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

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* (this 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). For example, 514 is a subsequence of 352148. 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 substrings, and for a string with length *n* with no character 0, there are 2^n-n-1 substrings)

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 strings is finite. 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 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 strings with length ≥2 in decimal (proofs for that this set is infinite) and the set of square number 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, 500000000000000000000000000027}, and we will prove that this set is complete, and the research of this set in other bases is 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, 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 $2 \leq b \leq 36$. For example, it is not even known whether the non-simple family $3^m5^n8^r44$ 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.

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:

$sub(L) := \{x \in \Sigma^* :$ there exists $y \in L$ such that x is a subsequence of $y\}$;
$sup(L) := \{x \in \Sigma^* :$ there exists $y \in L$ 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 $\Sigma^* - sub(L) = sup(M(\Sigma^* - sub(L)))$, and the superword language of a finite language is regular, since $sup(\{w_1, ..., w_n\}) = \cup_{i=1}^{n} \Sigma^* w_{i,1} \Sigma^* \ldots \Sigma^* w_{i,|w_i|} \Sigma^*$ where $w_i = w_{i,1} \ldots w_{i,|w\_i|}$ with $w_{i,j} \in \Sigma$.

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 $2 \le b \le 16$. (Also, I left as a challenge to readers the task of computing $M(L_b)$ for $17 \le b \le 36$)

Notation

In what follows, if x is a string of symbols over the alphabet $\Sigma_b := \{0, 1, ..., b - 1\}$ we let $[x]_b$ denote the evaluation of x in the positional numeral system with base 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 $L^* := \cup_{i \ge 0} L^i$.

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, ...
12	11, 15, 17, 1B, 25, 27, 31, 35, 37, 3B, 45, 4B, 51, 57, 5B, 61, 67, 6B, 75, 81, 85, 87, 8B, 91, 95, A7, AB, B5, B7, 105, 107, 111, 117, 11B, 125, 12B, 131, 13B, 141, 145, 147, 157, 167, 16B, 171, 175, 17B, 181, 18B, 195, 19B, 1A5, 1A7, 1B1, 1B5, 1B7, 205, 217, 21B, 221, 225, 237, 241, 24B, 251, 255, 25B, 267, 271, 277, 27B, 285, 291, 295, 2A1, 2AB, 2B1, 2BB, 301, 307, 30B, 315, 321, 325, 327, 32B, 33B, 347, 34B, 357, 35B, 365, 375, 377, 391, 397, 3A5, 3AB, 3B5, 3B7, ...
13	14, 16, 1A, 23, 25, 2B, 32, 34, 38, 41, 47, 49, 52, 56, 58, 61, 65, 6B, 76, 7A, 7C, 83, 85, 89, 9A, A1, A7, A9, B6, B8, C1, C7, CB, 104, 10A, 10C, 119, 11B, 122, 124, 133, 142, 146, 148, 14C, 155, 157, 164, 16A, 173, 179, 17B, 184, 188, 18A, 197, 1A8, 1AC, 1B1, 1B5, 1C6, 1CC, 209, 20B, 212, 218, 223, 229, 232, 236, 23C, 247, 24B, 256, 263, 265, 272, 274, 27A, 281, 287, 292, 296, 298, 29C, 2AB, 2B6, 2BA, 2C5, 2C9, 302, 311, 313, 328, 331, 33B, 344, 34A, 34C, 355, ...
14	13, 15, 19, 21, 23, 29, 2D, 31, 35, 3B, 43, 45, 4B, 51, 53, 59, 5D, 65, 6D, 73, 75, 79, 7B, 81, 91, 95, 9B, 9D, A9, AB, B3, B9, BD, C5, CB, CD, D9, DB, 101, 103, 111, 11D, 123, 125, 129, 131, 133, 13D, 145, 14B, 153, 155, 15B, 161, 163, 16D, 17D, 183, 185, 189, 199, 1A1, 1AB, 1AD, 1B3, 1B9, 1C3, 1C9, 1D1, 1D5, 1DB, 205, 209, 213, 21D, 221, 22B, 22D, 235, 239, 241, 249, 24D, 251, 255, 263, 26B, 271, 279, 27D, 285, 293, 295, 2A9, 2B1, 2BB, 2C3, 2C9, 2CB, 2D3, ...
15	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, 102, 104, 108, 10E, 111, 11B, 122, 128, 12E, 131, 137, 13B, 13D, 148, 157, 15B, 15D, 162, 171, 177, 182, 184, 188, 18E, 197, 19D, 1A4, 1A8, 1AE, 1B7, 1BB, 1C4, 1CE, 1D1, 1DB, 1DD, 1E4, 1E8, 1EE, 207, 20B, 20D, 212, 21E, 227, 22B, 234, 238, 23E, 24B, 24D, 261, 267, 272, 278, 27E, 281, 287, ...
16	11, 13, 17, 1D, 1F, 25, 29, 2B, 2F, 35, 3B, 3D, 43, 47, 49, 4F, 53, 59, 61, 65,

	67, 6B, 6D, 71, 7F, 83, 89, 8B, 95, 97, 9D, A3, A7, AD, B3, B5, BF, C1, C5, C7, D3, DF, E3, E5, E9, EF, F1, FB, 101, 107, 10D, 10F, 115, 119, 11B, 125, 133, 137, 139, 13D, 14B, 151, 15B, 15D, 161, 167, 16F, 175, 17B, 17F, 185, 18D, 191, 199, 1A3, 1A5, 1AF, 1B1, 1B7, 1BB, 1C1, 1C9, 1CD, 1CF, 1D3, 1DF, 1E7, 1EB, 1F3, 1F7, 1FD, 209, 20B, 21D, 223, 22D, 233, 239, 23B, 241, ...
17	12, 16, 1C, 1E, 23, 27, 29, 2D, 32, 38, 3A, 3G, 43, 45, 4B, 4F, 54, 5C, 5G, 61, 65, 67, 6B, 78, 7C, 81, 83, 8D, 8F, 94, 9A, 9E, A3, A9, AB, B4, B6, BA, BC, C7, D2, D6, D8, DC, E1, E3, ED, F2, F8, FE, FG, G5, G9, GB, 104, 111, 115, 117, 11B, 128, 12E, 137, 139, 13D, 142, 14A, 14G, 155, 159, 15F, 166, 16A, 171, 17B, 17D, 186, 188, 18E, 191, 197, 19F, 1A2, 1A4, 1A8, 1B3, 1BB, 1BF, 1C6, 1CA, 1CG, 1DB, 1DD, 1EE, 1F3, 1FD, 1G2, 1G8, 1GA, 1GG, 209, ...
18	11, 15, 1B, 1D, 21, 25, 27, 2B, 2H, 35, 37, 3D, 3H, 41, 47, 4B, 4H, 57, 5B, 5D, 5H, 61, 65, 71, 75, 7B, 7D, 85, 87, 8D, 91, 95, 9B, 9H, A1, AB, AD, AH, B1, BD, C7, CB, CD, CH, D5, D7, DH, E5, EB, EH, F1, F7, FB, FD, G5, H1, H5, H7, HB, 107, 10D, 115, 117, 11B, 11H, 127, 12D, 131, 135, 13B, 141, 145, 14D, 155, 157, 15H, 161, 167, 16B, 16H, 177, 17B, 17D, 17H, 18B, 191, 195, 19D, 19H, 1A5, 1AH, 1B1, 1C1, 1C7, 1CH, 1D5, 1DB, 1DD, 1E1, 1EB, ...
19	14, 1A, 1C, 1I, 23, 25, 29, 2F, 32, 34, 3A, 3E, 3G, 43, 47, 4D, 52, 56, 58, 5C, 5E, 5I, 6D, 6H, 74, 76, 7G, 7I, 85, 8B, 8F, 92, 98, 9A, A1, A3, A7, A9, B2, BE, BI, C1, C5, CB, CD, D4, DA, DG, E3, E5, EB, EF, EH, F8, G3, G7, G9, GD, H8, HE, I5, I7, IB, IH, 106, 10C, 10I, 113, 119, 11H, 122, 12A, 131, 133, 13D, 13F, 142, 146, 14C, 151, 155, 157, 15B, 164, 16C, 16G, 175, 179, 17F, 188, 18A, 199, 19F, 1A6, 1AC, 1AI, 1B1, 1B7, 1BH, 1C4, ...
20	13, 19, 1B, 1H, 21, 23, 27, 2D, 2J, 31, 37, 3B, 3D, 3J, 43, 49, 4H, 51, 53, 57, 59, 5D, 67, 6B, 6H, 6J, 79, 7B, 7H, 83, 87, 8D, 8J, 91, 9B, 9D, 9H, 9J, AB, B3, B7, B9, BD, BJ, C1, CB, CH, D3, D9, DB, DH, E1, E3, ED, F7, FB, FD, FH, GB, GH, H7, H9, HD, HJ, I7, ID, IJ, J3, J9, JH, 101, 109, 10J, 111, 11B, 11D, 11J, 123, 129, 12H, 131, 133, 137, 13J, 147, 14B, 14J, 153, 159, 161, 163, 171, 177, 17H, 183, 189, 18B, 18H, 197, 19D, ...
21	12, 18, 1A, 1G, 1K, 21, 25, 2B, 2H, 2J, 34, 38, 3A, 3G, 3K, 45, 4D, 4H, 4J, 52, 54, 58, 61, 65, 6B, 6D, 72, 74, 7A, 7G, 7K, 85, 8B, 8D, 92, 94, 98, 9A, A1, AD, AH, AJ, B2, B8, BA, BK, C5, CB, CH, CJ, D4, D8, DA, DK, ED, EH, EJ, F2, FG, G1, GB, GD, GH, H2, HA, HG, I1, I5, IB, IJ, J2, JA, JK, K1, KB, KD, KJ, 102, 108, 10G, 10K, 111, 115, 11H, 124, 128, 12G, 12K, 135, 13H, 13J, 14G, 151, 15B, 15H, 162, 164, 16A, 16K, 175, ...
22	11, 17, 19, 1F, 1J, 1L, 23, 29, 2F, 2H, 31, 35, 37, 3D, 3H, 41, 49, 4D, 4F, 4J, 4L, 53, 5H, 5L, 65, 67, 6H, 6J, 73, 79, 7D, 7J, 83, 85, 8F, 8H, 8L, 91, 9D, A3, A7, A9, AD, AJ, AL, B9, BF, BL, C5, C7, CD, CH, CJ, D7, DL, E3, E5, E9, F1, F7, FH, FJ, G1, G7, GF, GL, H5, H9, HF, I1, I5, ID, J1, J3, JD, JF, JL, K3, K9, KH, KL, L1, L5, LH, 103, 107, 10F, 10J, 113, 11F, 11H, 12D, 12J, 137, 13D, 13J, 13L, 145, 14F, 14L, ...
23	16, 18, 1E, 1I, 1K, 21, 27, 2D, 2F, 2L, 32, 34, 3A, 3E, 3K, 45, 49, 4B, 4F, 4H, 4L, 5C, 5G, 5M, 61, 6B, 6D, 6J, 72, 76, 7C, 7I, 7K, 87, 89, 8D, 8F, 94, 9G, 9K, 9M, A3, A9, AB, AL, B4, BA, BG, BI, C1, C5, C7, CH, D8, DC, DE, DI, E9, EF, F2, F4, F8, FE, FM, G5, GB, GF, GL, H6, HA, HI, I5, I7, IH, IJ, J2, J6, JC, JK, K1, K3, K7, KJ, L4, L8, LG, LK, M3, MF, MH, 10C, 10I, 115, 11B, 11H, 11J, 122, 12C, 12I, 131, ...

24	15, 17, 1D, 1H, 1J, 1N, 25, 2B, 2D, 2J, 2N, 31, 37, 3B, 3H, 41, 45, 47, 4B, 4D, 4H, 57, 5B, 5H, 5J, 65, 67, 6D, 6J, 6N, 75, 7B, 7D, 7N, 81, 85, 87, 8J, 97, 9B, 9D, 9H, 9N, A1, AB, AH, AN, B5, B7, BD, BH, BJ, C5, CJ, CN, D1, D5, DJ, E1, EB, ED, EH, EN, F7, FD, FJ, FN, G5, GD, GH, H1, HB, HD, HN, I1, I7, IB, IH, J1, J5, J7, JB, JN, K7, KB, KJ, KN, L5, LH, LJ, MD, MJ, N5, NB, NH, NJ, 101, 10B, 10H, 10N, ...
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, ...
27	12, 14, 1A, 1E, 1G, 1K, 1Q, 25, 27, 2D, 2H, 2J, 2P, 32, 38, 3G, 3K, 3M, 3Q, 41, 45, 4J, 4N, 52, 54, 5E, 5G, 5M, 61, 65, 6B, 6H, 6J, 72, 74, 78, 7A, 7M, 87, 8B, 8D, 8H, 8N, 8P, 98, 9E, 9K, 9Q, A1, A7, AB, AD, AN, BA, BE, BG, BK, C7, CD, CN, CP, D2, D8, DG, DM, E1, E5, EB, EJ, EN, F4, FE, FG, FQ, G1, G7, GB, GH, GP, H2, H4, H8, HK, I1, I5, ID, IH, IN, J8, JA, K1, K7, KH, KN, L2, L4, LA, LK, LQ, M5, ...
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, ...
30	11, 17, 1B, 1D, 1H, 1N, 1T, 21, 27, 2B, 2D, 2J, 2N, 2T, 37, 3B, 3D, 3H, 3J, 3N, 47, 4B, 4H, 4J, 4T, 51, 57, 5D, 5H, 5N, 5T, 61, 6B, 6D, 6H, 6J, 71, 7D, 7H, 7J, 7N, 7T, 81, 8B, 8H, 8N, 8T, 91, 97, 9B, 9D, 9N, A7, AB, AD, AH, B1, B7, BH, BJ, BN, BT, C7, CD, CJ, CN, CT, D7, DB, DJ, DT, E1, EB, ED, EJ, EN, ET, F7, FB, FD, FH, FT, G7, GB, GJ, GN, GT, HB, HD, I1, I7, IH, IN, IT, J1, J7, JH, JN, JT, K1, ...
31	16, 1A, 1C, 1G, 1M, 1S, 1U, 25, 29, 2B, 2H, 2L, 2R, 34, 38, 3A, 3E, 3G, 3K, 43, 47, 4D, 4F, 4P, 4R, 52, 58, 5C, 5I, 5O, 5Q, 65, 67, 6B, 6D, 6P, 76, 7A, 7C, 7G, 7M, 7O, 83, 89, 8F, 8L, 8N, 8T, 92, 94, 9E, 9S, A1, A3, A7, AL, AR, B6, B8, BC, BI, BQ, C1, C7, CB, CH, CP, CT, D6, DG, DI, DS, DU, E5, E9, EF, EN, ER, ET, F2, FE, FM, FQ, G3, G7, GD, GP, GR, HE, HK, HU, I5, IB, ID, IJ, IT, J4, JA, JC, JI, ...

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, this problem is an extension of the original minimal prime problem to include CRUS 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, in fact, to include these conjectures, we only need to exclude the single-digit primes (i.e. the primes < *b*), 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, thus, we also exclude the prime = *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, 500000000000000000000000000027}, 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}).

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, ..., 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 $10^{490000} + 3*(10^{7383} - 1)/9 * 10^{241309} + 1$, this number has 490001 digits, can also be written as $10^{241308}3^{7383}0^{241308}1$, 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, 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

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	$\lvert M(L_b)\rvert$	$max(x, x \in M(L_b))$	$max(\lvert x\rvert, x \in M(L_b))$	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
7①	≥71	$3^{16}1$	17	$\frac{7^{17}-5}{2}$
8	75	$4^{220}7$	221	$\frac{4 \cdot 8^{221}+17}{7}$
9①	≥149	$30^{1158}11$	1161	$3 \cdot 9^{1160}+10$
10	77	$50^{28}27$	31	$5 \cdot 10^{30}+27$
11①	≥914	557^{1011} or 57^n with n>50000	1013	$\frac{607 \cdot 11^{1011}-7}{10}$
12	106	$40^{39}77$	42	$4 \cdot 12^{41}+91$

13①②	≥2492	$80^{32017}111$ or 95^n with n>50000 or $A3^nA$ with n>50000	32021	$8\cdot13^{32020}+183$
14①	≥605	$4D^{19698}$	19699	$5\cdot14^{19698}-1$
15①	≥1171	$7^{155}97$	157	$\frac{15^{157}+59}{2}$
16①②	≥2050	DB^{32234}	32235	$\frac{206\cdot16^{32234}-1}{15}$

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.

Lists

The sets of bases 14, 16, and the odd bases >6 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.

There are five unsolved families found by me and searched to length 50000 with no (probable) prime found, they are 57^n in base 11, 95^n in base 13, $A3^nA$ in base 13, 3^nAF in base 16, and 4^nDD in base 16.

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,

1000000000000000000000000000000000000000000000000000000000000000000000000
00000000000000000000013

base 6

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

base 7 (not proved, only checked to the prime 5100000001)

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,
4444444444444444444444444444444444444444444444444444444444444444444444444
4444444444444444444444444444444444444444444444444444444444444444444444444
4444444444444444444444444444444444444444444444444444444444444444444444444
47

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, ..., 8888888888888888888335, ..., 30000000000000000000051, ..., 1000000000000000000000000057, ..., 56111111111111111111111111111111111111, ...,
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base 11 (not proved, only checked to the prime 1500000001)

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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)

14, 16, 1A, 23, 25, 2B, 32, 34, 38, 41, 47, 49, 52, 56, 58, 61, 65, 6B, 76, 7A, 7C, 83, 85, 89, 9A, A1, A7, A9, B6, B8, C1, C7, CB, 10C, 119, 11B, 122, 133, 155, 157, 173, 179, 17B, 188, 197, 1B1, 1B5, 1CC, 209, 212, 218, 229, 272, 274, 281, 287, 292, 296, 298, 29C, 2C9, 311, 313, 331, 33B, 355, 371, 373, 379, 397, 3A6, 3AA, 3B3, 3B9, 3BB, 3CA, 43C, 445, 44B, 45A, 463, 4A3, 4A5, 4B2, 4B4, 4BA, 50C, 511, 515, 533, 54A, 551, 559, 571, 575, 57B, 595, 599, 5B3, 5B9, 5CC, 607, 629, 63A, 643, 674, 704, 715, 724, 728, 731, 737, 739, 742, 751, 75B, 773, 775, 779, 782, 784, 791, 793, 797, 7B1, 812, 818, 874, 878, 8AB, 8B4, 902, 919, 922, 926, 92C, 937, 93B, 946, 95B, 962, 968, 971, 977, 979, 982, 98C, 9B3, 9B5, A03, A3C, A45, A4B, A54, AA3, AAB, B02, B0C, B11, B15, B17, B24, B33, B39, B42, B57, B59, B71, B93, B9B, BA4, BAA, BB1, BB9, BC2, BCC, C29, C43, C98, CA3, 1013, 1031, 1037, 105B, 1075, 10B7, 10BB, 1105, 1112, 1121, 1127, 113C, 1172, 1187, 1208, 1211, 1277, 12C8, 1307, 1309, 131C, 139C, 151C, 1721, 1727, 1787, 1901, 1909, 1912, 1918, 193C, 1981, 198B, 199C, 19B2, 19C3, 1B29, 1BB2, 1BBC, 1C28, 1C39, 2021, 2078, 2117, 2201, 2221, 2267, 2278, 2627, 2678, 2711, 2771, 2788, 3037, 3053, 306A, 3077, 3091, 309B, 30AC, 3305, 353C, 35AB, 35BA, 35BC, 3677, 3905, 390B, 39C5, 3A0C, 3AB5, 3B5C, 3C35, 3C59, 3C95, 403A, 40AB, 4333, 435B, 4403, 44C3, 4535, 4544, 454C, 45B5, 45BB, 480B, 4B35, 4B5B, 4C36, 5057, 5077, 509B, 50A4, 5107, 5305, 530B, 539C, 53AB, 53C9, 5444, 5455, 54C4, 5503, 5545, 55AB, 5774, 5794, 590B, 594B, 5974, 59B4, 5A4C, 5A53, 5AA4, 5AB5, 5ABB, 5ACA, 5B4B, 5B5A, 5BA5, 5CA4, 6227, 6278, 6667, 6698, 6733, 6872, 6928, 6944, 694C, 6973, 6986, 6997, 69C8, 6AC3, 6C92, 6C94, 7019, 7057, 70B5, 7103, 710B, 7118, 7127, 7129, 7172, 7178, 7192, 7211, 7217, 7219, 7271, 7303, 7408, 7433, 7444, 7505, 7507, 7574, 770B, 7774, 7778, 7787, 7871, 7877, 7888, 794B, 7994, 79B4, 7B43, 7B74, 7B94, 7BB2, 8027, 8072, 8081, 80BA, 8171, 8207, 821C, 848B, 8687, 8711, 8722, 87BB, 8867, 88B2, 88BA, 8B22, 8B2A, 8BAC, 9004, 9017, 9031, 9053, 9055, 9073, 9091, 90BB, 90C8, 9107, 9118, 913C, 9181, 91C3, 9284, 935C, 93C5, 9424, 9428, 9448, 9509, 959C, 96C4, 9703, 9743, 9745, 974B, 97B2, 9811, 981B, 987B, 98B1, 991C, 9967, 9998, 9B12, 9B74, 9B92, 9BBC, 9C55, 9C86, 9CC4, A0BA, A306, A436, A535, A5B5, A636, A6C3, A80B, AB04, AB22, AB35, AB3B, AB4C, AB55, ABAC, ABB5, AC36, ACA5, B044, B04A, B0B7, B129, B1B2, B219, B222, B291, B299, B2CA, B35A, B3A5, B404, B44C, B45B, B4B3, B501, B51C, B55A, B5A5, B5AB, B5C3, B707, B792, B794, B905, B912, B9C5, BA5B, BAB3, BB03, BB45, BB72, BBA5, BBB2, BC44, BC53, BC95, BC99, C30A, C36A, C395, C454, C535, C553, C593, C944, C953, C964, CC94, 10015, 10051, 10099, 10118, 10291, 10712, 10772, 10811, 10877, 10921, 10B92, 11111, 11135, 11171, 111C8, 11531, 11C03, 13001, 13177, 13777, 13915, 13951, 13991, 159BB, 17018, 17102, 17111, 17117, 17171, 17177, 17708, 17711, 17801, 18071, 18101, 18271, 18B27, 19003, 19153, 19315, 19351, 19591, 19913, 19951, 1C099, 20171, 20177, 20207, 20227, 20777, 21011, 21077, 2111C, 21707, 22207, 30017, 300B5, 301C9, 3033A, 303A3, 303C5, 3050B, 305C9, 3095C, 30B05, 31007, 3159B, 31999, 31C09, 3330A, 33353, 33593, 33757, 33C5C, 33CC5, 35003, 3591B, 39353, 39539, 39935, 39995, 3ACCC, 3C5C3, 3CC53, 40043, 40306, 405C4, 408BC, 40BBB, 40C54, 43066, 4366A, 4443A, 45055, 45505, 45554, 4555C, 455BC, 455C3, 45C04, 488BC, 4B03B, 4B0B5, 4B55C, 4BB0B, 4C003, 4C054, 4C5C4, 50053, 500B1, 5035A, 504B5, 5053A, 50554, 505B4, 50A35, 50B07, 50BBA, 5139B, 519BB,

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base 14 (not proved, only checked to the prime 108000000D)

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

11, 13, 17, 1D, 1F, 25, 29, 2B, 2F, 35, 3B, 3D, 43, 47, 49, 4F, 53, 59, 61, 65, 67, 6B, 6D, 71, 7F, 83, 89, 8B, 95, 97, 9D, A3, A7, AD, B3, B5, BF, C1, C5, C7, D3, DF, E3, E5, E9, EF, F1, FB, 14B, 15B, 185, 199, 1A5, 1BB, 1C9, 1EB, 223, 22D, 233, 241, 277, 281, 287, 28D, 2A1, 2D7, 2DD, 2E7, 301, 337, 373, 377, 38F, 3A1, 3A9, 41B, 42D, 445, 455, 45D, 481, 4B1, 4BD, 4CD, 4D5, 4E1, 4EB, 50B, 515, 51B, 527, 551, 557, 55D, 577, 581, 58F, 5AB, 5CB, 5CF, 5D1, 5D5, 5DB, 5E7, 623, 709, 727, 737, 745, 74B, 755, 757, 773, 779, 78D, 7BB, 7C3, 7C9, 7CD, 7DB, 7EB, 7ED, 805, 80F, 815, 821, 827, 841, 851, 85D, 85F, 8A5, 8DD, 8E1, 8F5, 923, 98F, 99B, 9A9, 9EB, A21, A6F, A81, A85, A99, A9F, AA9, AAB, ACF, B1B, B2D, B7B, B8D, B99, B9B, BB7, BB9, BCB, BDD, BE1, C0B, CB9, CBB, CEB, D01, D21, D2D, D55, D69, D79, D81, D85, D87, D8D, DAB, DB7, DBD, DC9, DCD, DD5, DDB, DE7, E21, E27, E4B, E7D, E87, EB1, EB7, ED1, EDB, EED, F07, F0D, F4D, FD9, FFD, 1069, 1505, 1609, 1669, 16A9, 19AB, 1A69, 1AB9, 2027, 204D, 2063, 207D, 20C3, 20ED, 2221, 22E1, 2327, 244D, 26C3, 274D, 2E01, 2E0D, 2ECD, 3023, 3079, 3109, 3263, 3341, 36AF, 3941, 3991, 39AF, 3E41, 3E81, 3EE1, 3EE7, 3F79, 4021, 40DB, 440B, 444B, 44A1, 44AB, 44DB, 4541, 45BB, 4A41, 4B0B, 4BBB, 4C4B, 4D41, 4DED, 5045, 50A1, 50ED, 540D, 5441, 555B, 556F, 5585, 560F, 56FF, 5705, 574D, 580D, 582D, 5855, 588D, 5A01, 5AA1, 5B01, 5B4B, 5B87, 5BB1, 5BEB, 5C4D, 5CDD, 5CED, 5DD7, 5DDD, 5E0D, 5E2D, 5EBB, 68FF, 6A69, 6AC9, 6C8F, 6CA9, 6CAF, 6F8F, 6FAF, 7033, 7063, 7075, 7087, 70A5, 70AB, 7303, 7393, 74DD, 754D, 7603, 7633, 7663, 7669, 7705, 772D, 775D, 77D5, 7807, 7877, 7885, 7939, 7969, 7993, 79AB, 7A05, 7A69, 7A9B, 7AA5, 7B77, 7BA9, 7D4D, 7D75, 7D77, 8077, 808D, 80D7, 80E7, 8587, 86CF, 8777, 8785, 8885, 88CF, 88ED, 88FD, 8C6F, 8C8F, 8E8D, 8EE7, 8F2D, 8F8D, 9031, 9041, 90AF, 90B9, 9221, 9319, 9401, 944B, 9881, 9931, 9941, 9991, 99AF, 9A0F, 9A1B, 9A4B, 9AFF, 9BA1, 9BB1, 9CAF, 9E81, 9EA1, 9FAF, A001, A05B, A0C9, A105, A10B, A4CB, A55B, A6C9, A88F, A91B, A9B1, A9BB, AA15, AB01, AB0B, AB19, ABBB, AC09, AF09, B041, B04B, B069, B07D, B087, B0B1, B0ED, B1A9, B201, B40B, B40D, B609, B70D, B7A9, B807, B9A1, BA41, BAA1, BB4B, BBB1, BBDB, BBED, BD19, BD41, BDBB, BDEB, BE07, BEE7, C0D9, C203, C24D, C6A9, C88D, C88F, C8CF, C8ED, C9AF, C9CB, CA09, CA4B, CA69, CAC9, CC0D, CC23, CC4D, CC9B, CD09, CDD9, CE4D, CEDD, CFA9, CFCD, D04B, D099, D405, D415, D44B, D4A5, D4DD, D50D, D70B, D74D, D77B, D7CB, D91B, D991, DA05, DA09, DA15, DA51, DB91, DBEB, DD7D, DDA1, DDED, DE0B, DE41, DE4D, DEA1, E02D, E07B, E0D7, E1CB, E2CD, E401, E801, EABB, EACB, EAEB, EBAB, EC4D, ECDD, ED07, EDD7, EE7B, EE81, EEAB, EEE1, F08F, F0A9, F227, F2ED, F3AF, F485, F58D, F72D, F763, F769, F787, F7A5, F7E7, F82D, F86F, F877, F88D, F8D7, F8E7, F8FF, FCCD, FED7, FF85, FF8F, FFA9, 100AB, 10BA9, 1A0CB, 1BA09, 200E1, 2C603, 2CC03, 30227, 303AF, 30AAF, 32003, 32207, 32CC3, 330AF, 33169, 33221, 33391, 33881, 33AFF, 38807, 38887, 3AFFF, 3F203, 3F887, 3FAFF, 400BB, 4084D, 40A4B, 42001, 44221, 44401, 444D1, 4480D, 4488D, 44CCB, 44D4D, 44E8D, 4804D, 4840D, 4A0CB, 4A54B, 4CACB, 4D0DD, 4D40D, 4D44D, 5004D, 50075, 502CD, 5044D, 50887, 50EE1, 5448D, 548ED, 55A45, 55F45, 5844D, 5A4A5, 5AE41, 5B0CD, 5B44D, 5BBCD, 5D4ED, 5E0E1, 5EB4D, 5EC8D, 5ECCD, 5EE41, 5F06F, 5F7DD, 5F885, 5F8CD, 5FC8D, 5FF75, 6088F, 60AFF, 630AF, 633AF, 660A9, 668CF, 669AF, 66A09, 66A0F, 66FA9, 6886F, 6A00F, 6A0FF, 6A8AF, 6AFFF, 7002D, 7024D, 70B0D, 70B7D, 7200D, 73363, 73999, 7444D, 770B7, 777D7, 77B07, 77D7D, 77DD7, 79003, 79999, 7B00D, 7D05D, 7D7DD, 8007D, 800D1, 8074D, 82CCD, 82E4D, 8448D, 8484D,

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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 some 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≥2 for 1^n in base 9, n≥0 for 10^n1 in base 8 and $B4^n1$ in base 16, n≥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≥0 for B^n9B in base 12, n≥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 $L = \emptyset$ 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 $\emptyset$)

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 $\cup_{x,z} \quad (xY \quad ^*z)$ 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 := $\cup_{x,z\in\sum b} \quad (xY \quad ^*z)$
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 there is no obvious reason why there can't be a prime, since by the prime number theorem, the chance that a random n-digit number is prime is approximately $1/n$. If one conjectures the numbers $xy*z$ behave similarly you would expect $\sum_{n=2}^{\infty} \frac{1}{n} = \infty$ 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 integers a, b, c where $a \geq 1$, $b \geq 2$ (b is the base), $c \neq 0$, $gcd(a,c)=1$, $gcd(b,c)=1$, 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). 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 $b \leq 128$ and primes $p \leq 4096$, list of primes p such that the multiplicative order of b mod p is n for $2 \leq b \leq 64$ and $1 \leq n \leq 64$, smallest prime p such that znorder(Mod(m,p)) = ($p-1$)/n for $2 \leq m \leq 128$ and $1 \leq n \leq 128$, 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 $b^n \pm 1$ (which is equivalent to factorization of $Zs(n,b,1)$) with $b \leq 12$ $13 \leq b \leq 99$ $b=10$ any b any b.

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), $c \neq 0$, $gcd(a,c)=1$, $gcd(b,c)=1$. Except in the special case $c = \pm 1$ and $gcd(a+c,b-1) = 1$, when n is large the known primality tests for such a number are too inefficient to run. In this case one must resort to a probable primality test such as a Miller–Rabin test or a Baillie–PSW test, unless a divisor of the number can be found. 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.

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 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.

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 **100000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000013**, 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.

* 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 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 4444444444444446411 (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
4444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444444447, 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
4477777777777777777777777777777777777777777777777777777777777777777777777777777
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7777777777777777777777777777777777777777777, 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 5555555555555555555555555555555555555555555555555555555555555555555555555555555
5555555555555555555555555555555555555555555555555555555555555555555555555555555
5555555555555555555550025 (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 7777777777

***** The smallest prime of the form 7{7}4441 is 7777777777

* 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 8555555555555555555551 (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 **4000000000000000000000000000000000000000077**

* 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 B0AAAAA1 (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 **B00000000000000000000000000009B**

******* 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
B0000000000000000000000000000000000000000000000000000000000000000000000000000
0000000000000000000000000000000000000000000000000000000000000000000000000000
0000000000000000000000000000000000000000000000000000000000000000000000000000
0000000000000000000000000000000000000000000000000000000000000000000000000000
0000000000000000000000000000000000000000000000000000000000000000000000000000
0000000000000000000000000000000000000000000000000000000000000000000000000000
0000000000000000000000000000000000000000000000000000000000000000000000000000
0000000000000000000000000000000000000000000000000000000000000000000000000000
0000000000000000000000000000000000000000000000000000000000000000000000000000
0000000000000000000000000000000000000000000000000000000000000000000000000000
0000000000000000000000000000000000000000000000000000000000000000000000000000
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0000000000000000000000000000000000000000000000000000000000000000000000000000
0000000000000000000000000000000000000000000000000000000000000000000000000000

0000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
0000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
0000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
0000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
0000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
0000000000000000000000000000000000000000000000000000000000000000000000000000000000000000
0000000000000000000000000000000000000000000000000000000000000000000000000000000000000999B (not minimal prime, since B00099B and B00000000000000000000000000009B are primes)

******* The smallest prime of the form B{B}999B is
BBBB

[10] https://cs.uwaterloo.ca/~cbright/talks/minimal-slides.pdf (the article for this minimal prime problem in bases b≤30, when the restriction of prime>base is not required)

[11] https://doi.org/10.1080/10586458.2015.1064048 (the article for this minimal prime problem in bases b≤30, when the restriction of prime>base is not required) (need access)

[12] https://github.com/curtisbright/mepn-data (data for these $M(L_b)$ sets and unsolved families for $2 \le b \le 30$, when the restriction of prime>base is not required, search limits of lengths: 1000000 for b=17, 707000 for b=19, 506000 for b=21, 292000 for b=25, 486000 for b=26, 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 $2 \le b \le 50$, when the restriction of prime>base is not required, search limits of lengths: 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 $2 \le b \le 16$, 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 $0 \le n \le 5$, 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 $1 \le b < a \le 12$)

[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 $k*2^n \pm 1$)

[24] http://www.noprimeleftbehind.net/crus/Sierp-conjectures.htm (generalized Sierpinski conjectures in bases b≤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≤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≤1030)

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

[31] https://mersenneforum.org/showthread.php?t=6545 (research for the mixed (original+dual) Riesel problem)

[32] https://mersenneforum.org/showthread.php?t=26328 (research for the mixed (original+dual) Sierpinski base 5 problem)

[33] http://www.fermatquotient.com/ (generalized repunit primes (primes of the form $(b^n-1)/(b-1)$) in bases b≤160, the smallest such prime for base b (if exists) is always minimal prime in base b, also list of generalized half Fermat primes (primes of the form $(b^{2^n}+1)/2$) sorted by n, the smallest such prime for base b (if exists) is always minimal prime in base b)

[34] https://web.archive.org/web/20021111141203/http://www.users.globalnet.co.uk/~aads/primes.html (generalized repunit primes (primes of the form $(b^n-1)/(b-1)$) in bases b≤1000, the smallest such prime for base b (if exists) is always minimal prime in base b)

[35] http://jeppesn.dk/generalized-fermat.html (generalized Fermat primes (primes of the form $b^{2^n}+1$) in even bases b≤1000, the smallest such prime for base b (if exists) is always minimal prime in base b)

[36] http://www.noprimeleftbehind.net/crus/GFN-primes.htm (generalized Fermat primes (primes of the form $b^{2^n}+1$) in even bases b≤1030, the smallest such prime for base b (if exists) is always minimal prime in base b)

[37] https://harvey563.tripod.com/wills.txt (primes of the form $(b-1)*b^n-1$ for bases b≤2049, 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 $b\leq 2049$, 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 $b\leq 1024$, these primes (if exists) is always minimal prime in base b)

[40] https://www.rieselprime.de/ziki/Riesel_prime_small_bases_least_n (the smallest primes of the form $k*b^n-1$ for $k\leq 12$ and bases $b\leq 1024$, these primes (if exists) is always minimal prime in base b if $b>k$)

[41] https://www.rieselprime.de/ziki/Proth_prime_small_bases_least_n (the smallest primes of the form $k*b^n+1$ for $k\leq 12$ and bases $b\leq 1024$, these primes (if exists) is always minimal prime in base b if $b>k$)

[42] https://docs.google.com/spreadsheets/d/e/2PACX-1vTKkSNKGVQkUINlp1B3cXe90FWPwiegdA07EE7-U7sqXntKAEQrynoI1sbFvvKriieda3LfkqRwmKME/pubhtml (my list for the smallest primes in given simple family in bases $b\leq 1024$)

[43] https://www.rose-hulman.edu/~rickert/Compositeseq (a problem related to this project)

[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)

[46] http://www.worldofnumbers.com/wing.htm (list of palindromic wing primes)

[47] https://stdkmd.net/nrr/prime/primecount.txt (near- and quasi- repdigit (probable) primes sorted by count)

[48] https://stdkmd.net/nrr/prime/primedifficulty.txt (near- and quasi- repdigit (probable) primes sorted by difficulty)

[49] https://stdkmd.net/nrr/coveringset.htm (covering set of near-repdigit-related sequences)

[50] http://www.rieselprime.de/dl/CRUS_pack.zip (*srsieve*, *sr1sieve*, *sr2sieve*, *pfgw*, and *llr* softwares)

[51] https://www.bc-team.org/app.php/dlext/?cat=3 (*srsieve*, *sr1sieve*, *sr2sieve*, *sr5sieve* software)

[52] https://sourceforge.net/projects/openpfgw/ (*pfgw* software)

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

[54] http://www.ellipsa.eu/public/primo/primo.html (*PRIMO* software)

[55] https://primes.utm.edu/prove/index.html (website for primality proving)

[56] https://www.rieselprime.de/ziki/Primality_test (list of known primality tests and probable primality tests)

[57] https://primes.utm.edu/notes/prp_prob.html (the probability that a random PRP is composite)

[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)

[59] https://primes.utm.edu/curios/page.php?number_id=22380 (the largest base 10 minimal prime in Prime Curios!)

[60] https://oeis.org/A071062 (OEIS sequence for base 10 minimal primes, when the restriction of prime>base is not required)

[61] https://oeis.org/A326609 (OEIS sequence for the largest base *b* minimal prime, when the restriction of prime>base is not required)

[62] https://primes.utm.edu/primes/lists/all.txt (top proven primes)

[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)