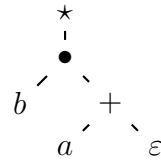


Analytic Combinatorics of Unlabeled Objects

Set of exercises II: responses

1. Consider the combinatorial class \mathcal{R} of regular expressions as unary-binary trees:

- leaves are decorated by the letters “ a ”, “ b ” or the empty word “ ε ”.
- internal binary nodes are decorated by the operators union “ $+$ ” or concatenation “ \bullet ”,
- internal unary-nodes are decorated by the Kleene-star “ \star ”.



$$(b \cdot (a + \varepsilon))^*$$

Give a combinatorial specification. Determine the ordinary generating function supposing that the size is the total number of nodes.

Response. The specification is

$$\mathcal{R} = \{a, b, \varepsilon\} + \{\star\} \times \mathcal{R} + \{+\} \times \mathcal{R} \times \mathcal{R} + \{\bullet\} \times \mathcal{R} \times \mathcal{R}.$$

This translates into an equation for the OGF $R(z)$,

$$R(z) = 3z + zR(z) + 2z(R(z))^2,$$

since here every node (even the leaves) have size 1.

Solving the equation we obtain:

$$R(z) = \frac{1 - z - \sqrt{1 - 2z - 23z^2}}{4z},$$

noting that the other root does not make sense at $z = 0$.

2. Postponed to TD3.

3. We recall that integer compositions are specified by

$$\mathcal{C} = \text{Seq}(\{1, 2, 3, \dots\}) \simeq \text{Seq}(\text{Seq}_{\geq 1}(\mathcal{Z})).$$

During class, we used OGFs to prove that the average number of terms in a composition of n is $\sim n/2$.

- What if we restricted the compositions to have an even number of terms? Find the total number of compositions of n into an even number of terms.
- Let us consider now the number of even terms in a general composition of n . Show that the average number of even terms is $\sim n/6$.
- Now we want to fix the number m of even terms. Find the generating function.

Responses.

- (a) This can be done by simply considering a constrained “Seq” constructor in which we just consider the even powers. We obtain

$$\mathcal{C}_2 = \text{Seq}_{\text{even}}(\{1, 2, 3, \dots\}) \implies C_2(z) = \frac{1}{1 - \left(\frac{z}{1-z}\right)^2} = \frac{(1-z)^2}{1-2z} = 1 + \frac{z^2}{1-2z}.$$

Another possible way to see this is to mark the number of terms and extract the even terms, or even considering that $\mathcal{C}_2 = \text{Seq}(\{1, 2, 3, \dots\} \times \{1, 2, 3, \dots\})$, a sequence of pairs.

For the total number of partitions into even parts we obtain, for $n \geq 2$

$$[z^n]C_2(z) = [z^n]\frac{z^2}{1-2z} = [z^{n-2}]\frac{1}{1-2z} = 2^{n-2}.$$

We note that $[z^0]C_2(z) = 1$ and $[z^1]C_2(z) = 0$.

- (b) We mark the even terms

$$\mathcal{C} = \text{Seq}(\mathcal{U} \times \{2, 4, 6, \dots\} + \{1, 3, 5, \dots\}) \implies C(z, u) = \frac{1}{1 - u\frac{z^2}{1-z^2} - \frac{z}{1-z^2}} = \frac{1-z^2}{1-z-(1+u)z^2}.$$

Differentiating in u and then setting $u = 1$ we obtain

$$\partial_u C(z, 1) = z^2 \frac{1-z}{(1+z)(1-2z)^2}.$$

Apply partial fractions

$$\frac{1-z}{(1+z)(1-2z)^2} = \frac{1/3}{(1-2z)^2} + \frac{-4/9}{1-2z} + \frac{2/9}{1+z}.$$

Extracting coefficients and noting that the dominant terms come from $\frac{1/3}{(1-2z)^2}$,

$$[z^n]\partial_u C(z, 1) = [z^{n-2}]\frac{1-z}{(1+z)(1-2z)^2} \sim [z^{n-2}]\frac{1/3}{(1-2z)^2} = \frac{1}{3}(n-1)2^{n-2}.$$

Since $[z^n]C(z, 1) = 2^{n-1}$, dividing we obtain $\frac{[z^n]\partial_u C(z, 1)}{[z^n]C(z, 1)} \sim \frac{1}{6}n$.

- (c) The generating function we look for is $F_m(z) = [u^m]C(z, u)$. Thus, expanding the binomials and summing the contributions

$$F_m(z) = [u^m] \sum_{k=0}^{\infty} \left(u \frac{z^2}{1-z^2} + \frac{z}{1-z^2} \right)^k = \sum_{k=0}^{\infty} \binom{k}{m} \frac{z^{2m}}{(1-z^2)^m} \left(\frac{z}{1-z^2} \right)^{k-m}.$$

We simplify the latter expression by using $\sum \binom{k}{m} u^k = \frac{u^m}{(1-u)^{m+1}}$,

$$F_m(z) = z^m \sum_{k=0}^{\infty} \binom{k}{m} \left(\frac{z}{1-z^2} \right)^k = z^m \frac{\left(\frac{z}{1-z^2} \right)^m}{\left(1 - \left(\frac{z}{1-z^2} \right) \right)^{m+1}} = \frac{z^{2m}}{(1-z-z^2)^{m+1}}.$$

4. We consider the binary trees

$$\mathcal{B} = \mathcal{E} + \mathcal{Z} \times \mathcal{B} \times \mathcal{B},$$

where the node \mathcal{E} is the empty-node, while \mathcal{Z} is an atom of weight 1.

- (a) Give a specification for the binary trees \mathcal{B}° marking the length of the left-most branch.
- (b) Solve the equation for $B(z, u)$ and show $\partial_u B(z, 1) = z(B(z))^3$.
- (c) Let $A(z) = zB(z)$. Apply the Lagrange Inversion Formula to compute $[z^n](A(z))^3$.
- (d) Deduce that the average length of the left-most branch tends to 3 as $n \rightarrow \infty$.
- (e) Generalize. Find the exact number of binary trees of size n with left-most branch of length m .

Responses.

- (a) We consider \mathcal{B} as given, and we have $\mathcal{B}^\circ = \mathcal{E} + \mathcal{Z} \times \mathcal{U} \times \mathcal{B}^\circ \times \mathcal{B}$.
Another specification is the following:

$$\mathcal{B}^\circ = \text{Seq}(\mathcal{Z} \times \mathcal{U} \times \mathcal{B}),$$

by seeing the left-most branch as a list with binary trees pending on the right of each node.

- (b) We have $B(z, u) = \frac{1}{1-zuB(z)}$. Differentiating we find $\partial_z B(z, 1) = \frac{zB(z)}{(1-zB(z))^2}$.
Recall that $B(z) = 1 + z(B(z))^2$, thus we derive $B(z) = \frac{1}{1-zB(z)}$. We deduce from this that $\partial_z B(z, 1) = z(B(z))^3$.
- (c) We have $A(z) = z\phi(A(z))$ with $\phi(u) = \frac{1}{1-u}$. Indeed $B(z) = \frac{1}{1-zB(z)}$. We deduce, applying the LIF with $f(u) = u^3$ and $\phi(u) = \frac{1}{1-u}$,

$$[z^n]A(z)^3 = \frac{[u^{n-1}]}{n} \{3u^2(\phi(u))^n\} = \frac{3}{n} [u^{n-3}] \left\{ \frac{1}{(1-u)^n} \right\} = \frac{3}{n} \binom{n-1+n-3}{n-3}.$$

Thus $[z^n]A(z)^3 = \frac{3}{n} \binom{2n-4}{n-3}$.

- (d) We have $[z^n]\partial_u B(z, 1) = [z^n]zB(z)^3 = [z^{n+2}]A(z)^3 = \frac{3}{n+2} \binom{2n}{n-1}$ while $[z^n]B(z) = \binom{2n}{n} \frac{1}{n+1}$. Dividing we obtain the average length:

$$3 \frac{n+1}{n+2} \frac{\binom{2n}{n-1}}{\binom{2n}{n}} = 3 \frac{n+1}{n+2} \times \frac{n}{n+1} = 3 \frac{n}{n+2} \rightarrow 3.$$

- (e) We extract $[u^m]B(z, u) = [u^m] \frac{1}{1-zuB(z)} = (zB(z))^m$, which is the generating function of the trees having left-most branch of length m . We apply the same argument to $A(z)$.
The total number of trees of size n with left-most branch of length m is:

$$[z^n]A(z)^m = \frac{m}{n} [u^{n-m}] \left\{ \frac{1}{(1-u)^n} \right\} = \frac{m}{n} \binom{n-1+n-m}{n-m}$$