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On primitive roots

Baum [2] has given useful criteria for certain primitive roots. Wilansky [6] pointed out that these results can be obtained without use of quadratic reciprocity. The purpose of this note is to derive their theorems and to obtain some more results with a quite simple counting method. We shall deal with odd primes p. We assume standard results on quadratic residues and primitive roots. An integer a relatively prime to p belongs to the exponent $k>0$, modulo p, if $a^k \equiv 1 \pmod p$ and $a^n \not\equiv 1 \pmod p$ for $0<n<k$. A primitive root modulo p is a residue which belongs to the exponent $p-1$. There are $\varphi(p-1)$ primitive roots modulo p, where $\varphi(x)$ is the Euler phi-function or totient. Euler's totient has the following property: if m is odd then $\varphi(2^n \cdot m)=2^{n-1}\varphi(m)\,(n\geq 1)$ and $\varphi(2^n \cdot m)=2^n\varphi(m)$ if m is even. A quadratic residue, modulo p, is an integer $a\not\equiv 0$ such that $x^2 \equiv a \pmod p$ has solutions. QR (QNR) denotes the set of residues, modulo p, which are quadratic residues (non-residues). With respect to the property of being a primitive root, modulo p, these sets are denoted by PR (NPR). We note the following familiar results: a is a quadratic residue modulo p if and only if $a^{(p-1)/2} \equiv 1 \pmod p$. This result is known as Euler's criterion. From Euler's criterion it follows that $(-1/p)=(-1)^{(p-1)/2}$, where (a/p) is the Legendre symbol, defined by $(a/p)=+1$ if $a \in \mathrm{QR}$, $(a/p)=-1$ if $a \in \mathrm{QNR}$. Gauss has given a theorem - known as Gauss' lemma - that puts the information contained in Euler's criterion into a slightly different form. Gauss' lemma makes it possible to evaluate $(2/p)$, $(3/p)$, $(7/p)$.
The Legendre symbol has the properties:

$$\left(\frac{a}{p}\right)\cdot\left(\frac{b}{p}\right)=\left(\frac{a\cdot b}{p}\right), \qquad \left(\frac{a}{p}\right)=\left(\frac{b}{p}\right) \quad \text{if} \quad a\equiv b \pmod p$$

where a, b are relatively prime to p. This makes it possible to calculate $(-a/p)$ if (a/p) is known. We give a list of values (a/p) needed in the sequel.

$$\left(\frac{-1}{p}\right)=\begin{cases}+1 & \text{if} \quad p\equiv 1 \pmod 4\\ -1 & \text{if} \quad p\equiv -1 \pmod 4\end{cases}$$

$$\left(\frac{2}{p}\right) = \begin{cases} +1 & \text{if } p \equiv \pm 1 \pmod 8 \\ -1 & \text{if } p \equiv \pm 3 \pmod 8 \end{cases}$$

$$\left(\frac{3}{p}\right) = \begin{cases} +1 & \text{if } p \equiv \pm 1 \pmod{12} \\ -1 & \text{if } p \equiv \pm 5 \pmod{12} \end{cases}$$

$$\left(\frac{-7}{p}\right) = \begin{cases} +1 & \text{if } p \equiv 1,2,4 \pmod 7 \\ -1 & \text{if } p \equiv 3,5,6 \pmod 7 \end{cases}$$

$$\left(\frac{-2}{p}\right) = \begin{cases} +1 & \text{if } p \equiv 1,3 \pmod 8 \\ -1 & \text{if } p \equiv -1,-3 \pmod 8 \end{cases}$$

$$\left(\frac{-3}{p}\right) = \begin{cases} +1 & \text{if } p \equiv 1 \pmod 6 \\ -1 & \text{if } p \equiv -1 \pmod 6 \end{cases}$$

Clearly no number is simultaneously a quadratic residue and a primitive root modulo p; and there are exactly $(p-1)/2$ quadratic residues modulo p. This means $\mathrm{PR} \subset \mathrm{QNR}$ and $|\mathrm{QR}| = (p-1)/2$, where $|M|$ denotes the number of elements in a finite set M.

Lemma 1. $|QNR| = |PR| + |NPR \cap QNR|$ *or with* $D = |NPR \cap QNR| = |QNR \setminus PR|$

$$\frac{p-1}{2} = \varphi(p-1) + D, \qquad D \geq 0. \tag{1}$$

The proof of lemma 1 is quite clear from what we said above.

Lemma 2. *If* $p \equiv 1 \pmod 4$, $p = 4q+1$ $(q \geq 1)$, *then* D *is even and* $4 \mid D$ *if* q *is even,* $2 \parallel D$ *if* q *is odd and* $q > 1$. D *is odd if* $p \equiv -1 \pmod 4$, $p = 2q+1$ $(q \geq 1$, q *odd) except for* $q = 1, p = 3$ *where* $D = 0$.

Proof: $D = (p-1)/2 - \varphi(p-1)$.
$p = 4q+1$: $D = 2q - \varphi(4q)$ and $2 \mid \varphi(4q)$ proves that D is even; q even means $\varphi(4q) = 4\varphi(q)$, $4 \mid 2q$ and $4 \mid D$ follows, q odd gives $\varphi(4q) = 2\varphi(q)$, $D = 2(q - \varphi(q))$ and $2 \nmid (q - \varphi(q))$ except for $q = 1$, but then $p = 5$ and $D = 0$. $p = 2q+1$, q odd: $D = q - \varphi(q)$ and D is odd except for $q = 1$.
Naturally we now ask whether there is - excepting 3 and 5 - any possibility that $D = 0$ happens, that means that all quadratic nonresidues are primitive roots. If

$-1 \in \mathrm{QNR}$ or $(-1/p) = -1$ $D = 0$ is impossible, except for $p = 3$, because $(-1)^2 \equiv 1 \pmod{p}$ and the exponent of -1 modulo p is 2, $-1 \in \mathrm{QNR} \setminus \mathrm{PR}$ except in case $p - 1 = 2$, that is $p = 3$. If $p \equiv -1 \pmod{4}$ then $(-1/p) = -1$, hence $D \geq 1$ if $p > 3$ and $p \equiv -1 \pmod{4}$.

Theorem 1. *$D = 0$ if and only if $p = 2^{2^n} + 1 = F(n)$ $(n \geq 0)$, the n-th Fermat number.*

Proof: If $D = 0$, then $p = 3 = F(0)$ or $p = 4q + 1$ $(q \geq 1)$ and from lemma 1 one gets $(p-1)/2 = \varphi(p-1)$. This given $2q = \varphi(4q)$, q odd: $q = \varphi(q)$ implies $q = 1$. q even: $q = 2\varphi(q)$, $q = 2^m \cdot r$ $(m \geq 1)$, $2 \nmid r$ this implies $r = \varphi(r)$ or $r = 1$. That means $p = 2^{m+2} + 1$ $(m \geq 1)$.
Thus $p = 2^t + 1$ $(t \geq 1)$, but it is well known that $t = 2^n$ $(n \geq 0)$ is necessary and these are the Fermat numbers. The converse follows by a simple computation.

Corollary 1.1. *An odd prime p is a Fermat prime if and only if all quadratic nonresidues, modulo p, are primitive roots.*

Corollary 1.2. *± 3 is a primitive root modulo $p = F(n)$ $(n \geq 1)$.*

Proof: $F(n) \equiv 5 \pmod{12}$ $(n \geq 1)$ as follows from $4^m \equiv 4 \pmod{12}$. From $p \equiv 5 \pmod{12}$ we get $(\pm 3/p) = -1$ or $\pm 3 \in \mathrm{QNR}$. Corollary 1.1 completes the proof.

Corollary 1.3. *± 7 is a primitive root of $p = F(n)$ $(n \geq 2)$.*

Proof: Note that $2^4 \equiv 2 \pmod{7}$ and $F(n) \equiv 3,5 \pmod{7}$ $(n \geq 2)$. Thus $(-7/p) = -1$, $-7 \in \mathrm{QNR}$ and $(-1/p) = +1$ gives $(-1/p) \cdot (-7/p) = (7/p) = -1$, $7 \in \mathrm{QNR}$. Corollary 1.1 then gives the conclusion.

Theorem 2. *$D = 1$ if and only if $p = 2q + 1$, where q is an odd prime.*

Proof: From lemma 2 we see that $p = 2q + 1$, q odd $(q > 1)$. (1) gives $q - 1 = \varphi(q)$ and q necessarily is an odd prime. The converse follows by computation.

Corollary 2.1. *All quadratic nonresidues modulo p beside -1 are primitive roots if and only if $p = 2q + 1$, where q is an odd prime.*

Corollary 2.2. *If p and q are odd primes, $p = 2q + 1$, then $(-1)^{(q-1)/2} \cdot 2$ is a primitive root modulo p.*

Proof: If $q \equiv 1 \pmod{4}$, then $2q + 1 \equiv 3 \pmod{8}$ but then $(2/p) = -1$, $2 \in \mathrm{QNR}$ and $2 \not\equiv -1 \pmod{p}$. From corollary 2.1 we see that $2 \in \mathrm{PR}$, modulo p. If $q \equiv -1 \pmod{4}$ we get $2q + 1 \equiv -1 \pmod{8}$, i.e. $(-2/p) = -1$ or $-2 \in \mathrm{QNR}$, $-2 \not\equiv -1 \pmod{p}$ and $-2 \in \mathrm{PR}$.

Corollary 2.3. *If p and q are odd primes, $p = 2q + 1$, then if $q \equiv 1 \pmod{4}$, $q + 1$ is a primitive root modulo p, while if $q \equiv -1 \pmod{4}$, q is a primitive root modulo p.*

Proof: If $q \equiv 1 \pmod 4$, then from corollary 2.2 we know $(2/p) = -1$. Since $2(q+1) = 2q+2 \equiv 1 \pmod p$ we have

$$\left(\frac{2}{p}\right) \cdot \left(\frac{q+1}{p}\right) = \left(\frac{1}{p}\right) = +1 \quad \text{and thus} \quad \left(\frac{q+1}{p}\right) = -1.$$

Hence $q+1 \in \mathrm{QNR}$ and $q+1 \not\equiv -1 \pmod p$ means $q+1 \in \mathrm{PR}$. If $q \equiv -1 \pmod 4$ the proof is similar: $2q \equiv -1 \pmod p$ or $(-2) \cdot q \equiv 1 \pmod p$ implies $(-2/p) \cdot (q/p) = +1$ and this again gives $q \in \mathrm{PR}$.
Note that in corollary 2.3 one can write the conclusion as: $(-1)^{(q+1)/2} \cdot q$ is a primitive root modulo p.

Remark: Theorem 1 is exercise 3.8, No. 11, in Agnew [1], p. 144, while corollary 1.2 is given by Trost [5], IV.25, p. 40, and corollary 1.3 is just problem 3, chap. 5.3, in Le Veque [4], p. 69. Corollaries 2.1, 2.2 and 2.3 are what Baum [2] proved but compare with theorem 5-6 (b), (c) in [4], p. 68.

Theorem 3. *$D=2$ if and only if $p=4q+1$, where q is an odd prime, and in this case $a \in QNR \setminus PR$ iff a belongs to the exponent 4 modulo p.*

Proof: Half of the theorem is trivial, we prove the rest. If $D=2$, then $(p-1)/2 = \varphi(p-1)+2$ or $2q = \varphi(4q)+2$, because lemma 2 gives $p=4q+1$ and q is odd. Therefore $2q = 2\varphi(q)+2$ or $q-1 = \varphi(q)$ and q is an odd prime. If $a \in \mathrm{QNR} \setminus \mathrm{PR}$, then $a^k \equiv 1 \pmod p$, where $k \mid p-1$ $(k \neq p-1)$ is the exponent of a modulo p. Now $p-1 = 4q$ and $a^{2q} \equiv -1 \pmod p$ from Euler's criterion. Hence $k \nmid 2q$ while q is an odd prime, thus $k=4$.

Corollary 3.1. *± 2 is a primitive root of $p=4q+1$ if q is an odd prime.*

Proof: From $p=4q+1$, q an odd prime it follows that $p \equiv -3 \pmod 8$. Hence $(\pm 2/p) = -1$ or $\pm 2 \in \mathrm{QNR}$. But $2^4 \equiv 1 \pmod p$ means $p=3$ or $p=5$ while $4q+1 \geq 13$. An application of theorem 3 completes the proof.

Corollary 3.2. *$2q$, $2q+1$ are primitive roots modulo $p=4q+1$, if q is an odd prime.*

Proof: First of all note that $2q+1 \equiv -2q \pmod p$. Therefore it is enough to show that $2q$ is a primitive root modulo p. $2(2q) \equiv -1 \pmod p$ gives $(2/p) \cdot (2q/p) = (-1/p) = +1$. From corollary 3.1 we know $(2/p) = -1$, hence $(2q/p) = -1$. Next we have to prove $(2q)^4 \not\equiv 1 \pmod p$. $(2q)^4 = (4q)^2 \cdot q^2$ and $(4q)^2 \equiv 1 \pmod p$ gives $(2q)^4 \equiv q^2 \pmod p$. But $q^2 - 1 = (q+1) \cdot (q-1)$ and from $q^2 \equiv (2q)^4 \equiv 1 \pmod p$ $p \mid q+1$ or $p \mid q-1$. It is easy to see that this cannot happen. This completes the proof.

Remark: For corollary 3.1 see theorem 5-6 (a) in [4], p. 68.

Theorem 4. *$D=2^n$ $(n \geq 2)$ if and only if $p=2^{n+1} \cdot r+1 = 2D \cdot r+1$, where r is an odd prime, and in this case $a \in QNR \setminus PR$ iff a belongs to the exponent $2D$ modulo p.*

Proof: From lemma 2 we see that $p=4q+1$ and $q=2^m \cdot r\,(m\geq 1)$, r odd. Hence from (1) $2q=4\varphi(q)+2^n$ or $q-2^{n-1}=2\varphi(q)$. $q=2^m \cdot r$ gives $2^m \cdot r-2^{n-1}=2^m \cdot \varphi(r)$ hence $r\neq 1$ and $2 \mid \varphi$ (r).
If $n-1<m$ we rewrite $2^{n-1}=2^m(r-\varphi(r))$ or $1=2^{m-n+1}(r-\varphi(r))$, a contradiction. If $n-1>m$ write $2^m \cdot r=2^m(\varphi(r)+2^{n-m-1})$ where $2 \mid (\varphi(r)+2^{n-m-1})$ but $2 \nmid r$, a contradiction. Hence $m=n-1$. This gives $r-1=\varphi(r)$ and r is an odd prime. The converse is almost trivial. If $a \in \mathrm{QNR}$ and k is the exponent of a modulo p, then $a^{D \cdot r} \equiv -1 \pmod{p}$ and $k \mid 2D \cdot r$. Thus $k \nmid D \cdot r$ and r is prime. Therefore $k=2D$ since $k \neq 2D \cdot r$ and the proof is complete.

Lemma 3. *Let $p=2D \cdot r+1$, $D=2^n (n\geq 2)$ as in theorem 4. Then, except possibly for $r=3, \pm 3$ resp. ± 6 is a primitive root modulo p if and only if 3^{2D} resp. $6^{2D} \not\equiv 1 \pmod{p}$.*

Proof: Note that $4 \equiv 1 \pmod 3$ and hence $2^m \equiv 1 \pmod 3$ if m is even, $2^m \equiv 2 \pmod 3$ if m is odd. If $m=n+1$, then $p \equiv r+1$ or $2r+1 \pmod 3$ according as n is odd or even. $r \equiv 1, 2 \pmod 3$ always gives $p \equiv 2 \pmod 3$, $p \equiv 0 \pmod 3$ is not possible. Hence $3 \mid p+1$, trivially $2 \mid p+1$, therefore $6 \mid p+1$ or $p \equiv -1 \pmod 6$.
From our list of computed Legendre symbols we see $(-3/p)=-1$. Taking into account $-1, 2 \in \mathrm{QR}$ and theorem 4 the proof is complete.

Corollary 4.1. *If $p=8 \cdot r+1$, where r is an odd prime, then ± 6 is a primitive root modulo p. ± 3 is a primitive root modulo p if $r \neq 5$.*

Proof: From theorem 4 we see that $D=4$ and lemma 3 shows that one has to consider 3^8-1, 6^8-1 modulo p. Note that $r=3$ is not possible. The computation gives

$$3^8-1=6560=2^5 \cdot 5 \cdot 41,$$
$$6^8-1=1\,679\,615=5 \cdot 7 \cdot 37 \cdot 1297.$$

It is now easy to check that (except for $r=5$) $p=8r+1$ will never divide either 3^8-1 or 6^8-1.

Corollary 4.2. *If $p=16 \cdot r+1$, where r is an odd prime, then ± 3, ± 6 are primitive roots modulo p.*

Proof: $D=8$ and

$$3^{16}-1=43\,046\,720=2^6 \cdot 5 \cdot 17 \cdot 41 \cdot 193,$$
$$6^{16}-1=5 \cdot 7 \cdot 17 \cdot 37 \cdot 1297 \cdot 98801$$

($r=3$ again is impossible). A simple consideration as in the foregoing corollary now completes the proof.
Note that $p=2^{n+2} \cdot r+1$, r an integer, are just the prime divisors of $F(n)$.