the sets of $M(L_b)$ have errors for b = 8 and b = 10, b = 8 misses the prime 6101 and b = 10 missing the primes 9001 and 9049 and instead wrongly including the primes 90001, 90469, and 9000049, thus the correct values of $|M(L_b)|$ for b = 8 and b = 10 are 15 and 26 (instead of 14 and 27), respectively)

[9] https://cs.uwaterloo.ca/~cbright/reports/mepn.pdf (the article for this minimal prime problem in bases $b \le 30$, when the restriction of prime>base is not required)

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removed from the list of unsolved families, and we cannot definitely compute this part of the sets $M(L_b)$, search limits of lengths for the unsolved families (families for which not even a probable prime is known nor can be ruled out as only contain composites) in base *b*: 1000000 for *b* = 17, 707000 for *b* = 19, 506000 for *b* = 21, 292000 for *b* = 25, 486000 for *b* = 26, 368000 for *b* = 27, 543000 for *b* = 28, 233000 for *b* = 29)

[13] https://github.com/RaymondDevillers/primes (data for these $M(L_b)$ sets and unsolved families for 28 ≤ *b* ≤ 50, when the restriction of prime>base is not required, using lowercase letters a – n to represent digit values 36 to 49 for bases *b* > 36, file "kernel *b*" is the data of all known minimal primes or PRPs in base *b*, and file "left *b*" is the list of all unsolved families (families for which not even a probable prime is known nor can be ruled out as only contain composites) in base *b*, the format of the unsolved families is *x*{*y*}*z* for *xyyy*...*yyyz*, only bases *b* = 30 and *b* = 42 are completely solved, search limits of lengths for the unsolved families (families for which not even a probable prime is known nor can be ruled out as only contain composites) in base *b*: 10000 for all *b*)

[14] http://www.bitman.name/math/article/730 (article for minimal primes, when the restriction of prime>base is not required)

[15] http://www.bitman.name/math/table/497 (data for minimal primes in bases 2 ≤ *b* ≤ 16, when the restriction of prime>base is not required)

[16] https://oeis.org/A071071/a071071.pdf (research of minimal sets of powers of 2, when the restriction of >base is not required)

[17] http://nntdm.net/papers/nntdm-25/NNTDM-25-1-036-047.pdf (research of minimal set of totients+*n* for 0≤*n*≤5, when the restriction of >base is not required)

[18] http://www.prothsearch.com/sierp.html (the Sierpinski problem)

[19] http://www.prothsearch.com/rieselprob.html (the Riesel problem)

[20] http://www.primegrid.com/ (with projects for the Sierpinski problem, the Riesel problem, the Prime Sierpinski problem, the Extended Sierpinski problem, Sierpinski/Riesel base 5 problem, generalized Fermat prime search)

[21] http://www.prothsearch.com/ (lists for primes of the form $k*2^n+1$ for odd *k*<1200, also factoring status of generalized Fermat numbers of the form $a^{2^n} + b^{2^n}$ for 1≤*b*<*a*≤12)

[22] http://www.15k.org/ (lists for primes of the form $k*2^n-1$ for odd *k*<10000)

[23] https://www.rieselprime.de/default.htm (lists for primes of the form $k*2^n\pm1$)

[24] http://www.noprimeleftbehind.net/crus/Sierp-conjectures.htm (generalized Sierpinski conjectures in bases $b \le 1030$, some primes found in these conjectures are minimal primes in base b, especially, all primes for $k<b$ (if exist for a (k,b) combo) are always minimal primes in the base b) (also some examples for simple families contain no primes > b)

[25] http://www.noprimeleftbehind.net/crus/Riesel-conjectures.htm (generalized Riesel conjectures in bases $b \le 1030$, some primes found in these conjectures are minimal primes in base b, especially, all primes for $k<b$ (if exist for a (k,b) combo) are always minimal primes in the base b) (also some examples for simple families contain no primes > b)

[26] http://www.noprimeleftbehind.net/crus/tab/CRUS_tab.htm (list for the status of the generalized Sierpinski conjectures and the generalized Riesel conjectures in bases $b \le 1030$)

[27] https://www.utm.edu/staff/caldwell/preprints/2to100.pdf (article for generalized Sierpinski conjectures in bases $b \le 100$)

[28] https://oeis.org/A076336/a076336c.html (the dual Sierpinski problem)

[29] https://mersenneforum.org/showthread.php?t=10761 (list of large (probable) primes for the dual Sierpinski problem)

[30] http://www.kurims.kyoto-u.ac.jp/EMIS/journals/INTEGERS/papers/i61/i61.pdf (article for the mixed (original+dual) Sierpinski problem)

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[37] https://harvey563.tripod.com/wills.txt (primes of the form $(b-1)*b^n-1$ for bases $b\le2049$, the smallest such prime for base b (if exists) is always minimal prime in base b)

[38] https://www.rieselprime.de/ziki/Williams_prime_MM_least (the smallest primes of the form $(b-1)*b^n-1$ for bases $b\le2049$, these primes (if exists) is always minimal prime in base b)

[39] https://www.rieselprime.de/ziki/Williams_prime_MP_least (the smallest primes of the form $(b-1)*b^n+1$ for bases $b\le1024$, these primes (if exists) is always minimal prime in base b)

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[44] http://www.worldofnumbers.com/Appending%201s%20to%20n.txt (a problem related to this project)

[45] http://www.worldofnumbers.com/deplat.htm (list of plateau and depression primes)

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[53] http://jpenne.free.fr/index2.html (*llr* software)

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[58] https://oeis.org/wiki/User:Charles_R_Greathouse_IV/Tables_of_special_primes (expected number of primes in first *n* terms of a given sequence)

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[63] http://www.primenumbers.net/prptop/prptop.php (top PRPs)

[64] http://factordb.com (online factor database, including many primes which are minimal primes in a small base)

For list of more references, see
https://mersenneforum.org/showpost.php?p=571731&postcount=140 and
https://mersenneforum.org/showpost.php?p=582061&postcount=154

Also see https://primes.utm.edu/curios/includes/primetest.php?file=primetest.html and https://www.numberempire.com/primenumbers.php and https://www.bigprimes.net/primalitytest and http://www.proftnj.com/calcprem.htm and https://www.archimedes-lab.org/primOmatic.html and http://www.sonic.net/~undoc/java/PrimeCalc.html for links of prime checkers.

Also see https://www.numberempire.com/numberfactorizer.php and https://www.alpertron.com.ar/ECM.HTM and http://www.javascripter.net/math/calculators/primefactorscalculator.htm and https://primefan.tripod.com/Factorer.html and http://www.se16.info/js/factor.htm and http://math.fau.edu/Richman/mla/factor-f.htm for links of integer factorizers.

Also see https://primes.utm.edu/lists/small/1000.txt and https://primes.utm.edu/lists/small/millions/ and https://oeis.org/A000040/b000040_1.txt and https://oeis.org/A000040/a000040_1B.7z and http://www.primos.mat.br/indexen.html and https://www.walter-fendt.de/html5/men/primenumbers_en.htm and http://www.rsok.com/~jrm/printprimes.html for links of lists of small primes.

Also see https://baseconvert.com/ and https://www.calculand.com/unit-converter/zahlen.php for links of base converters.

(In fact, you can use Wolfram Alpha for prime checker, integer factorizer, and base converter, besides, many mathematical softwares also already have prime checkers, integer factorizers, and base converters, including *Maple*, *wolfram Mathematica*, *PARI/GP*, *Python*, *GMP*, *Magma*, *SageMath*, see the table below, you can download these softwares by clicking the links)

software	*Maple*	*Wolfram Mathematica*	*PARI/GP*	*Python*	*GMP*	*Magma*	*SageMath*
check if a number is probable prime		PrimeQ[*number*]	ispseudoprime(*number*)				
check if a number is proven prime		ProvablePrimeQ[*number*]	isprime(*number*)				
factor a number		FactorInteger[*number*]	factor(*number*)				
convert a number		BaseForm[*numbe*	digits(*number*,	int(*number*, *base*)			

to base *b*		*r*, *base*] IntegerDigits[*number*, *base*]	*base*)				

Finally, there is a C code for the problem in this article: (need run with *GMP*), see this forum post.