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On image sets of integer-valued polynomials

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ABSTRACT

Let $\text{Int}(\mathbb{Z})$ represent the ring of polynomials with rational coefficients which are integer-valued at integers. We determine criteria for two such polynomials to have the same image set on $\mathbb{Z}$.

If $\mathbb{Z}$ represents the integers and $\mathbb{Q}$ the rationals, then let

$$\text{Int}(\mathbb{Z}) = \{ f(X) \mid f(X) \in \mathbb{Q}[X] \text{ with } f(z) \in \mathbb{Z} \text{ for all } z \in \mathbb{Z} \}$$

represent the much studied ring of integer-valued polynomials. Given $f \in \text{Int}(\mathbb{Z})$, we denote the image set of f on $\mathbb{Z}$ as $f(\mathbb{Z}) = \{f(x) \mid x \in \mathbb{Z}\}$, the leading coefficient of f as $\text{lc}(f)$ and the degree of $f(X)$ as $\deg(f(X))$. We also denote the set of nonnegative integers as $\mathbb{N}_0$ and the set of positive integers as $\mathbb{N}$. For $n \in \mathbb{N}_0$, let $\binom{X}{n} = \frac{X(X-1)\cdots(X-n+1)}{n!}$ represent the nth element of the well-known binomial basis of $\text{Int}(\mathbb{Z})$ over $\mathbb{Z}$. The purpose of this note is to characterize the pairs of polynomials (f, g) in $\text{Int}(\mathbb{Z})$ such that $f(\mathbb{Z}) = g(\mathbb{Z})$. Clearly, if $f(X) = z_1$ and $g(X) = z_2$ in $\text{Int}(\mathbb{Z})$ are constant polynomials, then $f(\mathbb{Z}) = g(\mathbb{Z})$ if and only if $z_1 = z_2$. If $f(X)$ in $\text{Int}(\mathbb{Z})$ is not constant, then the image set $f(\mathbb{Z})$ is unbounded. Moreover, if $\deg(f(X))$ and $\deg(g(X))$ have opposite parity (i.e., one even and the other odd), then $f(\mathbb{Z}) \neq g(\mathbb{Z})$.

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Our work is motivated by several papers by McQuillan [8,9] and Gilmer [7] which explore properties related to the rings

$$\mathrm{Int}(S,D)=\{f(X)\mid f(X)\in K[X] \text{ with } f(s)\in D \text{ for all } s\in S\}$$

where D is an integral domain with quotient field K. Particular interest in $\mathrm{Int}(S,D)$ has appeared in the recent literature for the case where $D=\mathbb{Z}$ and $S=\mathbb{P}$ is the set of prime numbers in $\mathbb{Z}$ (see [4,5]). Good general references for rings of integer-valued polynomials determined by subsets are the monograph of Cahen and Chabert [1] or their succeeding survey paper [2]. There is also a connection between the question we explore here and the notions of an interpolation domain (considered in [6,3]) and the parameterization of integral values of polynomials (considered in [10]).

We begin by defining an equivalence relation on $\mathrm{Int}(\mathbb{Z})$, setting $f\sim g$ (for $f,g\in\mathrm{Int}(\mathbb{Z})$) if there is some $n\in\mathbb{Z}$ such that for all $X\in\mathbb{Z}$ either $f(X)=g(X-n)$ or $f(X)=g(-X-n)$. Certainly if $f\sim g$ then $f(\mathbb{Z})=g(\mathbb{Z})$. The converse does not hold, as demonstrated by Lemma 1.

Lemma 1. *Let $f\in\mathrm{Int}(\mathbb{Z})$ be such that $f(-X)=f(X-k)$ for some odd integer k, and set $h(X)=f(2X)$. Then $h(\mathbb{Z})=f(\mathbb{Z})$.*

Proof. Let $x\in\mathbb{Z}$. Then

$$f(x)=\begin{cases} h(\frac{x}{2}) & \text{if } x \text{ is even,}\\ h(\frac{-x-k}{2}) & \text{if } x \text{ is odd}\end{cases}$$

and hence $f(x)\in h(\mathbb{Z})$ so $f(\mathbb{Z})\subseteq h(\mathbb{Z})$. The reverse containment is trivial. □

Note that the condition $f(-X)=f(X-k)$ in Lemma 1 is equivalent to the condition that $f(X-\frac{k}{2})$ be an even function, which in turn implies that $\deg(f)$ is even. This condition applies to all even binomial polynomials $\binom{X}{2n}=\frac{x(x-1)(x-2)\cdots(x-2n+1)}{(2n)!}$.

Our main result is that the equivalence relation $\sim$ together with the phenomenon from Lemma 1 suffice to provide a converse.

Theorem 2. *Let $f,g\in\mathrm{Int}(\mathbb{Z})$, with $|\mathrm{lc}(f)|\leqslant|\mathrm{lc}(g)|$. Then $f(\mathbb{Z})=g(\mathbb{Z})$ if and only if one of the following holds:*

(1) *$f\sim g$, or*
(2) *$f(-X)=f(X-k)$ for some odd integer k, and $g\sim h$ where $h(X)=f(2X)$.*

The remainder of this note is dedicated to the proof of this theorem. In both cases above, $\deg(f)=\deg(g)$. By the comments following Lemma 1, in case (2) this degree must be even. Further, in case (1), $|\mathrm{lc}(f)|=|\mathrm{lc}(g)|$; whereas in case (2), $|\mathrm{lc}(f)|<|\mathrm{lc}(g)|$ (provided $\deg(f)>0$).

We assume henceforth that $f(\mathbb{Z})$, for $f(X)\in\mathrm{Int}(\mathbb{Z})$, is unbounded above. In particular we exclude constant polynomials f. If $\deg(f)>0$, then $|f(\mathbb{Z})|$ is infinite. If $f(\mathbb{Z})$ were bounded above, then it must be unbounded below, so to compare $\{f,g\}$ we instead compare $\{-f,-g\}$, because $(-f)(\mathbb{Z})=(-g)(\mathbb{Z})$ is unbounded above. Hence the function

$$\sigma(x)=\min\{y\colon\ y\in f(\mathbb{Z}),\ y>x\}$$

is well defined. By taking $f(-X)\sim f(X)$ if necessary, we may also assume that $\mathrm{lc}(f)>0$. With this notation and assumptions, we make the following definitions.

Definition 3. Let $f \in \mathrm{Int}(\mathbb{Z})$.

(a) If there exists an $A \in \mathbb{R}$ such that $f(x+1) = \sigma(f(x))$ for all $x \in \mathbb{Z}$ with $x > A$, then f is of *type* 1.
(b) If there exists an $A \in \mathbb{R}$ such that $f(x+1) = \sigma^2(f(x))$ for all $x \in \mathbb{Z}$ with $x > A$, then f is of *type* 2.

Before proceeding to a proof of Theorem 2, Lemmas 5 and 6 will offer a proof of the following (under the above assumptions).

Proposition 4. *Each $f \in \mathrm{Int}(\mathbb{Z})$ is of type 1 or 2.*

Because the conditions of Definition 3 are mutually exclusive, no $f \in \mathrm{Int}(\mathbb{Z})$ can be of both type 1 and type 2. Note that if $f \sim g$, then f, g are of the same type. Our first lemma considers polynomials of odd degree.

Lemma 5. *Let $f \in \mathrm{Int}(\mathbb{Z})$ be of odd degree. Then f is of type 1.*

Proof. Recall that we assume $\mathrm{lc}(f) > 0$, and hence $\lim_{x\to+\infty} f'(x) = +\infty$. We choose $B > 0$ with $f'(x) > 0$ for all $x \geqslant B$. Because $\lim_{x\to+\infty} f(x) = +\infty$ and $\lim_{x\to-\infty} f(x) = -\infty$, we may choose $A > B$ satisfying $f(x) < f(A)$ for all $x < A$ and $f(x) > f(A)$ for all $x > A$. Let $x \in \mathbb{Z}$ with $x > A$. Because $f' > 0$ on $[B, +\infty) \supseteq [A, +\infty)$, $f(x+1) > f(x)$. If there were some $y \in \mathbb{Z}$ with $f(x+1) > f(y) > f(x)$, then $y > A$ by choice of A, but then $x < y < x+1$ by choice of B, which is impossible as $x, y \in \mathbb{Z}$. Hence $f(x+1) = \sigma(f(x))$ and f is of type 1. $\square$

We now consider polynomials of even degree.

Lemma 6. *Let $f \in \mathrm{Int}(\mathbb{Z})$ be of even degree. Then f is of type 1 or 2. It is of type 1 if and only if there is some $k \in \mathbb{Z}$ with $f(X-k) = f(-X)$. Lastly, if f is of type 2 then there is some $k \in \mathbb{Z}$ with $f(x+1) = \sigma(f(-x-k)) = \sigma^2(f(x))$ for all $x > A-k$.*

Proof. Let f be of even degree. As in Lemma 5, there is a constant B so that for all $x > B$, $f(x) < f(x+1)$. However, these might not be consecutive in $f(\mathbb{Z})$.

Suppose first that for some $k \in \mathbb{Z}$, $f(-X) = f(X-k)$. Then $f([B-k, +\infty)) = f((-\infty, -B])$. Thus the only values that can be between $f(x)$ and $f(x+1)$ for $x > N$ are $f((-B, B-k))$. As this set of potential exceptions is finite and $\lim_{x\to+\infty} f(x) = +\infty$, there is some $A > B$ such that, for all $x > A$, $f(x+1) = \sigma(f(x))$. Hence f is of type 1.

Suppose on the other hand that there is no $k \in \mathbb{Z}$ such that $f(-X) = f(X-k)$. We will show that f is of type 2 (and hence not of type 1). Write $f = aX^n + bX^{n-1} + O(X^{n-2})$, with n even. We set $g_t(X) = f(X-t) - f(-X) = (2b - ant)X^{n-1} + O(X^{n-2})$, and set $c = \frac{2b}{an}$. For $t \neq c$, we have $\mathrm{lc}(g_t) = 2b - ant$. Hence $\mathrm{lc}(g_t) > 0$ for $t < c$ and $\mathrm{lc}(g_t) < 0$ for $t > c$. We claim there exists $k \in \mathbb{Z}$ such that $\mathrm{lc}(g_{k-1}) > 0$ and $\mathrm{lc}(g_k) < 0$. If $c \notin \mathbb{Z}$, then choose $k = 1 + \lfloor c \rfloor$. If $c \in \mathbb{Z}$, then by our hypothesis g_c is not the zero polynomial so $\mathrm{lc}(g_c) \neq 0$. If $\mathrm{lc}(g_c) < 0$ choose $k = c$, otherwise choose $k = c+1$.

It follows that there is an integer constant $C > B$ so that, for all $x \geqslant C$, $g_{k-1}(x) > 0$ and $g_k(x) < 0$, that is $f(x-k+1) > f(-x) > f(x-k)$. Applying these inequalities repeatedly yields $f(C-k) < f(-C) < f(C-k+1) < f(-C-1) < f(C-k+2) < \cdots$. Only $f((-C, C-k))$ does not appear here. As this list is finite, there is some constant $A > C$ so that for all $x > A$, $f(x+1) = \sigma^2(f(x))$. Hence f is of type 2. $\square$

We are now ready to consider the case of $f, g \in \mathrm{Int}(\mathbb{Z})$ with $f(\mathbb{Z}) = g(\mathbb{Z})$. In Lemma 7 we will show that if f, g are of the same type then $f \sim g$. We will then show in Lemma 8 that if f is of type 1 and g is of type 2, then $f \nsim g$ and in fact $g(X) \sim f(2X)$.

Lemma 7. *Let $f, g \in \mathrm{Int}(\mathbb{Z})$ be of the same type with $f(\mathbb{Z}) = g(\mathbb{Z})$. Then $f \sim g$.*

Proof. Suppose first that f, g are of type 1, with corresponding constants A_f, A_g. Let $x \in \mathbb{Z}$ be chosen with $x > \max(A_f, A_g)$. Assume without loss that $f(x) \geqslant g(x)$. Since $x > A_g$ and $f(x) \in g(\mathbb{Z})$, it follows that $f(x) = \sigma^n(g(x)) = g(x+n)$ for some $n \in \mathbb{N}_0$. But now $f(x+j) = \sigma^j(f(x)) = \sigma^{n+j}(g(x)) = g(x+n+j)$ for all $j \in \mathbb{N}_0$. Hence $f(X) = g(X+n)$ and thus $f \sim g$.

Suppose now that f, g are of type 2, with corresponding constants A_f, A_g. There are integers $x, k, y, h \in \mathbb{Z}$ so that $f(x) < f(-x-k) < f(x+1) < f(-x-k-1) < \cdots$, these being consecutive values of f, and $g(y) < g(-y-h) < g(y+1) < g(-y-h-1) < \cdots$, these being consecutive values of g. As $f(\mathbb{Z}) = g(\mathbb{Z})$, we can arrange x and y to be such that either $f(x) = g(y)$ or $f(x) = g(-y-h)$, the values of both lists agreeing from then on. In the first case, let $n = y - x$. Then, $f(X)$ and $g(X+n)$ agree on $x, x+1, \ldots$ and thus $f(X) = g(X+n)$. In the second case, let $n = y + h - x$. Then $f(X)$ and $g(-X-n)$ agree on $x, x+1, \ldots$ and thus $f(X) = g(-X-n)$. In both cases $f \sim g$. $\square$

Lemma 8. *Let $f, g \in \mathrm{Int}(\mathbb{Z})$ with $f(\mathbb{Z}) = g(\mathbb{Z})$. Suppose that f is of type* 1 *and g is of type* 2. *Then $f(-X) = f(X-k)$ for some odd integer k, and $g \sim h$ where $h(X) = f(2X)$.*

Proof. Let $x, y, k \in \mathbb{Z}$ be such that $f(x) < f(x+1) < f(x+2) < \cdots$, these being consecutive values of f, and $g(y) < g(-y-k) < g(y+1) < g(-y-k-1) < \cdots$, these being consecutive values of g. Let $h(X) = f(2X)$. We arrange the lists so that either $h(x) = g(y)$ or $h(x) = g(-y-k)$. In the first case, for all $j \in \mathbb{N}_0$ we have that $h(x+j) = f(2x+2j) = \sigma^{2j}(f(2x)) = \sigma^{2j}(h(x)) = \sigma^{2j}(g(y)) = g(y+j)$ and hence $h(X) = g(Y)$. In the second case, for all $j \in \mathbb{N}_0$, $h(x+j) = f(2x+2j) = \sigma^{2j}(f(2x)) = \sigma^{2j}(h(x)) = \sigma^{2j}(g(-y-k)) = g(-y-k-j)$ and hence $h(X) = g(-Y-k)$. In either case, $h \sim g$.

As g is of type 2, $\deg(g)$ is even. Since $h \sim g$, $\deg(h)$ must be even. Finally $\deg(f) = \deg(h)$, so $\deg(f)$ is even. As f is of type 1, by Lemma 6 there is some $k \in \mathbb{Z}$ with $f(X-k) = f(-X)$. Now h satisfies $h(-X) = h(X - \frac{k}{2})$. But h is of type 2 since $h \sim g$. Hence, by Lemma 6, $\frac{k}{2}$ is not an integer and hence k is odd. $\square$

By Lemma 6 we know that all type 1 even-degree polynomials f satisfy $f(X-k) = f(-X)$ for some $k \in \mathbb{Z}$. By Lemma 8 we know that if such a polynomial shares an image set with a type 2 polynomial, then k must be odd. Lemma 1 gives the converse of this statement and completes the proof of Theorem 2.

We note that our proofs did not use the full power of $f(\mathbb{Z}) = g(\mathbb{Z})$, rather the intersection of each image set with some ray $[C, +\infty)$. This raises the question of what other infinite subsets of $\mathbb{Z}$ might be used instead of such a ray. Also, if we replace $(\mathbb{Z}, \mathbb{Q})$ with some other pair of domains, a natural question is to characterize when f, g have the same image on the subdomain.

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