PRIME POWERS UNITS AND FINITE SUBGROUPS OF $\mathrm{GL}_n(\mathbf{Q})$

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1. Introduction

For an integer $m \geq 2$, write $(\mathbf{Z}/m)^\times$ for the units modulo m: these are the numbers mod m with multiplicative inverses. We have $a \bmod m \in (\mathbf{Z}/m)^\times$ if and only if $\gcd(a, m) = 1$. When m is a prime power p^k with $k \geq 1$, the units modulo p^k are all residues mod p^k besides the multiples of p, since being relatively prime to p^k is the same as not being divisible by p. Therefore

$$|(\mathbf{Z}/p^k)^\times| = |\{0, 1, 2, \ldots, p^k - 1\} - \{0, p, 2p, 3p, \ldots, (p^k - 1)p\}| = p^k - p^{k-1} = p^{k-1}(p-1).$$

A fundamental result in number theory, going back to Gauss, is that the group $(\mathbf{Z}/p)^\times$ is cyclic for every prime p: there is an element of $(\mathbf{Z}/p)^\times$ with order $p-1$. When p is an odd prime, there is a similar result for powers of p.

Theorem 1.1. *For an odd prime p and integer $k \geq 2$, the group $(\mathbf{Z}/p^k)^\times$ is cyclic.*

This is false for 2^k when $k \geq 3$, *e.g.* $(\mathbf{Z}/8)^\times = \{1, 3, 5, 7 \bmod 8\}$ has order 4 and each unit modulo 8 squares to 1, so no unit modulo 8 has order 4.

A proof that all groups $(\mathbf{Z}/p)^\times$ are cyclic is in Appendix A. Building on that, we will show how to prove Theorem 1.1 using p-adic numbers. Then, using p-adic numbers in another way, we will apply Theorem 1.1 to compute a bound on the order of finite subgroups of $\mathrm{GL}_n(\mathbf{Q})$.

2. The groups $(\mathbf{Z}/(p^k))^\times$ are cyclic

We will prove Theorem 1.1 by using a Teichmüller representative to lift a generator of $(\mathbf{Z}/p)^\times$ multiplicatively into the p-adics.

Proof. By Theorem A.6, $(\mathbf{Z}/p)^\times$ is cyclic. Let a generator of it be $g \bmod p$ and let $\omega(g) \in \mathbf{Z}_p^\times$ be the Teichmuller representative for g, so $\omega(g)^{p-1} = 1$ and $\boxed{\omega(g) \equiv g \bmod p}$.

Integers modulo p^k and p-adic integers modulo p^k amount to the same thing. In the language of algebra, $\mathbf{Z}/p^k$ and $\mathbf{Z}_p/p^k$ are isomorphic rings in a natural way.

We are going to show the product $(1+p)\omega(g)$ is a generator of $(\mathbf{Z}/p^k)^\times$ for all k. That is, if a is an integer such that $a \equiv (1+p)\omega(g) \bmod p^k$ then $a \bmod p^k$ generates $(\mathbf{Z}/p^k)^\times$.

Since $(\mathbf{Z}/p^k)^\times$ has size $p^{k-1}(p-1)$, it suffices to prove $((1+p)\omega(g))^m \equiv 1 \bmod p^k$ only if m is divisible by $p^{k-1}(p-1)$.

Congruences mod p^k remain valid as congruences mod p, so

$$((1+p)\omega(g))^m \equiv 1 \bmod p^k \Longrightarrow ((1+p)\omega(g))^m \equiv 1 \bmod p \Longrightarrow g^m \equiv 1 \bmod p,$$

so $\boxed{(p-1) \mid m}$ since $g \bmod p$ is a generator of $(\mathbf{Z}/p)^\times$. Thus

$$((1+p)\omega(g))^m = (1+p)^m\omega(g)^m = (1+p)^m,$$

so

$$((1+p)\omega(g))^m \equiv 1 \bmod p^k \Longrightarrow (1+p)^m \equiv 1 \bmod p^k \Longrightarrow |(1+p)^m - 1|_p \leq \frac{1}{p^k}.$$

For $m \in \mathbf{Z}^+$ and $b \in 1 + p\mathbf{Z}_p$, we have $|b^m - 1|_p = |m|_p|b-1|_p$ when $p \neq 2$: see Appendix B. Taking $b = 1+p$,

$$|(1+p)^m - 1|_p = |m|_p|(1+p) - 1|_p = \frac{|m|_p}{p}.$$

Therefore $|(1+p)^m - 1|_p \leq 1/p^k \Longrightarrow |m|_p/p \leq 1/p^k \Longrightarrow |m|_p \leq 1/p^{k-1} \Longrightarrow \boxed{p^{k-1} \mid m}$.

From $(p-1) \mid m$ and $p^{k-1} \mid m$ we get $p^{k-1}(p-1) \mid m$ since $p-1$ and p^{k-1} are relatively prime. That completes the proof. □

Corollary 2.1. *If p is an odd prime and $a \bmod p^2$ is a generator of $(\mathbf{Z}/p^2)^\times$ then $a \bmod p^k$ is a generator of $(\mathbf{Z}/p^k)^\times$ for all $k \geq 2$.*

Proof. In $\mathbf{Z}_p^\times$ set $a = \omega(a)u$, where $\omega(a)$ is the Teichmuller representative of a, so $u \in 1+p\mathbf{Z}_p$ (since $a \equiv \omega(a) \bmod p$).

Claim: $\omega(a)$ has order $p-1$ and $|u-1|_p = 1/p$ (*i.e.*, $u \in 1+p\mathbf{Z}_p$ and $u \not\in 1+p^2\mathbf{Z}_p$).

Proof of claim: Let $d \geq 1$ be the order of $a \bmod p$, so $d \mid (p-1)$. We want to prove $d = p-1$. From $a^d \equiv 1 \bmod p$, raising both sides to the pth power gives us $a^{dp} \equiv 1 \bmod p^2$ with the modulus "improved" to p^2.[1] Therefore $p(p-1) \mid dp$, so $(p-1) \mid d$. We noted earlier that $d \mid (p-1)$ too, so $d = p-1$. The order of $a \bmod p$ and $\omega(a)$ are the same, so $\omega(a)$ has order $p-1$.

Since $|u-1|_p \leq 1/p$, if $|u-1|_p \neq 1/p$ then $|u-1|_p \leq 1/p^2$, so $u \equiv 1 \bmod p^2$. Then $a = \omega(a)u \equiv \omega(a) \bmod p^2$, so $a^{p-1} \equiv \omega(a)^{p-1} \equiv 1 \bmod p^2$, which contradicts $a \bmod p^2$ being a generator of $(\mathbf{Z}/p^2)^\times$. Thus $|u-1|_p = 1/p$. This finishes the proof of the claim.

When we proved in Theorem 1.1 that $(1+p)\omega(g) \bmod p^k$ has order $(p-1)p^{k-1}$, the properties we used about g and $1+p$ were that $g \bmod p$ has order $p-1$ and $|(1+p)-1|_p = 1/p$. Since $\omega(a)$ has order $p-1$ and $|u-1|_p = 1/p$, the arguments used for $(1+p)\omega(g)$ can be applied word for word to $u\omega(a) = a$, so $a \bmod p^k$ generates $(\mathbf{Z}/p^k)^\times$ for all $k \geq 2$. □

Remark 2.2. Here is a more conceptual description of what is going on in terms of p-adic quotient groups. We can view $(\mathbf{Z}_p/p^k)^\times$ as an isomorphic group built from p-adic units:

$$(\mathbf{Z}/p^k)^\times \cong (\mathbf{Z}_p/p^k)^\times \cong \mathbf{Z}_p^\times/(1+p^k\mathbf{Z}_p).$$

The second isomorphism arises because elements of $(\mathbf{Z}_p/p^k)^\times$ are represented by p-adic units, and when u and v are p-adic units we have

$$u = v \text{ in } \mathbf{Z}_p/p^k \Longleftrightarrow u \in v + p^k\mathbf{Z}_p \Longleftrightarrow \frac{u}{v} \in 1+p^k\mathbf{Z}_p \Longleftrightarrow u = v \text{ in } \mathbf{Z}_p^\times/(1+p^k\mathbf{Z}_p).$$

What makes $\mathbf{Z}_p^\times/(1+p^k\mathbf{Z}_p)$ a nice model for the multiplicative group $(\mathbf{Z}/p^k)^\times$ is that it is an actual quotient of multiplicative groups. This can't be done working in the integers alone, where the only units are ± 1.

Writing $a = \omega(a)u$ provides a direct product decomposition $\mathbf{Z}_p^\times \cong \mu_{p-1} \times (1+p\mathbf{Z}_p)$, where μ_{p-1} is the (cyclic) group of $(p-1)$th roots of unity in the p-adic integers. Thus

$$\mathbf{Z}_p^\times/(1+p^k\mathbf{Z}_p) \cong (\mu_{p-1} \times (1+p\mathbf{Z}_p))/(1+p^k\mathbf{Z}_p) \cong \mu_{p-1} \times (1+p\mathbf{Z}_p)/(1+p^k\mathbf{Z}_p).$$

[1] In general for x and y in $\mathbf{Z}_p$, if $x \equiv y \bmod p$ then $x^p \equiv y^p \bmod p^2$. More generally, if $x \equiv y \bmod p^k$ then $x^p \equiv y^p \bmod p^{k+1}$.

We can figure out what the multiplicative quotient group $(1+p\mathbf{Z}_p)/(1+p^k\mathbf{Z}_p)$ looks like concretely by using the p-adic logarithm to turn it into an additive quotient group. Since $p \neq 2$, the function $\log\colon 1+p\mathbf{Z}_p \to p\mathbf{Z}_p$ is an isomorphism, and since the p-adic logarithm is an isometry we get $\log(1+p^k\mathbf{Z}_p) = p^k\mathbf{Z}_p$. Thus

$$(1+p\mathbf{Z}_p)/(1+p^k\mathbf{Z}_p) \overset{\log}{\cong} p\mathbf{Z}_p/p^k\mathbf{Z}_p \cong \mathbf{Z}_p/p^{k-1} \cong \mathbf{Z}/p^{k-1} = \text{cyclic group of order } p^{k-1}.$$

Therefore

$$(\mathbf{Z}/p^k)^\times \cong \mathbf{Z}_p^\times/(1+p^k\mathbf{Z}_p) \cong \mu_{p-1} \times (1+p\mathbf{Z}_p)/(1+p^k\mathbf{Z}_p) \cong \mathbf{Z}/(p-1) \times \mathbf{Z}/p^{k-1}.$$

This is a direct product of cyclic groups of orders $p-1$ and p^{k-1}, which are relatively prime, so the direct product is also cyclic.

The structure of the group $(\mathbf{Z}/2^k)^\times$ can be studied similarly to the case of odd p, but for $k \geq 3$ these groups will turn out not to be cyclic. They are almost cyclic: there is a cyclic subgroup of order equal to half the size of the group.

Theorem 2.3. *For $k \geq 3$, $(\mathbf{Z}/2^k)^\times = \langle -1, 5 \bmod 2^k\rangle = \{\pm 5^j \bmod 2^k : j \geq 0\}$.*

Proof. The group $(\mathbf{Z}/2^k)^\times$ has order $2^{k-1}(2-1) = 2^{k-1}$. We will show $5 \bmod 2^k$ has order 2^{k-2}. For $m \in \mathbf{Z}^+$ and $b \in 1+4\mathbf{Z}_2$ we have $|b^m-1|_2 = |m|_2|b-1|_2$: see Appendix B. Therefore

$$5^m \equiv 1 \bmod 2^k \iff |5^m-1|_2 \leq \frac{1}{2^k} \iff |m|_2|5-1|_2 \leq \frac{1}{2^k} \iff |m|_2 \leq \frac{1}{2^{k-2}} \iff 2^{k-2} \mid m,$$

so $5 \bmod 2^k$ has order 2^{k-2}. No power of $5 \bmod 2^k$ is ever $-1 \bmod 2^k$ since $5 \equiv 1 \bmod 4$ while $-1 \equiv 3 \bmod 4$. Therefore $-1 \bmod 2^k \notin \langle 5 \bmod 2^k\rangle$, and since $-1 \bmod 2^k$ has order 2 the subgroup $\{\pm 5^j \bmod 2^k : j \geq 0\}$ of $(\mathbf{Z}/2^k)^\times$ has order $2 \cdot 2^{k-2} = 2^{k-1} = |(\mathbf{Z}/2^k)^\times|$, which makes this subgroup equal to the whole group. $\square$

Remark 2.4. We can explain the group structure of $(\mathbf{Z}/2^k)^\times$ by writing it as a quotient group of $\mathbf{Z}_2^\times$. Since $\mathbf{Z}_2^\times = \{\pm 1\} \times (1+4\mathbf{Z}_2)$, for $k \geq 2$ we have

$$\begin{aligned}
(\mathbf{Z}/2^k)^\times &\cong (\mathbf{Z}_2/2^k)^\times \\
&\cong \mathbf{Z}_2^\times/(1+2^k\mathbf{Z}_2) \\
&\cong (\{\pm 1\} \times (1+4\mathbf{Z}_2))/(1+2^k\mathbf{Z}_2) \\
&\cong \{\pm 1\} \times (1+4\mathbf{Z}_2)/(1+2^k\mathbf{Z}_2).
\end{aligned}$$

Using the 2-adic logarithm isomorphism $1+4\mathbf{Z}_2 \cong 4\mathbf{Z}_2$, which is also an isometry, we get

$$(1+4\mathbf{Z}_2)/(1+2^k\mathbf{Z}_2) \overset{\log}{\cong} 4\mathbf{Z}_2/2^k\mathbf{Z}_2 \cong \mathbf{Z}_2/2^{k-2} \cong \mathbf{Z}/2^{k-2},$$

so $(\mathbf{Z}/2^k)^\times \cong \{\pm 1\} \times \mathbf{Z}/2^{k-2}$.

3. Bounding finite subgroups of $\mathrm{GL}_n(\mathbf{Q})$

How large can a finite group of matrices be? If we allow matrix entries from the complex numbers, or even the real numbers, then there is no upper bound in general. For example, if d if a positive integer then a counterclockwise rotation by $2\pi/d$ radians in the plane $\mathbf{R}^2$ is represented by the matrix

$$\begin{pmatrix} \cos(2\pi/d) & -\sin(2\pi/d) \\ \sin(2\pi/d) & \cos(2\pi/d) \end{pmatrix}$$

in $\mathrm{GL}_2(\mathbf{R})$ that has order d, so $\mathrm{GL}_2(\mathbf{R})$ contains finite subgroups of arbitrarily large order.

If we restrict the numbers in the matrices to be rational, however, then there *is* an upper bound on how large a finite matrix group can be in terms of the size of the matrices. This result is due to Minkowski [4]. Our argument is adapted from [2, Chap. 4, Sect. 2].

Theorem 3.1 (Minkowski, 1887)**.** *For each $n \geq 1$ every finite subgroup of $\mathrm{GL}_n(\mathbf{Q})$ has order dividing a number $M(n)$ that depends only on n.*

For example, it turns out that $M(2) = 24$, so every finite subgroup of $\mathrm{GL}_2(\mathbf{Q})$ has order dividing $24 = 2^3 \cdot 3$. We are not claiming that there actually is a subgroup of $\mathrm{GL}_2(\mathbf{Q})$ with order 24. In fact the largest size is 12, but there are subgroups of order not dividing 12 and those orders all divide 24 (see below for a subgroup of order 8).

Example 3.2. The matrix $\left(\begin{smallmatrix} 0 & -1 \\ 1 & 1 \end{smallmatrix}\right)$ has order 6.

Example 3.3. Let $r = \left(\begin{smallmatrix} 0 & -1 \\ 1 & 0 \end{smallmatrix}\right)$ and $s = \left(\begin{smallmatrix} 1 & 0 \\ 0 & -1 \end{smallmatrix}\right)$. Then r has order 4, s has order 2, and $sr = r^{-1}s$, so the group $\langle r, s\rangle$ generated by r and s in $\mathrm{GL}_2(\mathbf{Q})$ has order 8.

The proof of Theorem 3.1 will use the finite groups $\mathrm{GL}_n(\mathbf{Z}/p)$. Just as the symmetric group S_n has order $n!$ that is a product of n integers, the order of $\mathrm{GL}_n(\mathbf{Z}/p)$ has an explicit formula that is a product of n terms.

Lemma 3.4. *For each prime p, $|\operatorname{GL}_n(\mathbf{Z}/p)| = (p^n - 1)(p^n - p)\cdots(p^n - p^{n-1})$.*

Proof. See Appendix C. The proof is based on linear algebra over the field $\mathbf{Z}/p$. $\square$

Now we prove Theorem 3.1.

Proof. Let G be a finite subgroup of $\mathrm{GL}_n(\mathbf{Q})$. Since G contains only finitely many matrices, and each rational number is in $\mathbf{Z}_p$ for all large primes p, the matrices in G have entries in $\mathbf{Z}_p$ for all large p, so there is a prime p_0 such that $G \subset \mathrm{M}_n(\mathbf{Z}_p)$ for all $p > p_0$. We write $\mathrm{GL}_n(\mathbf{Z}_p)$ for the group of $n \times n$ matrices with $\mathbf{Z}_p$-entries that have inverses also with $\mathbf{Z}_p$-entries; the condition for a matrix $A \in \mathrm{M}_n(\mathbf{Z}_p)$ to belong to $\mathrm{GL}_n(\mathbf{Z}_p)$ is that $\det A \in \mathbf{Z}_p^\times$. If $A \in \mathrm{GL}_n(\mathbf{Q})$ has finite order then $\det A \in \mathbf{Q}^\times$ has finite order, so $\det A = \pm 1$. Therefore by Cramer's rule for inverting matrices, $G \subset \mathrm{GL}_n(\mathbf{Z}_p)$ for all $p > p_0$.

Claim: For every prime $p > p_0$, the order of G divides $|\operatorname{GL}_n(\mathbf{Z}/p)|$.

Proof of claim: We can view G inside $\mathrm{GL}_n(\mathbf{Z}_p)$. Reducing matrix entries modulo p sends each matrix A in $\mathrm{GL}_n(\mathbf{Z}_p)$ to a matrix $\overline{A}$ in $\mathrm{GL}_n(\mathbf{Z}_p/p)$, which can be regarded as $\mathrm{GL}_n(\mathbf{Z}/p)$ by the natural identification of $\mathbf{Z}_p/p$ with $\mathbf{Z}/p$. (We have $\overline{A} \in \mathrm{GL}_n(\mathbf{Z}_p/p)$ since $\det A = \pm 1 \Longrightarrow \det A \not\equiv 0 \bmod p \Longrightarrow \det \overline{A} \neq 0$ in $\mathbf{Z}/p$.) Reduction $\mathrm{GL}_n(\mathbf{Z}_p) \to \mathrm{GL}_n(\mathbf{Z}_p/p)$ is a group homomorphism.

The key point is that when $p > p_0$, two matrices A and B in the *finite* group G can't reduce mod p to the same matrix in $\mathrm{GL}_n(\mathbf{Z}_p/p)$. Indeed, suppose $A \equiv B \bmod p$. Then AB^{-1} belongs to G, so it has finite order, and $AB^{-1} \equiv I_n \bmod p$. We will show $AB^{-1} = I_n$, so $A = B$, by using a norm on p-adic matrices.

For each $n \times n$ matrix $X = (x_{ij})$ in $\mathrm{M}_n(\mathbf{Q}_p)$, define its p-adic matrix norm to be the maximum p-adic absolute value of the entries:

$$||X||_p := \max_{i,j} |x_{ij}|_p.$$

Thus $\mathrm{M}_n(\mathbf{Z}_p) = \{X \in \mathrm{M}_n(\mathbf{Q}_p) : ||X||_p \leq 1\}$. Check that (i) $||X+Y||_p \leq \max(||X||_p, ||Y||_p)$, (ii) $||XY||_p \leq ||X||_p ||Y||_p$, and (iii) $||aX||_p = |a|_p ||X||_p$ for a in $\mathbf{Q}_p$ and p-adic matrices X

and Y. Often $||XY||_p \neq ||X||_p||Y||_p$, but the inequality (ii) will be sufficient for us. It implies, for instance, that $||X^k||_p \leq ||X||_p^k$ for all $k \geq 1$. By (i), when $X \neq Y$, $||X \pm Y||_p = \max(||X||_p, ||Y||_p)$.

For $p > 2$ and $x \in 1+p\mathbf{Z}_p$, $|x^m-1|_p = |m|_p|x-1|_p$ for all $m \geq 1$: see Appendix B. It turns out the same equation holds for matrices: if $X \in I_n + p\mathrm{M}_n(\mathbf{Z}_p)$ (that is, $||X - I_n||_p \leq 1/p$), then $||X^m-I_n||_p = |m|_p||X-I_n||_p$ for all $m \geq 1$: see Appendix B. Returning to the matrices A and B in G such that $A \equiv B \bmod p$, where $p > p_0$ (so $p > 2$), we have

$$AB^{-1} \equiv I_n \bmod p \Longrightarrow AB^{-1} \in I_n + p\mathrm{M}_n(\mathbf{Z}_p) \Longrightarrow ||(AB^{-1})^m - I_n||_p = |m|_p||AB^{-1} - I_n||_p$$

for all $m \geq 1$. In the last equation, let m be the (finite!) order of AB^{-1} in G to see that $0 = |m|_p||AB^{-1} - I_n||_p$. Thus $||AB^{-1} - I_n||_p = 0$, so $AB^{-1} - I_n = O$, from which we get $A = B$.

We have shown the reduction mod p homomorphism $G \to \mathrm{GL}_n(\mathbf{Z}_p/p)$ is injective for $p > p_0$, so $|G|$ divides the order of $\mathrm{GL}_n(\mathbf{Z}_p/p) \cong \mathrm{GL}_n(\mathbf{Z}/p)$. This completes the proof of the claim.

The order of $\mathrm{GL}_n(\mathbf{Z}/p)$ in Lemma 3.4 can be rewritten by factoring out the largest power of p:

$$\begin{aligned}(p^n-1)(p^n-p)\cdots(p^n-p^{n-1}) &= (p^n-1)p(p^{n-1}-1)\cdots p^{n-1}(p-1)\\ &= p^{1+\cdots+n-1}(p^n-1)(p^{n-1}-1)\cdots(p-1)\\ &= p^{n(n-1)/2}(p^n-1)(p^{n-1}-1)\cdots(p-1).\end{aligned} \tag{3.1}$$

To bound $|G|$, pick a prime q. We will get an upper bound $e_n(q)$ for $\mathrm{ord}_q(|G|)$ and find $e_n(q) = 0$ if $q > n+1$, so $|G|$ divides $\prod_{q \leq n+1} q^{e_n(q)}$, where the product runs over primes less than or equal to $n+1$. (Recall the examples of finite subgroups of $\mathrm{GL}_2(\mathbf{Q})$ earlier had order divisible only 2 and 3, which are less than or equal to $n+1 = 3$ in this case.)

For prime $p > p_0$, $\mathrm{ord}_q(|G|) \leq \mathrm{ord}_q(|\,\mathrm{GL}_n(\mathbf{Z}/p)|)$. If $p \neq q$ then by (3.1)

$$\mathrm{ord}_q(|\,\mathrm{GL}_n(\mathbf{Z}/p)|) \leq \mathrm{ord}_q((p^n-1)(p^{n-1}-1)\cdots(p-1)) = \sum_{i=1}^{n-1} \mathrm{ord}_q(p^i-1).$$

We will choose for p a large prime different from q that makes $\mathrm{ord}_q(p^i - 1)$ easy to calculate.

If $\boxed{q \neq 2}$ then $(\mathbf{Z}/q^k)^\times$ is cyclic for all $k \geq 1$. An integer that is a generator of $(\mathbf{Z}/q^2)^\times$ is also a generator of $(\mathbf{Z}/q^k)^\times$ for all $k \geq 1$ by Corollary 2.1. Let $b \bmod q^2$ generate $(\mathbf{Z}/q^2)^\times$, so $(b, q^2) = 1$. We will now use a famous theorem of Dirichlet about primes in arithmetic progression: if a and m are relatively prime integers then there are infinitely many primes $p \equiv a \bmod m$.

By Dirichlet's theorem, there are infinitely many primes $p \equiv b \bmod q^2$. Choose such a prime p with $p > p_0$. Necessarily $p \neq q$ since $(p, q^2) = (b, q^2) = 1$. The number $\mathrm{ord}_q(p^i - 1)$ is the largest integer k that makes $q^k \mid (p^i - 1)$, or equivalently that makes $p^i \equiv 1 \bmod q^k$. Since $p \bmod q^k$ generates $(\mathbf{Z}/q^k)^\times$,

$$q^k \mid (p^i-1) \Longleftrightarrow p^i \equiv 1 \bmod q^k \Longleftrightarrow q^{k-1}(q-1) \mid i. \tag{3.2}$$

From the equivalence of the first and third relations in (3.2) we can start counting.

- The number of $p^i - 1$ with $1 \leq i \leq n$ that are divisible by q is the number of multiples of $q-1$ up to n, and that number is $\lfloor n/(q-1) \rfloor$.

- The number of $p^i - 1$ with $1 \leq i \leq n$ that are divisible by q^2 is the number of multiples of $q(q-1)$ up to n, and that number is $\lfloor n/(q(q-1))\rfloor$.
- The number of $p^i - 1$ with $1 \leq i \leq n$ that are divisible by q^3 is the number of multiples of $q^2(q-1)$ up to n, and that number is $\lfloor n/(q^2(q-1))\rfloor$.
- For each $k \geq 1$, the number of $p^i - 1$ with $1 \leq i \leq n$ that are divisible by q^k is the number of multiples of $q^{k-1}(q-1)$ up to n, and that number is $\lfloor n/(q^{k-1}(q-1))\rfloor$.

Putting this all together, the multiplicity of the prime q in $|\operatorname{GL}_n(\mathbf{Z}/p)|$, if $p \bmod q^2$ generates $(\mathbf{Z}/q^2)^\times$, is

$$e_n(q) := \left\lfloor \frac{n}{q-1} \right\rfloor + \left\lfloor \frac{n}{q(q-1)} \right\rfloor + \left\lfloor \frac{n}{q^2(q-1)} \right\rfloor + \cdots = \sum_{j\geq 0} \left\lfloor \frac{n}{q^j(q-1)} \right\rfloor. \tag{3.3}$$

This formally infinite series is really finite because the j-th term is 0 once $q^j(q-1) > n$. In particular, if $q > n+1$ then $q - 1 > n$ and all terms in the sum vanish. Thus q does not divide $|G|$ if $q > n+1$, so the only possible odd prime factors of $|G|$ are primes up to $n+1$, and the highest power of q dividing $|G|$ is at most $q^{e_n(q)}$.

When $\boxed{q = 2}$ a similar analysis can be made with Dirichlet's theorem for modulus 8 (not for modulus $4 = 2^2$, as the case of odd q might suggest), although it is a bit more complicated because the groups $(\mathbf{Z}/2^k)^\times$ for $k \geq 3$ are not cyclic but only "half-cyclic": there's a cyclic subgroup filling up half the group. The result, whose details we omit (see [5, Sect. 1.3.4]), is that $\operatorname{ord}_2(|G|)$ is bounded above by the same formula as (3.3) when $q = 2$, that is, by the sum

$$e_n(2) := \sum_{j\geq 0} \left\lfloor \frac{n}{2^j} \right\rfloor,$$

Putting everything together, each finite subgroup of $\operatorname{GL}_n(\mathbf{Q})$ divides the integer

$$M(n) = \prod_q q^{e_n(q)} = \prod_{q\leq n+1} q^{e_n(q)}$$

where $e_n(q)$ is given by (3.3) for all primes q. The table below gives some sample values.

n	1	2	3	4	5	6	7
$M(n)$	2	24	48	5760	11520	2903040	5806080

$\square$

For each prime q the exponent $e_n(q)$ in $M(n)$ is optimal in the sense that there does exist a subgroup of $\operatorname{GL}_n(\mathbf{Q})$ of order $q^{e_n(q)}$ [1, pp. 392-394], [5, Sect. 1.4].

Remark 3.5. The largest possible order of a finite subgroup of $\operatorname{GL}_n(\mathbf{Q})$ is $2^n n!$ except when $n = 2, 4, 6, 7, 8, 9$, and 10, and for every n (no exceptions) the subgroups of $\operatorname{GL}_n(\mathbf{Q})$ with maximal order are conjugate. See [3].

Appendix A. Cyclicity of $(\mathbf{Z}/p)^\times$

To prove $(\mathbf{Z}/p)^\times$ is cyclic for each prime p, we can suppose $p > 2$. We are going to use the prime factorization of $p - 1$. Say

$$p - 1 = q_1^{e_1} q_2^{e_2} \cdots q_m^{e_m},$$

where the q_i are distinct primes and $e_i \geq 1$. We will show $(\mathbf{Z}/p)^\times$ has elements of order $q_i^{e_i}$ for each i and their product furnishes a generator of $(\mathbf{Z}/p)^\times$.

As a warm-up, let's show for each prime q dividing $p-1$ that there is an element of order q in $(\mathbf{Z}/p)^\times$. While this a consequence of Cauchy's theorem for all finite groups, abelian or nonabelian, we want to give a proof that uses a special feature of $(\mathbf{Z}/p)^\times$: it is the nonzero elements of the field $\mathbf{Z}/p$.

Lemma A.1. *If q is a prime dividing $p-1$ then there is an element of $(\mathbf{Z}/p)^\times$ with order q. Specifically, there is an $a \in (\mathbf{Z}/p)^\times$ such that $a^{(p-1)/q} \neq 1$, and necessarily $a^{(p-1)/q}$ has order q in $(\mathbf{Z}/p)^\times$.*

Proof. The polynomial equation $a^{(p-1)/q} = 1$ in $\mathbf{Z}/p$ has at most $(p-1)/q$ solutions in $\mathbf{Z}/p$ since $\mathbf{Z}/p$ is a field, and $(p-1)/q$ is less than $p-1 = |(\mathbf{Z}/p)^\times|$. Therefore $(\mathbf{Z}/p)^\times$ has an element a such that $a^{(p-1)/q} \neq 1$.

Set $b = a^{(p-1)/q}$ in $\mathbf{Z}/p$. Then $b \neq 1$ and $b^q = (a^{(p-1)/q})^q = a^{p-1} = 1$ in $(\mathbf{Z}/p)^\times$ by Fermat's little theorem, so the order of $b \bmod p$ divides q and is not 1. Since q is prime, the only choice for the order of $b \bmod p$ is q. $\square$

That proof is *not* saying that if $a^{(p-1)/q} \neq 1$ in $\mathbf{Z}/p$ then $a \bmod p$ has order q. It is saying that a power of the form $a^{(p-1)/q} \bmod p$ has order q if the power is not 1 (or 0).

Example A.2. Take $p = 19$. By Fermat's little theorem, all a in $(\mathbf{Z}/19)^\times$ satisfy $a^{18} = 1$. Since 18 is divisible by 3, the lemma is telling us that whenever $a^{18/3} \neq 1$, $a^{18/3}$ has order 3. From the second row of the table below, which runs over the nonzero numbers mod 19, we find 2 different values of a^6 mod 19 other than 1: 7 and 11. They both have order 3.

a mod 19	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
a^6 mod 19	1	7	7	11	7	11	1	1	11	11	1	1	11	7	11	7	7	1

If a prime q divides $p-1$ more than once, then the same reasoning as in Lemma A.1 leads to elements of higher q-power order in $(\mathbf{Z}/p)^\times$.

Lemma A.3. *If q is a prime and $q^e \mid (p-1)$ for a positive integer e, then there is an element of $(\mathbf{Z}/p)^\times$ with order q^e. Specifically, there is an $a \in (\mathbf{Z}/p)^\times$ such that $a^{(p-1)/q} \neq 1$ in $(\mathbf{Z}/p)^\times$, and necessarily $a^{(p-1)/q^e}$ has order q^e in $(\mathbf{Z}/p)^\times$.*

Proof. As in the proof of Lemma A.1, there are fewer than $p-1$ solutions to $a^{(p-1)/q} = 1$ in $\mathbf{Z}/p$ since $\mathbf{Z}/p$ is a field, so there is an a in $(\mathbf{Z}/p)^\times$ where $a^{(p-1)/q} \neq 1$ in $\mathbf{Z}/p$.

Set $b = a^{(p-1)/q^e}$ in $\mathbf{Z}/p$, which makes sense since q^e is a factor of $p-1$ (we are not using fractional exponents). Then $b^{q^e} = (a^{(p-1)/q^e})^{q^e} = a^{p-1} = 1$ in $(\mathbf{Z}/p)^\times$ by Fermat's little theorem, so the order of $b \bmod p$ divides q^e. Since q is prime, the (positive) factors of q^e other than q^e are factors of q^{e-1}. Since $b^{q^{e-1}} = (a^{(p-1)/q^e})^{q^{e-1}} = a^{(p-1)/q} \neq 1$ in $(\mathbf{Z}/p)^\times$, by the choice of a, the order of $b \bmod p$ does not divide q^{e-1}. Thus the order of b in $(\mathbf{Z}/p)^\times$ must be q^e. $\square$

Example A.4. Returning to $p = 19$, the number $p-1 = 18$ is divisible by the prime power 9. In the table below we list the a for which $a^{(p-1)/3} = a^6 \neq 1$ and below that list the corresponding values of $a^{18/9} = a^2$: these are 4, 5, 6, 9, 16, and 17, and all have order 9.

a mod 19	2	3	4	5	6	9	10	13	14	15	16	17
a^6 mod 19	7	7	11	7	11	11	11	11	7	11	7	7
a^2 mod 19	4	9	16	6	17	5	5	17	6	16	9	4

Remark A.5. Lemma A.3 can be proved in another way using unique factorization of polynomials with coefficients in $\mathbf{Z}/p$. Because all nonzero numbers mod p are roots of

$T^{p-1}-1$, this polynomial factors mod p as $(T-1)(T-2)\cdots(T-(p-1))$. Being a product of distinct linear factors, every factor of $T^{p-1}-1$ is also a product of distinct linear factors, so in particular, every factor of $T^{p-1}-1$ has as many roots in $\mathbf{Z}/p$ as its degree. For a prime power q^e dividing $p-1$, $T^{q^e}-1$ divides $T^{p-1}-1$, so there are q^e solutions of $a^{q^e}=1$ in $\mathbf{Z}/p$. This exceeds the number of solutions of $a^{q^{e-1}}=1$ in $\mathbf{Z}/p$, which is at most q^{e-1} since a nonzero polynomial over a field has no more roots than its degree. Therefore there is an a in $\mathbf{Z}/p$ fitting $a^{q^e}=1$ and $a^{q^{e-1}}\neq 1$. All such a have order q^e.

Theorem A.6. *For each prime p, the group $(\mathbf{Z}/p)^\times$ is cyclic.*

Proof. We may take $p>2$, so $p-1>1$. Write $p-1$ as a product of primes:

$$p-1=q_1^{e_1}q_2^{e_2}\cdots q_m^{e_m}.$$

By Lemma A.3, for each i from 1 to m there is $b_i\in(\mathbf{Z}/p)^\times$ with order $q_i^{e_i}$. These orders are relatively prime, and $(\mathbf{Z}/p)^\times$ is abelian, so the product of the b_i's has order equal to the product of the $q_i^{e_i}$'s, which is $p-1$. Thus, $b_1b_2\cdots b_m$ generates $(\mathbf{Z}/p)^\times$. □

Appendix B. Computing $|b^m-1|_p$ and $||B^m-I_n||_p$

The two theorems we prove here were used in the proofs of Theorems 1.1, 2.3, and 3.1.

Theorem B.1. *Let p be prime. When $p>2$ and $b\in 1+p\mathbf{Z}_p$,*

$$|b^m-1|_p=|m|_p|b-1|_p$$

for $m\geq 1$. When $p=2$ and $b\in 1+4\mathbf{Z}_2$, $|b^m-1|_2=|m|_2|b-1|_2$ for $m\geq 1$.

Proof. We will present the case $p>2$ and leave the case $p=2$ to the reader.

Check the identity for general $m\geq 1$ follows from the cases $(p,m)=1$ and $m=p$:

$$(p,m)=1\Longrightarrow |b^m-1|_p=|b-1|_p,\quad\text{and}\quad |b^p-1|_p=\frac{1}{p}|b-1|_p.$$

<u>Case 1</u>: $(p,m)=1$.

To prove $|b^m-1|_p=|b-1|_p$, we can assume $b\neq 1$ and $m\geq 2$ since it is obvious when $b=1$ or $m=1$. Set $c=b-1$, so

$$b^m-1=(1+c)^m-1=mc+\sum_{k=2}^{m}\binom{m}{k}c^k.$$

We have $|mc|_p=|c|_p=|b-1|_p$. Since $0<|c|_p\leq 1/p$, $|\sum_{k=2}^m\binom{m}{k}c^k|_p\leq\max_{2\leq k\leq m}|c|_p^k=|c|_p^2<|c|_p=|b-1|_p$ (the last inequality would not be correct if $c=0$). Thus

$$|b^m-1|_p=|b-1|_p.$$

<u>Case 2</u>: $m=p$.

To prove $|b^p-1|_p=(1/p)|b-1|_p$, as in Case 1 we can assume $b\neq 1$. Set $c=b-1$, so

$$b^p-1=(1+c)^p-1=pc+\sum_{k=2}^{p}\binom{p}{k}c^p.$$

We have $|pc|_p=(1/p)|c|_p=(1/p)|b-1|_p$. Since $0<|c|_p\leq 1/p$, if $2\leq k\leq p-1$ (there are such k since $p>2$), then $p\mid\binom{p}{k}$, so $|\binom{p}{k}c^k|_p\leq(1/p)|c|_p^k\leq(1/p)|c|_p^2<(1/p)|c|_p=(1/p)|b-1|_p$. Also $|\binom{p}{p}c^p|_p=|c|_p^p\leq|c|_p^3\leq(1/p)|c|_p^2<(1/p)|c|_p=(1/p)|b-1|_p$, so

$$|b^p-1|_p=\frac{1}{p}|b-1|_p.$$ □

Theorem B.2. *Let p be prime. When $p > 2$ and $B \in 1 + p\,\mathrm{M}_n(\mathbf{Z}_p)$*
$$||B^m - I_n||_p = |m|_p||B - I_n||_p$$
for $m \geq 1$. When $p = 2$ and $B \in 1 + 4\,\mathrm{M}_n(\mathbf{Z}_2)$, $||B^m - I_n||_2 = |m|_2||B - I_n||_2$ for $m \geq 1$.

When this was used in the proof of Theorem 3.1, we did not need the case $p = 2$.

Proof. It is left to the reader to check the proof of Theorem B.1 still works in the matrix setting, using $||XY||_p \leq ||X||_p||Y||_p$ with p-adic matrices instead of $|xy|_p = |x|_p|y|_p$ with p-adic numbers and using $||aX||_p = |a|_p||X||$ for p-adic scalars a and matrices X. Even though matrix multiplication is not usually commutative, we can use the binomial theorem to expand $(I_n + B)^m$ just as with $(1 + b)^m$ since I_n and B commute. □

Appendix C. The order of $\mathrm{GL}_n(\mathbf{Z}/p)$

To compute $|\,\mathrm{GL}_n(\mathbf{Z}/p)|$ in Lemma 3.4, view the columns of a matrix in $\mathrm{M}_n(\mathbf{Z}/p)$ as an ordered list of n elements of $(\mathbf{Z}/p)^n$. The matrix is invertible if and only if *the columns are a basis of* $(\mathbf{Z}/p)^n$. In an n-dimensional vector space, n vectors are a basis if and only if they are linearly independent, so count how many ordered lists of n vectors in $(\mathbf{Z}/p)^n$ are linearly independent. Every set of linearly independent vectors in $(\mathbf{Z}/p)^n$ can be extended to a basis, so we can build up elements of $\mathrm{GL}_n(\mathbf{Z}/p)$ column by column.

(1) The first column can be anything in $(\mathbf{Z}/p)^n$ but the zero vector, since every nonzero vector can be extended to a basis. Therefore the first column has $p^n - 1$ choices.
(2) Having picked the first column, the second column can be an arbitrary vector in $(\mathbf{Z}/p)^n$ that is linearly independent of the first column: such a choice makes the first two columns linearly independent and every pair of linearly independent vectors in $(\mathbf{Z}/p)^n$ can be extended to a basis (if $n \geq 2$). Since the first column has p scalar multiples, the second column has $p^n - p$ choices.
(3) The third column (if $ngeq3$) has to be chosen linearly independently of the first two, which span a 2-dimensional subspace of $(\mathbf{Z}/p)^n$, so the third column has $p^n - p^2$ choices and every such choice is allowed since a set of 3 linearly independent vectors in $(\mathbf{Z}/p)^n$ can be extended to a basis (if $n \geq 3$).

The process continues, with the jth column being anything outside the span of the first $j - 1$ columns, so the jth column has $p^n - p^{j-1}$ choices. We are done when $j = n$, so $|\,\mathrm{GL}_n(\mathbf{Z}/p)| = (p^n - 1)(p^n - p)\cdots(p^n - p^{n-1})$.

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