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Divisibility of Finite Geometric Series

Robert E. Hartwig[1] · Pedro Patrício[2]

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Abstract

We give necessary and sufficient conditions for the divisibility of two finite geometric series $G_n(x) = 1 + x + x^2 + \cdots + x^{n-1}$ over a field of characteristic zero.

Keywords Finite geometric series · Divisibility · Greatest common divisor

Mathematics Subject Classification 13F07 · 11A05

1 Introduction

The geometric series

$$G_n(x) = 1 + x + x^2 + \cdots + x^{n-1}$$

(also called geometric progression or GP for short) is an important two-parameter concept used in many branches of mathematics, such as in power series, convergence, telescoping matrix theory [4], number theory [2, 3] and algebraic curves, and has applications in cryptography [1].

For convenience, we shall write G_n for $G_n(x)$, when there is no risk of confusion. It is well known that $(x - 1)G_n(x) = x^n - 1$. As such, it is clear that many of the properties of $G_n(x)$ follow from those of $x^n - 1$. We shall refer to the latter as the "binomial" of the geometric progression.

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✉ Pedro Patrício
pedro@math.uminho.pt

Robert E. Hartwig
hartwig@unity.ncsu.edu

1 Mathematics Department, N.C.S.U., Raleigh, NC 27695-8205, USA

2 CMAT – Centro de Matemática and Departamento de Matemática, Universidade do Minho, 4710-057 Braga, Portugal

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When q is a prime power, say $q = p^e$, the geometric ratio $G_n(q)$ corresponds to the number of points and of hyperplanes of the projective space $\mathbb{P}^{n-1}(\mathbb{F}_q)$; if it is a prime number, then $G_n(q)$ is called a *projective prime*.

The case $G_2\left(2^{2^e}\right)$ turns into a Fermat number, whereas $2^n - 1 = G_n(2)$ is a Mersènne number. As in these two particular cases, it is conjectured that there exist infinitely many projective primes.

As in the Mersènne numbers, the primality of $G_n(q)$ implies the primality of n. Indeed, we may use the Product Rule (see (1)) that we will address later to write $G_n(q) = G_{dt}(q) = G_d(q)G_t(q^d)$, assuming $n = dt$ is a non-trivial factorization.

Our aim is investigate the fundamental question of when $G_n(x^p)$ divides $G_m(x^q)$—as a polynomial. This four-parameter problem will be referred to as the (n, p, m, q) property.

As always, we shall build on the simpler cases, such as the $(n, 1, n, q)$ and $(n, 1, m, q)$ cases, where $m = n$ and $p = 1$, or just when $p = 1$.

All our results will be over a field $\mathbb{F}$ with $char(\mathbb{F}) = 0$. The greatest common divisor and the least common multiple of a and b will be denoted by (a, b) and $[a, b]$, respectively.

We shall need a multitude of preliminary results, which are needed to build our case.

2 Building Blocks

Given integers m and n, let $(m, n) = d$ and suppose that $n = mq + r$, where $0 \le r < m \le n$. Then,

$$x^n - 1 = x^r(x^{mq} - 1) + x^r - 1 = (x^m - 1)x^r G_q(x^m) + x^r - 1.$$

This shows at once that

$$m|n \Leftrightarrow x^m - 1|x^n - 1 \Leftrightarrow G_m(x)|G_n(x)$$

and hence that

$$(x^m - 1, x^n - 1) = x^d - 1 = (x - 1)(G_m, G_n).$$

Consequently,

$$G_d = \frac{x^d - 1}{x - 1} = (G_m, G_n)$$

and thus

$$(G_m, G_n) = 1 \Leftrightarrow (m, n) = 1.$$

Next, let $L = [m, n] = lcm(m, n) = \frac{mn}{d}$. We also set $m = dm'$ and $n = dn'$ so that $L = mn' = nm' = m'n'd$.

We now observe that if $n|L$ and $m|L$, then $x^n-1|x^L-1$ and $x^m-1|x^L-1$. Hence, $[x^m-1, x^n-1]|x^L-1|x^{mn}-1$, and thus

$$\frac{(x^m-1)(x^n-1)}{(x^d-1)}|x^L-1|x^{mn}-1$$

which may be expressed as

$$G_m(x)G_n(x)|G_L(x)G_d(x)|G_{mn}(x)G_d(x).$$

For $x \neq 1$, we have

$$\frac{G_{np}(x)}{G_p(x)} = \frac{x^{np}-1}{x-1}.\frac{x-1}{x^p-1} = \frac{x^{np}-1}{x^p-1} = G_n(x^p),$$

and thus for all x

$$G_{np}(x) = G_p(x)G_n(x^p), \tag{1}$$

which we refer to as the Product Rule.

It immediately extends to larger products such as

$$G_{abc} = G_a G_{bc}(x^a) = G_a G_b(x^a) G_c(x^{ab}).$$

A further consequence of the Product Rule is the "q equals one lemma":

Lemma 2.1 (The $q=1$ case) *The following are equivalent:*

(i) $(n, p, n, 1)$ *holds.*
(ii) $G_n(x^p)|G_n(x)$.
(iii) $G_{np}|G_n G_p$.
(iv) $n = 1$ *or* $p = 1$.

Proof The equivalence of (ii)–(iii) follows from the definition and the Product Rule.

If (iii) holds, then using degrees we see that $(np-1) \leq (n-1)+(p-1)$, which tells us that

$$(n-1)(p-1) \leq 0.$$

Since $n \geq 1$ and $p \geq 1$, it follows that (iv) must hold. Lastly, it is clear that (iv) implies (ii). □

The following is a key result, which critically depends on the fact that char($\mathbb{F}$) = 0. This will be referred to it as the Linking Lemma with parameter m and links the sub- and superscripts in the two GPs, each of which contains the parameter m.

Lemma 2.2 (Linking Lemma) *For any m, n and k,*

$$(G_m(x), G_n(x^{km})) = 1.$$

Proof We begin by noting that $G_n(1) = n$, which when $char(\mathbb{F}) = 0$ cannot be equal to 0. Now by the remainder theorem

$$G_n(x) = (x-1)Q(x) + G_n(1)$$

and thus as $G_n(1) \neq 0$, we conclude that $(x-1) \not| \, G_n(x)$, or

$$(x-1, G_n(x)) = 1.$$

Replacing x by x^{mk} gives $\left(x^{mk}-1, G_n(x^{mk})\right) = 1$ and so

$$\Big((x-1)G_m(x)G_k(x^m), G_n(x^{mk})\Big) = 1.$$

This means that for any m, n and k

$$\Big(G_m(x), G_n(x^{mk})\Big) = 1.$$

□

We use both the Product Rule and the Linking Lemma in the following Basic Lemma, which is a first step in our investigation of $G_n(x^p)|G_m(x^q)$.

Lemma 2.3 *((n,1,n,q)) The following are equivalent:*

(1) $G_n(x)|G_n(x^q)$ *i.e.* $(n, 1, n, q)$ *holds.*
(2) $G_n(x)G_q(x)|G_{qn}(x)$.
(3) $(q, n) = 1$.

Proof From the Product Rule, it is clear that (1) $\Leftrightarrow$ (2).
Let $(q, n) = d$ and $q = q'd$, $n = n'd$ and suppose that (1) holds. Then,

$$G_n(x)|G_n(x^q) \Rightarrow G_{n'd}(x)|G_n(x^{q'd}) \Rightarrow G_d G_{n'}(x^d)|G_n(x^{q'd}).$$

By the Linking Lemma, we now get $G_d = 1$ and thus (3) follows.
Conversely, we always have that

$$G_q G_n | G_{qn} G_d$$

and hence, if $d = 1$, then (2) follows. □

We can immediately extend this to

Lemma 2.4 (Key (n,1,m,q)) *The following are equivalent:*

(1) $G_n(x)|G_m(x^q)$ *i.e. (n,1,m,q) holds.*
(2) $G_n(x)G_q(x)|G_{mq}(x)$.
(3) $(n,q)=1$ *and* $n|m$.

Proof The equivalence of (1) and (2) follows again from the Product Rule.

Let $(m,n)=d$ and $m=m'd, n=n'd$. Also set $(n,q)=e$ and $n=n''e, q=q''e$. Then, $G_n(x)=G_e(x)G_{n''}(x^e)|G_m(x^{q''e})$. By the Linking Lemma, with exponent e, we see that $G_e(x)=1$ and thus $e=(q,n)=1$. Applying the Basic Lemma, we get $G_nG_q|G_{nq}$. Combining this with (2), we conclude that

$$G_nG_q|(G_{mq},G_{nq})=G_{(mq,nq)}=G_{qd}.$$

This implies that $G_n|G_{dq}$ and thus $n|dq$. Since $(n,q)=1$, it follows that $n|d$, and we may conclude that $n=d$ and $n|m$ so that (3) follows.

Conversely, if $(n,q)=1$, then Lemma 2.3, $G_nG_q|G_{nq}$ and since $n|m$, we also have $G_{nq}|G_{mq}$. Combining these, we arrive at $G_nG_q|G_{mq}$ giving (2). □

3 The Polynomial Ratio

In what follows, we shall need several polynomial results dealing with greatest common divisors. In particular, we recall

Lemma 3.1 *Over an Euclidean domain,*

1. *The gcd Product Rule holds:*

$$(ab,cd)=(a,c)(b,d)(a'b',c'd'),$$

where $a'=a/(a,c), c'=c/(a,c), b'=b/(b,d), d'=d/(b,d)$.

2.

$$(ab,cd)=1 \text{ if and only if } 1=(a,c)=(a,d)=(b,c)=(b,d).$$

We now come to a refinement of the four parameters m, n, p and q, indicating the interaction between them.

Given p and q, let $(p,q)=w$ and set $p=p'w$ and $q=q'w$, with $(p',q')=1$.

Consider the rational ratio

$$R=\frac{G_m(x^q)}{G_n(x^p)}=\frac{G_m(x^{q'w})}{G_n(x^{p'w})}=\frac{G_m(y^{q'})}{G_n(y^{p'})},$$

where $y=x^w$. Thus, without loss of generality we may assume that $(p,q)=1$; otherwise, in the final answer replace x by x^w.

We begin by establishing the desired splitting of our four parameters. As such, we define:

$$\begin{array}{llll} d=(m,n), & m=m'd, & n=n'd, & \text{with } (m',n')=1 \\ f=(m',p), & m'=\hat{m}f, & p=\hat{p}f, & \text{with } (\hat{m},\hat{p})=1 \\ g=(n',q), & n'=\bar{n}g, & q=\bar{q}g, & \text{with } (\bar{n},\bar{q})=1 \\ h=(\hat{p},d), & \hat{p}=\tilde{p}h, & d=\tilde{d}h, & \text{with } (\tilde{p},\tilde{d})=1 \\ t=(\bar{q},d), & \bar{q}=q''t, & d=d''t, & \text{with } (q'',d'')=1. \end{array}$$

Further, we set $r=\hat{m}\bar{q}$ and $s=\hat{p}\bar{n}$.

Because $(m',n')=1=(p,q)$, we know that $e=(m'q,n'p)=(m',p)(n',q)=fg$.

We also observe that

$$(s,r)=(\hat{p}\cdot\bar{n},\hat{m}\bar{q})=1,$$

because all four partial gcds equal one, i.e. $(\hat{p},\bar{q})=1=(\hat{m},\bar{n})=(\hat{p},\hat{m})=(\bar{n},\bar{q})$.

From the Product Rule, we know that

$$R \text{ is a polynomial} \Leftrightarrow G_n(x^p)|G_m(x^q) \Leftrightarrow \frac{G_{np}}{G_p}\Big|\frac{G_{mq}}{G_q} \Leftrightarrow G_qG_{np}|G_pG_{mq}.$$

Now $np=(de)(\hat{p}\bar{n})=(de)s$ and $mq=(de)\hat{m}\bar{q}=(de)r$ and hence

$$R \text{ is a polynomial} \Leftrightarrow G_qG_{de}G_{\hat{p}\bar{n}}(x^{de})|G_pG_{de}G_{\hat{m}\bar{q}}(x^{de}) \Leftrightarrow G_qG_s(x^{de})|G_pG_r(x^{de}).$$

Because $(p,q)=1=(r,s)$, we know that $(G_p(x),G_q(x))=1=(G_r(x^{de}), G_s(x^{de}))$. And thus R will be a polynomial if and only if both of the following conditions hold:

$$\text{(I)} \quad G_q(x)|G_r(x^{de}) \text{ and (II)} \quad G_s(x^{de})|G_p.$$

Let us now examine these two conditions.

Turning to condition (I), we have $q=g\bar{q}$ and $r=\hat{m}\bar{q}$, and thus

$$G_q(x)|G_r(x^{de}) \Leftrightarrow G_g(x)G_{\bar{q}}(x^g)|G_{\bar{q}}(x^{de})G_{\hat{m}}(x^{de\bar{q}}).$$

Since g divides de, we can use the Linking Lemma to conclude that G_g is coprime to both factors of the RHS. As such, we must have $G_g=1$, and thus $g=1$. This means that $n'=\bar{n}$ and $q=\bar{q}$.

We are left with

$$G_{\bar{q}}|G_{\bar{q}}(x^{de})G_{\hat{m}}(x^{de\bar{q}}).$$

Again, the Linking Lemma implies that

$$(G_{\bar{q}},G_{\hat{m}}(x^{de\bar{q}}))=1$$

which leaves us with

$$G_{\bar{q}}|G_{\bar{q}}(x^{de}).$$

Using the Basic $(n, 1, n, q)$ Lemma, we arrive at $(\bar{q}, de) = (q, de) = 1$. This shows that

$$t = (q, d) = 1 \tag{2}$$

in addition to $(q, e) = (q, f) = 1$.

Turning to the second condition (II) with $e = f$, we see that splitting $s = \hat{p}\bar{n}$ and $p = \hat{p}f$, we deduce that

$$G_s(x^{df})|G_p \Leftrightarrow G_{\hat{p}}(x^{df}) \cdot G_{\bar{n}}(x^{de\hat{p}})|G_f \cdot G_{\hat{p}}(x^f).$$

Because $f|df|df\hat{p}$ and $\hat{p}|df\hat{p}$, we may conclude that

$$G_{\bar{n}}(x^{de\hat{p}}) = 1$$

and thus we must have

$$\bar{n} = 1.$$

This ensures that $n' = \bar{n} \cdot g = 1$ and hence $n = d = (m, n)$ or

$$n|m.$$

We are left with

$$G_{\hat{p}}(x^{de})|G_{\hat{p}}(x^f).$$

Comparing degrees

$$(\hat{p} - 1)df \leq (\hat{p} - 1)f$$

or by using the "q equals one Lemma", we see that either $\hat{p} = 1$ or $d = 1$. In the latter case, we get $n = n'd = 1 \cdot 1 = 1$, which is excluded.

On the other hand, when $\hat{p} = 1$, $p = f = (m', p)$ so that $p|m' = \frac{m}{d} = \frac{m}{n}$.

Combining these results with (2), we see that if R is a polynomial, then $n|m$, $p|\frac{m}{n}$ and $(n, q) = 1$.

Conversely, suppose $n|m$, $p|\frac{m}{n}$ and $(q, n) = 1$.

The latter shows that $(q, pn) = (q, p)(q, n) = 1$. Next, let $m = m'n$, $m' = p$ and $m = npw$. As np divides npw, and $(np, q) = 1$, we see by the Key $(n, 1, m, q)$ Lemma that $G_{np}|G_{npw}(x^q)$. Hence,

$$G_{np}|G_pG_{pnw}(x^q) \text{ or } G_n(x^p)|G_m(x^q).$$

We have proven

Theorem 3.1

$$\frac{G_m\,(x^q)}{G_n\,(x^p)} \text{ is a polynomial}$$

if and only if

$$n|m,\ \ p|\frac{m}{n},\ \ (n,q)=1.$$

4 Remarks

The above establishes when the ratio R will be a polynomial. However, it does not tell us what the actual polynomial is or when it will again be a GP. Also, the ratio question is a first step towards the computation of the gcd of two GPs. These topics will involve geometric series of the form $G_n(-x)$ with negative arguments and will be addressed in a later examination.

We close with a couple of non-trivial examples.

1. The (6, 3, 18, 5) case, with $n = 6$, $p = 3, m = 18, q = 5$. In this case, it is clear that $3|(18/6)$ and $(5, 6) = 1$. The GPs are $G_{18}(x^5) = x^{85} + x^{80} + x^{75} + x^{70} + x^{65} + x^{60} + x^{55} + x^{50} + x^{45} + x^{40} + x^{35} + x^{30} + x^{25} + x^{20} + x^{15} + x^{10} + x^5 + 1$, and $G_6(x^3) = x^{15} + x^{12} + x^9 + x^6 + x^3 + 1$. The quotient $R = \dfrac{G_{18}(x^5)}{G_6(x^3)}$ equals $x^{70} - x^{67} + x^{65} - x^{62} + x^{60} - x^{57} + x^{55} + x^{50} - x^{49} + x^{45} - x^{44} + x^{40} - x^{39} + x^{35} - x^{31} + x^{30} - x^{26} + x^{25} - x^{21} + x^{20} + x^{15} - x^{13} + x^{10} - x^8 + x^5 - x^3 + 1$.
2. The (4, 1, 4, 3) case, with $n = 4$, $p = 1, m = 4, q = 3$. The GPs are $G_4(x^3) = x^9 + x^6 + x^3 + 1$ and $G_4(x) = x^3 + x^2 + x + 1$. This time, $R = \dfrac{G_4(x^3)}{G_4(x)} = x^6 - x^5 + x^3 - x + 1 = G_3(-x^2)G_3(-x)$.

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