Congruence Identities Arising From Dynamical Systems

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Abstract

By counting the numbers of periodic points of all periods for some interval maps, we obtain infinitely many new congruence identities in number theory.

Let S be a nonempty set and let f be a map from S into itself. For every positive integer n, we define the n^{th} iterate of f by letting $f^1 = f$ and $f^n = f \circ f^{n-1}$ for $n \geq 2$. For $y \in S$, we call the set $\{ f^k(y) : k \geq 0 \}$ the orbit of y under f. If $f^m(y) = y$ for some positive integer m, we call y a periodic point of f and call the smallest such positive integer m the least period of y under f. We also call periodic points of least period 1 fixed points. It is clear that if y is a periodic point of f with least period m, then, for every integer $1 \leq k \leq m-1$, $f^k(y)$ is also a periodic point of f with least period m and they are all distinct. So, every periodic orbit of f with least period m consists of exactly m points. Since distinct periodic orbits of f are pairwise disjoint, the number (if finite) of distinct periodic points of f with least period m is divisible by m and the quotient equals the number of distinct periodic orbits of f with least period m. Therefore, if there is a way to find the numbers of periodic points of all periods for a map, then we obtain infinitely many congruence identities in number theory. This is an interesting application of dynamical systems theory to number theory which is not found in [**1, 2**].

Let $\phi(m)$ be an integer-valued function defined on the set of all positive integers. If $m = p_1^{k_1} p_2^{k_2} \cdots p_r^{k_r}$, where the p_i's are distinct prime numbers, r and k_i's are positive integers, we let $\Phi_1(1, \phi) = \phi(1)$ and let $\Phi_1(m, \phi) =$

$$\phi(m) - \sum_{i=1}^{r} \phi(\frac{m}{p_i}) + \sum_{i_1 < i_2} \phi(\frac{m}{p_{i_1} p_{i_2}}) - \sum_{i_1 < i_2 < i_3} \phi(\frac{m}{p_{i_1} p_{i_2} p_{i_3}}) + \cdots + (-1)^r \phi(\frac{m}{p_1 p_2 \cdots p_r}),$$

where the summation $\sum_{i_1<i_2<\cdots<i_j}$ is taken over all integers $i_1, i_2, \cdots, i_j$ with $1 \le i_1 < i_2 < \cdots < i_j \le r$. If $m = 2^{k_0} p_1^{k_1} p_2^{k_2} \cdots p_r^{k_r}$, where the p_i's are distinct odd prime numbers, and $k_0 \ge 0, r \ge 1$, and the k_i's ≥ 1 are integers, we let $\Phi_2(m, \phi) =$

$$\phi(m) - \sum_{i=1}^{r} \phi(\frac{m}{p_i}) + \sum_{i_1<i_2} \phi(\frac{m}{p_{i_1} p_{i_2}}) - \sum_{i_1<i_2<i_3} \phi(\frac{m}{p_{i_1} p_{i_2} p_{i_3}}) + \cdots + (-1)^r \phi(\frac{m}{p_1 p_2 \cdots p_r}),$$

If $m = 2^k$, where $k \ge 0$ is an integer, we let $\Phi_2(m, \phi) = \phi(m) - 1$.

Let f be a map from the set S into itself. For every positive integer $m = p_1^{k_1} p_2^{k_2} \cdots p_r^{k_r}$, where p_i's and k_i's are defined as above, if $\phi(m)$ represents the number of distinct solutions of the equation $f^m(x) = x$ (i.e. the number of fixed points of $f^m(x)$) in S, then in the above formula for $\Phi_1(m, \phi)$, the periodic points of f with least period $\frac{m}{p_{i_1}^{t_{i_1}} p_{i_2}^{t_{i_2}} \cdots p_{i_j}^{t_{i_j}}} < m$, where $1 \le t_{i_s} \le k_{i_s}$, $1 \le s \le j$ are integers, have been counted

$$\begin{array}{lll} j & \text{times in the evaluation of} & \phi(\frac{m}{p_{i_u}}), 1 \le u \le j, \\ \binom{j}{2} & \text{times in the evaluation of} & \phi(\frac{m}{p_{i_u} p_{i_v}}), 1 \le u < v \le j, \\ \binom{j}{3} & \text{times in the evaluation of} & \phi(\frac{m}{p_{i_u} p_{i_v} p_{i_w}}), 1 \le u < v < w \le j, \\ & \vdots & \\ \binom{j}{j} & \text{times in the evaluation of} & \phi(\frac{m}{p_{i_1} p_{i_2} \cdots p_{i_j}}). \end{array}$$

Totally, they have been counted

$$-j + \binom{j}{2} - \binom{j}{3} + \cdots + (-1)^j \binom{j}{j} = [(1-1)^j - 1] = -1$$

times. Therefore, $\Phi_1(m, \phi)$ is indeed the number of periodic points of f with least period m. Similar argument applies to Φ_2. So, we obtain the following result:

Theorem 1. *Let S be a nonempty set and let g be a map from S into itself such that, for every positive integer m, the equation $g^m(x) = x$ (or $g^m(x) = -x$ respectively) has only finitely many distinct solutions. Let $\phi(m)$ (or $\psi(m)$ respectively) denote the number of these solutions. Then, for every positive integer m, the following hold:*

(1) The number of periodic points of g with least period m is $\Phi_1(m, \phi)$. Consequently, $\Phi_1(m, \phi) \equiv 0$ (mod m).

(2) If $0 \in S$ and g is odd, then the number of symmetric periodic points (i.e. periodic points whose orbits are symmetric with respect to the origin) of g with least period $2m$ is $\Phi_2(m, \psi)$. Consequently, $\Phi_2(m, \psi) \equiv 0$ (mod $2m$).

Successful applications of the above theorem depend of course on a knowledge of the function ϕ or ψ. For continuous maps from a compact interval into itself, the method of symbolic representations as introduced in **[3, 4, 5]** is very powerful in enumerating the numbers (and hence generating the function ϕ or ψ) of the fixed points of all positive integral powers of the maps. However, to get simple recursive formulas for the function ϕ or ψ, an appropriate map must be chosen. The method of symbolic representations is simple, powerful, and easy to use. Once you get the hang of it, the rest is only routine. See **[3, 4, 5]** for some examples regarding how this method works. In the following, we present some new sequences which are found neither in **[2]** nor in "superseekerresearch.att.com". Proofs of these results can be followed from those of **[3, 4, 5]**.

Theorem 2. *For integers $n \geq 4$ and $1 < m < n-1$, let $f_{m,n}(x)$ be the continuous map from $[1, n]$ onto itself defined by: $f_{m,n}(1) = m+1$, $f_{m,n}(2) = 1$, $f_{m,n}(m) = m-1$, $f_{m,n}(m+1) = m+2$, $f_{m,n}(n-1) = n$, $f_{m,n}(n) = m$, and $f_{m,n}(x)$ is linear on $[j, j+1]$ for every integer j with $1 \leq j \leq n-1$. Also let $f(x)$ be the continuous map from $[1, 4]$ onto itself defined by: $f(1) = f(3) = 4$, $f(2) = 1$, $f(4) = 2$, and $f(x)$ is linear on $[1, 2]$, $[2, 3]$, and on $[3, 4]$. For integers $n \geq 3$, we also define sequences $< a_{n,k} >$ as follows:*

$$a_{n,k} = \begin{cases} 2^{k+1} - 1, & \text{for } 1 \leq k \leq n-1, \\ 3a_{n,k-1} - \sum_{i=2}^{n-1} a_{n,k-i}, & \text{for } n \leq k. \end{cases}$$

Then the following hold:

(a) For any positive integer k, $a_{3,k}$ is the number of distinct fixed points of the map $f^k(x)$ in $[1, 4]$, and for any positive integer k, any integers $n \geq 4$ and $1 < m < n-1$, the number of distinct fixed points of the map $f_{m,n}^k(x)$ in $[1, n]$ is $a_{n,k}$ which is clearly independent of m for all $1 < m < n-1$. Consequently, for any integer $n \geq 3$, if $\phi_{a_n}(k) = a_{n,k}$ and Φ_1 is defined as in Theorem 1, then $\Phi_1(k, \phi_{a_n}) \equiv 0$ (mod k) for all integers $k \geq 1$.

(b) For every integer $n \geq 3$, the generating function $G_{a_n}(z)$ of the sequence $< a_{n,k} >$ is $G_{a_n}(z) = (3z - \sum_{k=2}^{n-1} kz^k)/(1 - 3z + \sum_{k=2}^{n-1} z^k)$.

Theorem 3. *For every integer $n \geq 1$, let $g_n(x)$ be the continuous map from $[1, 2n+1]$ onto itself defined by: $g_n(1) = n+1$, $g_n(2) = 2n+1$, $g_n(n+1) = n+2$, $g_n(n+2) = n$, $g_n(2n+1) = 1$, and $g_n(x)$ is linear on $[j, j+1]$ for every integer j with $1 \leq j \leq 2n$. We also define sequences $< b_{n,k} >$ as follows:*

$$\begin{cases} b_{n,2k-1} = 1, & \text{for } 1 \leq k \leq n, \\ b_{n,2k-1} = 2^{k-n-1}(2k-1) + 1, & \text{for } n+1 \leq k \leq 2n, \\ b_{n,2k} = 2^{k+1} - 1, & \text{for } 1 \leq k \leq 2n, \\ b_{n,k} = 3b_{n,k-2} - \sum_{i=2}^{2n} b_{n,k-2i}, & \text{for } k \geq 4n+1. \end{cases}$$

Then, for any integers $k \geq 1$ and $n \geq 1$, $b_{n,k}$ is the number of distinct fixed points of the map $g_n^k(x)$ in $[1, 2n+1]$. Consequently, if $\phi_{b_n}(k) = b_{n,k}$ and Φ_1 is defined as in Theorem 1, then $\Phi_1(k, \phi_{b_n}) \equiv 0$ (mod k) for all integers $k \geq 1$. Moreover, the generating function $G_{b_n}(z)$ of the sequence $< b_{n,k} >$ is $G_{b_n}(z) = (z + \sum_{k=2}^{2n} (-1)^k kz^k)/(1 - z - \sum_{k=2}^{2n} (-1)^k z^k)$.

Remark. In Theorem 3, when $n = 1$, the sequence $< b_{n,k} >$ becomes the Lucas sequence: 1,3,4,7,11, $\cdots$.

Theorem 4. *For integers $n \geq 2$, $2 \leq j \leq 2n+1$, and $2 \leq m \leq 2n+1$, let $h_{j,m,n}(x)$ be the continuous map from $[1, 2n+2]$ onto itself defined by: $h_{j,m,n}(1) = j$, $h_{j,m,n}(x) = 1$ for all even* *integers x in $[2, 2n]$, $h_{j,m,n}(x) = 2n+2$ for all odd integers x in $[3, 2n+1]$, $h_{j,m,n}(2n+2) = m$, and $h_{j,m,n}(x)$ is linear on $[j, j+1]$ for every integer j with $1 \leq j \leq 2n+1$. We also define sequences $< c_{j,m,n,k} >$ as follows:*

$$c_{j,m,n,k} = \begin{cases} 2n+1, & \textit{for } k = 1, \\ (2n+1)^2 - 2[2n-(j-m)], & \textit{for } k = 2, \\ (2n+1)^3 - 6n[2n+1-(j-m)], & \textit{for } k = 3, \\ (2n+1)c_{j,m,n,k-1} - [2n-(j-m)]c_{j,m,n,k-2} - (j-m)c_{j,m,n,k-3}, & \textit{for } k \geq 4. \end{cases}$$

Then, for any integers $n \geq 2$, $2 \leq j \leq 2n+1$, $2 \leq m \leq 2n+1$, and $k \geq 1$, $c_{j,m,n,k}$ is the number of distinct fixed points of the map $h_{j,m,n}^k(x)$ in $[1, 2n+2]$. Consequently, if $\phi_{c_{j,m,n}}(k) = c_{j,m,n,k}$ and Φ_1 is defined as in Theorem 1, then $\Phi_1(k, \phi_{c_{j,m,n}}) \equiv 0 \pmod{k}$ for all integers $k \geq 1$. Moreover, the generating function $G_{c_{j,m,n}}(z)$ of the sequence $< c_{j,m,n,k} >$ is $G_{c_{j,m,n}}(z) = \{ (2n+1)z - 2[2n-(j-m)]z^2 - 3(j-m)z^3 \} / \{ 1 - (2n+1)z + [2n-(j-m)]z^2 + (j-m)z^3 \}$.

Remarks. (1) For fixed integers $n \geq 2, q, r$, and s, let $\phi(k)$ be the map on the set of all positive integers defined by: $\phi(1) = 2n+1$, $\phi(2) = (2n+1)^2 - 2q$, $\phi(3) = (2n+1)^3 - 6r$ and $\phi(k) = (2n+1)\phi(k-1) - q\phi(k-2) - s\phi(k-3)$ for all integers $k \geq 4$. Then Theorem 4 implies that, for some suitable choices of q, r, s, and a map f, $\phi(k)$ are the numbers of fixed points of $f^k(x)$ and hence, for Φ_1 defined as in Theorem 1, $\Phi_1(k, \phi) \equiv 0 \pmod{k}$ for all integers $k \geq 1$. If we only consider $\phi(k)$ as a sequence of positive integers and disregard whether it represents the numbers of fixed points of all positive integral powers of some map, we can still ask if $\Phi_1(k, \phi) \equiv 0 \pmod{k}$ for all integers $k \geq 1$. Extensive computer experiments suggest that this seems to be the case for some other choices of q, r, and s. Therefore, there should be a number-theoretic approach to this more general problem as does in Theorem 5 below.

(2) Note that, in Theorem 4 above, when $j = 2$ nd $m = 2n+1$, we actually have $c_{2,2n+1,n,k} = (2n-1)^k + 2$ which satisfies the difference equation $c_{2,2n+1,n,k+1} = (2n-1)c_{2,2n+1,n,k} - 4(n-1)$ for all positive integers k.

The following result concerning the linear recurrence of second-order can be obtained by counting the fixed points of all positive integral powers of maps similar to those considered in Theorem 4. The number-theoretic approach can also be found in [**6, 7**].

Theorem 5. *For integers $n \geq 2$ and $1-n \leq m \leq n$, let $< d_{m,n,k} >$ be the sequences defined by*

$$d_{m,n,k} = \begin{cases} n, & \textit{for } k = 1, \\ n^2 + 2m, & \textit{for } k = 2, \\ nd_{m,n,k-1} + md_{m,n,k-2}, & \textit{for } k \geq 3. \end{cases}$$

For any integers $n \geq 2$, $1-n \leq m \leq n$ and $k \geq 1$, if $\phi_{d_{m,n}}(k) = d_{m,n,k}$ and Φ_1 is defined as in Theorem 1, then $\Phi_1(k, \phi_{d_{m,n}}) \equiv 0$ (mod k) for all integers $k \geq 1$. Moreover, the generating function $G_{d_{m,n}}(z)$ of the sequence $< d_{m,n,k} >$ is $G_{d_{m,n}}(z) = (nz + 2mz^2)/(1 - nz - mz^2)$.

The following result is taken from [**4**, Theorem 3]. More similar examples can also be found in [**4**].

Theorem 6. *For every integer $n \geq 2$, let $p_n(x)$ be the continuous odd map from $[-n, n]$ onto itself defined by $p_n(i) = i + 1$ for every integer i with $1 \leq i \leq n-1$, $p_n(n) = -1$, and $p_n(x)$ is linear on $[j, j+1]$ for every integer j with $-n \leq j \leq n-1$. We also define sequences $< s_{n,k} >$ as follows:*

$$s_{n,k} = \begin{cases} 1, & \text{for } 1 \leq k \leq n-1, \\ 2^{k-n}(2k) + 1, & \text{for } n \leq k \leq 2n-1, \\ 3s_{n,k-1} - \sum_{i=2}^{2n-1} s_{n,k-i}, & \text{for } 2n \leq k. \end{cases}$$

Then, for any integers $n \geq 2$ and $k \geq 1$, $a_{2n,k}$ is the number of distinct fixed points of the map $p_n^k(x)$ in $[-n, n]$, where $a_{2n,k}$ is defined as in Theorem 2, and $s_{n,k}$ is the number of distinct solutions of the equation $p_n^k(x) = -x$ in $[-n, n]$. Consequently, if $\psi_{s_n}(k) = s_{n,k}$ and Φ_2 is defined as in Theorem 1, then $\Phi_2(k, \psi_{s_n}) \equiv 0$ (mod $2k$). Moreover, the generating function $G_{s_n}(z)$ of $< s_{n,k} >$ is $G_{s_n}(z) = [z - 2z^2 - z^3 + \sum_{k=5}^{n-1}(k-4)z^k + (3n-4)z^n - \sum_{k=n+1}^{2n-1}(2n-k)z^k]/(1 - 3z + \sum_{k=2}^{2n-1} z^k)$. (When $n = 2$, ignore $-2x^2$, and when $n = 3$, ignore $-x^3$).

Remark. Numerical computations suggest that the maps ψ_{s_n} in Theorem 6 also satisfy $\Phi_1(k, \psi_{s_n}) \equiv 0$ (mod k) for all integers $k \geq 1$. However, our method cannot verify this. There may be an algebraic-theoretic verification of it.

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