Series Polynomials

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The challenge question in Exercise 3B of the Edexcel AS and A Level Further Maths Core book is about series sums of polynomials.

Part a of this question asks for polynomials $f_2(x)$, $f_3(x)$, $f_4(x)$ such that for every $n \in \mathbb{N}$, $n > 1$,

$$\sum_{r=1}^{n} f_2(r) = n^2$$
$$\sum_{r=1}^{n} f_3(r) = n^3$$
$$\sum_{r=1}^{n} f_4(r) = n^4$$

Finding these polynomials reveals a very interesting pattern, links to the Bernoulli numbers, and has a very nice general form.

1 Finding Polynomials

Throughout this paper, all $n \in \mathbb{N}$, $n > 1$.

Let's first establish some basic lemmas about series.

Lemma 1 $\displaystyle\sum_{r=1}^{n}(f(r) + g(r)) = \sum_{r=1}^{n} f(r) + \sum_{r=1}^{n} g(r)$

Lemma 2 $\displaystyle\sum_{r=1}^{n} kf(r) = k\sum_{r=1}^{n} f(r)$

Lemma 3 $\displaystyle\sum_{r=1}^{n} 1 = n$

Lemma 4 $\displaystyle\sum_{r=1}^{n} r = \frac{1}{2}n(n+1)$

Lemma 5 $\displaystyle\sum_{r=1}^{n} r^2 = \frac{1}{6}n(n+1)(2n+1)$

Lemma 6 $\displaystyle\sum_{r=1}^{n} r^3 = \frac{1}{4}n^2(n+1)^2$

1.1 Finding $f_2(r)$

We want a polynomial $f_2(r)$ such that $\sum\limits_{r=1}^{n} f_2(r) = n^2$.

We already have, by Lemma 4,

$$\sum_{r=1}^{n} r = \frac{1}{2}n(n+1) = \frac{1}{2}\left(n^2+n\right)$$

We need to get rid of the $\frac{1}{2}$, which we can do by multiplying by 2 to get

$$2\sum_{r=1}^{n} r = \sum_{r=1}^{n} 2r = n^2 + n$$

Then, we just need to get rid of the n.

We know, by Lemma 3, that $\sum\limits_{r=1}^{n} 1 = n$, so

$$\sum_{r=1}^{n} 2r - \sum_{r=1}^{n} 1 = \sum_{r=1}^{n}(2r-1) = n^2$$
$$\therefore f_2(r) = 2r - 1$$

1.2 Finding $f_3(r)$

Next, we want a polynomial $f_3(r)$ such that $\sum\limits_{r=1}^{n} f_3(r) = n^3$.

Similarly to with $f_2(r)$, by Lemma 5, we already have

$$\begin{aligned}\sum_{r=1}^{n} r^2 &= \frac{1}{6}n(n+1)(2n+1)\\ &= \frac{1}{3}n^3 + \frac{1}{2}n^2 + \frac{1}{6}n\\ &= \frac{1}{3}\left(n^3 + \frac{3}{2}n^2 + \frac{1}{2}n\right)\end{aligned}$$

We can then multiply by 3 to remove the $\frac{1}{3}$ and get

$$3\sum_{r=1}^{n} r^2 = \sum_{r=1}^{n} 3r^2 = n^3 + \frac{3}{2}n^2 + \frac{1}{2}n$$

To get rid of the $\frac{1}{2}n$, we can just do

$$\sum_{r=1}^{n} 3r^2 - \sum_{r=1}^{n} \frac{1}{2} = \sum_{r=1}^{n}\left(3r^2 - \frac{1}{2}\right) = n^3 + \frac{3}{2}n^2$$

We know that $\sum\limits_{r=1}^{n} f_2(r) = n^2$, so we simply need to subtract $\frac{3}{2}f_2(r)$ from our polynomial to get rid of the resultant $\frac{3}{2}n^2$.

$$3r^2 - \frac{1}{2} - \frac{3}{2}(2r-1) = 3r^2 - 3r + 1$$
$$\therefore f_3(r) = 3r^2 - 3r + 1$$

1.3 Finding $f_4(r)$

Next, we want a polynomial $f_4(r)$ such that $\sum_{r=1}^{n} f_4(r) = n^4$.

We know, by Lemma 6, that

$$\begin{aligned}\sum_{r=1}^{n} r^3 &= \frac{1}{4}n^2(n+1)^2 \\ &= \frac{1}{4}\left(n^4 + 2n^3 + n^2\right)\end{aligned}$$

We can multiply by 4 to get

$$4\sum_{r=1}^{n} r^3 = \sum_{r=1}^{n} 4r^3 = n^4 + 2n^3 + n^2$$

We can then get n^4 on its own by subtracting $2f_3(r)$ and $f_2(r)$ from $4r^3$.

$$\begin{gathered}4r^3 - 2\left(3r^2 - 3r + 1\right) - (2r - 1) \\ = 4r^3 - 6r^2 + 6r - 2 - 2r + 1 \\ = 4r^3 - 6r^2 + 4r - 1 \\ \therefore f_4(r) = 4r^3 - 6r^2 + 4r - 1\end{gathered}$$

2 Finding Patterns

We can find $f_1(r)$, where $\sum_{r=1}^{n} f_1(r) = n^1 = n$ to trivially be 1.

These are our polynomials:

$$\begin{aligned}&f_1(r) = 1 \\ &f_2(r) = 2r - 1 \\ &f_3(r) = 3r^2 - 3r + 1 \\ &f_4(r) = 4r^3 - 6r^2 + 4r - 1\end{aligned}$$

After looking at these for a while, we can notice a few things. Firstly, the constants are always ± 1, and the signs of these constants alternate with increasing degrees of polynomial. In fact, all the signs alternate.

Secondly, we can notice that the first term of $f_a(r)$ is always of the form ar^{a-1}.

However, the most interesting thing to notice with these polynomials is that the coefficients look like binomial expansions of $(r-1)^a$, albeit with the leading term removed and the signs flipped.

We can continue this pattern to make a conjecture about $f_5(r)$.

Conjecture 1 $f_5(r) = 5r^4 - 10r^3 + 10r^2 - 5r + 1$

To conjecture a general form, we have to think about how we go from $(r-1)^a$ to these polynomials.

Lets look at the example of $f_4(r)$.

$$(r-1)^4 = r^4 - 4r^3 + 6r^2 - 4r + 1$$

We have the change the signs of all of these, so we get

$$-(r-1)^4 = -r^4 + 4r^3 - 6r^2 + 4r - 1$$

Then we have to remove the leading $-r^4$ and we get $-(r-1)^4 + r^4$, or more simply, $r^4 - (r-1)^4$.

This form of $r^a - (r-1)^a$ gives the results seen previously for $f_a(r)$, so we can conjecture that this pattern continues for all $a \in \mathbb{Z}^+$.

$\mathbb{Z}^+$ is simply the set of positive integers, not including 0. This is simpler than writing $a \in \mathbb{N},\ a > 0$.

Rather than conjecturing about $f_a(r)$, we want to conjecture about its sum to n.

Conjecture 2 $\forall\ a, n \in \mathbb{Z}^+,\ n > 1,\ \sum_{r=1}^{n} (r^a - (r-1)^a) = n^a$

2.1 Proving Conjecture 1

In order to prove Conjecture 1, we need to know the formula for $\sum_{r=1}^{n} r^4$. Wolfram Alpha says:

Lemma 7 $\sum_{r=1}^{n} r^4 = \frac{1}{30} n(n+1)(2n+1)\left(3n^2 + 3n - 1\right)$

This can then be expanded to give

$$\frac{1}{5}n^5 + \frac{1}{2}n^4 + \frac{1}{3}n^3 - \frac{1}{30}n$$
$$= \frac{1}{5}\left(n^5 + \frac{5}{2}n^4 + \frac{5}{3}n^3 - \frac{1}{6}n\right)$$

We can multiply by 5 to get

$$5\sum_{r=1}^{n} r^4 = \sum_{r=1}^{n} 5r^4 = n^5 + \frac{5}{2}n^4 + \frac{5}{3}n^3 - \frac{1}{6}n$$

Now, we just need to get rid of the other terms to get a polynomial $f_5(r)$ such that $\sum_{r=1}^{n} f_5(r) = n^5$.

$$f_5(r) = 5r^4 - \frac{5}{2}f_4(r) - \frac{5}{3}f_3(r) + \frac{1}{6}f_1(r)$$
$$= 5r^4 - \frac{5}{2}\left(4r^3 - 6r^2 + 4r - 1\right) - \frac{5}{3}\left(3r^2 - 3r + 1\right) + \frac{1}{6}$$
$$= 5r^4 - 10r^3 + 10r^2 - 5r + 1$$

This proves Conjecture 1.

However, to prove Conjecture 2, we need to find more patterns.

3 Finding Patterns (again)

Let's look at sums of powers of r. By Lemmas 3 to 7, we have

$$\begin{aligned}
\sum_{r=1}^{n} r^0 &= n &&= n \\
\sum_{r=1}^{n} r^1 &= \frac{1}{2}n(n+1) &&= \frac{1}{2}n^2 + \frac{1}{2}n \\
\sum_{r=1}^{n} r^2 &= \frac{1}{6}n(n+1)(2n+1) &&= \frac{1}{3}n^3 + \frac{1}{2}n^2 + \frac{1}{6}n \\
\sum_{r=1}^{n} r^3 &= \frac{1}{4}n^2(n+1)^2 &&= \frac{1}{4}n^4 + \frac{1}{2}n^3 + \frac{1}{4}n^2 \\
\sum_{r=1}^{n} r^4 &= \frac{1}{30}n(n+1)(2n+1)\left(3n^2+3n-1\right) &&= \frac{1}{5}n^5 + \frac{1}{2}n^4 + \frac{1}{3}n^3 - \frac{1}{30}n
\end{aligned}$$

I can't see much of a pattern here, but the first term of $\sum\limits_{r=1}^{n} r^b$ always seems to be $\frac{1}{b+1}n^{b+1}$ and the second term always seems to be $\frac{1}{2}n^b$, except in the case of $b = 0$.

I don't think I would able to find a formula for $\sum\limits_{r=1}^{n} r^b$ on my own, but in doing some research on this topic, I found Faulhaber's formula on a wiki page on brilliant.org[1]. I shall rewrite the formula here.

$$\sum_{r=1}^{n} r^b = \frac{1}{b+1}\sum_{j=0}^{b}(-1)^j\binom{b+1}{j}B_j n^{b+1-j}$$

where B_j is the jth Bernoulli number.

In doing further research, I found that this is where the Bernoulli numbers were originally found by Jacob Bernoulli in *Ars Conjectandi*, published in 1713. He was trying to find a general formula for $\sum\limits_{r=1}^{n} r^b$ and found these numbers. He could not relate them to any previously known sequence, and de Moivre named them after him.[2]

Not only that, but Jacob Bernoulli mentioned Faulhaber by name in *Ars Conjectandi*. People have wondered about this problem long before me, and this is where the famous Bernoulli numbers originally came from.

Bernoulli might have written $\sum\limits_{r=1}^{n} r^b$ as

$$\sum_{r=1}^{n} r^b = \sum_{r=0}^{b} \frac{B_r}{r!} b^{\underline{r-1}} n^{b-r+1}$$

where $p^{\underline{q}}$ is the falling factorial $p \times (p-1) \times (p-2) \times \cdots \times (p-q+1)$.

4 Proving Conjecture 2

I expected proving Conjecture 2 to be hard, but it's actually quite easy and doesn't require the Bernoulli numbers at all. I got these ideas from a phenomenal Mathologer video[3], in which Burkard talks about Bernoulli's attempts to find a general formula for $\sum\limits_{r=1}^{n} r^b$, but not before showing off a beautiful recurrence relation for finding these formulas.

I am incredibly thankful for Burkard and the people at Mathologer for producing such wonderful and engaging mathematical content. They have definitely helped to foster my love of mathematics, and I highly recommend the channel to anyone with an interest in maths. Anyway, onto the proof.

4.1 The Proof

We can find successive summation formulas by manipulating binomial expansions. For the sake of notation, let $\sum_{r=1}^{n} r^b$ be written as S_b.

The formulas for S_0, S_1, and S_2 can be found relatively easily through many different methods, which I won't talk about here. But let's say we wanted to find a formula for S_3. How would we do this? Well, we want to relate different powers, and we can do that nicely with some binomial expansion.

To find S_3, we look at $(r-1)^4$. This expands to give $r^4 - 4r^3 + 6r^2 - 4r + 1$. We can manipulate this and get

$$(r-1)^4 = r^4 - 4r^3 + 6r^2 - 4r + 1$$
$$\implies 4r^3 - 6r^2 + 4r - 1 = r^4 - (r-1)^4$$

We can now substitute different values for r and get a list of equations.

$$\begin{gathered}
4 \cdot 1^3 - 6 \cdot 1^2 + 4 \cdot 1^1 - 1 \cdot 1^0 = 1^4 - \cancel{(1-1)^4} \\
4 \cdot 2^3 - 6 \cdot 2^2 + 4 \cdot 2^1 - 1 \cdot 2^0 = 2^4 - (2-1)^4 \\
4 \cdot 3^3 - 6 \cdot 3^2 + 4 \cdot 3^1 - 1 \cdot 3^0 = 3^4 - (3-1)^4 \\
\vdots \\
4 \cdot n^3 - 6 \cdot n^2 + 4 \cdot n^1 - 1 \cdot n^0 = n^4 - (n-1)^4
\end{gathered}$$

We can now sum these equations. On the RHS, the terms in brackets are cancelled out by the first term on the RHS in the line above. $-(2-1)^4$ cancels with 1^4, $-(3-1)^4$ cancels with 2^4, etc. and we end up with just n^4.

On the LHS, we simply get $4S_3 - 6S_2 + 4S_1 - 1S_0$. This means that

$$4S_3 - 6S_2 + 4S_1 - 1S_0 = n^4$$

Since we know S_0, S_1, and S_2, we can simply solve for S_3 and get

$$\begin{aligned}
S_3 &= \frac{n^4 + 6S_2 - 4S_1 + 1S_0}{4} \\
&= \frac{n^4 + n(n+1)(2n+1) - 2n(n+1) + n}{4} \\
&= \frac{n(n^3 + (n+1)(2n+1) - 2(n+1) + 1)}{4} \\
&= \frac{n(n^3 + 2n^2 + 3n + 1 - 2n - 2 + 1)}{4} \\
&= \frac{n(n^3 + 2n^2 + n)}{4} \\
&= \frac{n^2(n+1)^2}{4}
\end{aligned}$$

This is the formula given by Lemma 6, so we know we've done this correctly.

It can be quite easily seen that this process continues and can be used to generate $S_b \; \forall \; b \in \mathbb{Z}^+$.

Now that we have a way of generating every S_b, we can use that to prove Conjecture 2. It's actually remarkably simple.

Let's backtrack a little to when we had $4S_3 - 6S_2 + 4S_1 - 1S_0 = n^4$. This equation is all we need. We can expand the S_b terms to their equivalent sums and use Lemmas 1 and 2 to manipulate this.

$$4S_3 - 6S_2 + 4S_1 - 1S_0 = n^4$$
$$\implies 4\sum_{r=1}^{n} r^3 - 6\sum_{r=1}^{n} r^2 + 4\sum_{r=1}^{n} r^1 - 1\sum_{r=1}^{n} r^0 = n^4$$
$$\implies \sum_{r=1}^{n}(4r^3 - 6r^2 + 4r - 1) = n^4$$

This is exactly $f_4(r)$. Since this process can generate all S_b, it will also generate all $f_a(r)$.

Therefore, $\sum_{r=1}^{n}(r^a - (r-1)^a) = n^a$. Thus, we have proven Conjecture 2.

$\square$

5 Conclusion

I first did that challenge question months ago. This conjecture has bugged me since I first posited it, but I hadn't properly looked into it until recently, and when I did, I could prove it in a day. I quite like this proof, and it is quite elegant in my eyes. I think the reason I didn't find it sooner was because I assumed the problem to be harder than it was. I assumed I'd have to find a general formula for $\sum_{r=1}^{n} r^b$, and then I'd have to manipulate it in quite a complicated proof, but this recurrence relation thing to generate S_b is beautiful, because $f_a(r)$ just falls out of it.

I assume there's a name for this polynomial $f_a(r)$ in the context of these sums, where $\sum_{r=1}^{n} f_a(r) = n^a$, but I don't know what it's called. So for now, I'm going to call it the Dyson Sum Function.

Humility? Sorry, I don't know what that is.

References

[1] *Sum of n, n^2, or n^3*. Brilliant. URL: `https://brilliant.org/wiki/sum-of-n-n2-or-n3/`.

[2] *Bernoulli number*. URL: `https://en.wikipedia.org/wiki/Bernoulli_number`.

[3] Mathologer. *Power sum MASTER CLASS: How to sum quadrillions of powers ... by hand! (Euler-Maclaurin formula)*. Oct. 26, 2019. URL: `https://www.youtube.com/watch?v=fw1kRz83Fj0`.