The "Monkey Typing Shakespeare" Problem for Compositions

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Pattern Avoidance

The *theme* of *pattern-avoidance*, i.e. the question

'How Many objects of such and such kind avoid such and such patterns?'

is everywhere dense in combinatorics. Often the problems are so hard that the *mere* existence is highly non-trivial, for example in Ramsey theory and Roth and Szemerédi's theorems.

[We understand the word 'pattern' in a general sense, the notion of 'permutation pattern' ([Wi],[HM]) is only one case.]

One of the simplest such problems is when the objects are *words* in a fixed finite alphabet (say our very own A-Z, consisting of 26 letters) and the pattern to avoid is a fixed *consecutive* subword (say the collected works of the Bard arranged in lexicographic order of titles, ignoring spaces and punctuation marks). It is easy to see that the probability that a monkey typing n letters randomly will *avoid* a run of the (long but finite) string consisting of Willie's opus is less than α^n for some fixed constant α *strictly* less than 1, hence if the monkey lives long enough he will sooner or later succeed. Of course it is latttttttttttttttttttttttttttttttttter rather than sooner, but we mathematicians pretend that we, and our monkeys, are immortal.

The problem of finding the *exact* probability of a random word in a fixed (finite) alphabet avoiding a pre-determined string (or set of strings) as *consecutive* subwords (or equivalently counting the number of such words) is handled by the *Goulden-Jackson Cluster Method* [GJ], beautifully exposited, and extended, in [NZ].

Another, much harder, example of the notion of *pattern-avoidance* is the one used in the very active field of *permutation patterns* [Wi], that has been beautifully extended to compositions and words in Silvia Heurbach and Toufik Mansour's magnum opus [MH].

This article

In this article we will also talk about compositions, but the notion of *pattern* is different. If we define a pattern just as the *literal* occurrence of a consecutive subword, then we get a straightforward generalization of the Goulden-Jackson set-up ([GJ] [NZ]). In this article, we fill a much needed gap (Oops, we meant 'fill a gap that was in great need of being filled') and describe an algorithm, fully implemented in Maple, to enumerate the problem of avoiding (consecutive) *containment* of *compositions*, in a sense to be explained shortly.

The algorithm is fully implemented in the Maple package `Compositions.txt`, written by the second-named author, available from the url

`http://sites.math.rutgers.edu/~zeilberg/mamamrim/mamarimhtml/kof.html` ,

where one can also find extensive sample output files, created by the first-named author.

First we must recall the definition of *composition* and then what we mean by a composition *avoiding* another composition by *containment*.

Compositions

Recall that a *composition* of a non-negative integer n is an **ordered** list $a_1\, a_2\, \dots\, a_k$ of **positive** integers that add-up to n.

For example, the set of compositions of 4 is

$$\{4, 13, 31, 22, 112, 121, 211, 1111\} \quad .$$

The number of compositions of n is famously 2^{n-1} for $n > 0$ and 1 for $n = 0$. A quick way to see it is by assigning the composition $a_1 a_2 \dots a_k$ to the subset of $\{1, ..., n-1\}$ given by $\{a_1, a_1 + a_2, \dots, a_1 + \dots + a_{k-1}\}$. This is a bijection. Another way to prove this trivial fact is via generating functions. The generating function of a single entry is $\sum_{i=1}^{\infty} x^i = \frac{x}{x-1}$. The generating function of compositions into exactly k parts is, by 'independence', $(\frac{x}{x-1})^k$, hence the generating function of all compositions is $\sum_{k=0}^{\infty} (\frac{x}{x-1})^k = 1/(1 - \frac{x}{x-1}) = \frac{1-x}{1-2x} = 1 + \frac{x}{1-2x}$.

When does a composition include another composition?

Definition: The composition $a_1 \dots a_k$ *includes* the composition $b_1 \dots b_s$ if $k \geq s$ and there exists an i, $1 \leq i \leq k - s + 1$ such that

$$b_1 \leq a_i \quad , \quad b_2 \leq a_{i+1} \quad , \quad \dots \quad , \quad b_s \leq a_{i+s-1} \quad .$$

For example, the composition 222 includes all the members of the set of compositions $\{1, 2, 11, 12, 21, 22\}$.

Definition: The composition $a_1 \dots a_k$ *avoids* the composition $b_1 \dots b_s$ if it does **not** include it.

For example, the set of compositions of 4 that do not include the composition 12 is

$$\{4, 31, 211, 1111\}.$$

Definition: The composition $a = a_1 \dots a_k$ *avoids* the set of compositions A, if it avoids every member of A.

For example, the set of compositions of 4 that do not include the members of the set $\{12, 21\}$ is

$$\{4, 1111\}.$$

The **million dollar question** that we will answer in this article is

Question: Design an algorithm that inputs an arbitrary finite set of compositions, A, *all of the same length*, and a variable x and outputs an explicit expression (a rational function of x) for

$$\sum_{n=0}^{\infty} a(n)x^n \quad ,$$

where $a(n)$ is the number of compositions of n that do **not contain** any of the members of A.

For the sake of simplicity, we only treat the case where all the members of the forbidden set are of the same length. The extension to the more general case is left to the interested reader.

Note that when the set A consists of a single composition of length 1, i.e. $A = \{k\}$, then the answer is very easy. It is the set of compositions where the parts are from $\{1, \dots, k-1\}$ and hence the required generating function is simply $1/(1 - x - x^2 - \dots - x^{k-1})$. For example when $A = \{3\}$ then $a(n) = F_{n+1}$.

Before going on, let's give two sample theorems. Using our Maple package, the reader can generate (potentially) infinitely many such theorems.

The first theorem enumerates compositions that never contain the composition 34543.

It was obtained, *in less than a second*, by typing

```
InfoV( {[3,4,5,4,3] },x,30):
```

in the Maple package `Compositions.txt` .

Theorem 1: Let $a(n)$ be the number of compositions of n avoiding, as a subcomposition, 34543, then

$$\sum_{n=0}^{\infty} a(n)\, x^n \; =$$

$$-\frac{1 - 4\,x + 6\,x^2 - 4\,x^3 + x^4 + x^{16} + x^{13} - x^{14} + x^9 - 2\,x^{10} + x^{11} + x^5 - 3\,x^6 + 3\,x^7 - x^8}{x^{18} + x^{17} - x^{16} + 2\,x^{14} - x^{13} - 2\,x^{11} + 3\,x^{10} - x^9 + 2\,x^8 - 5\,x^7 + 4\,x^6 - x^5 - 2\,x^4 + 7\,x^3 - 9\,x^2 + 5\,x - 1}.$$

The first 31 terms of $a(n)$, starting at $n = 0$, are:

$$1, 1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, 2048, 4096, 8192, 16384, 32768, 65536, 131072, 262143,$$

$$524281, 1048546, 2097050, 4194001, 8387784, 16775108, 33549270, 67096623, 134189393, 268371074, 536726740.$$

The limit of $a(n+1)/a(n)$ as n goes to infinity is $1.99994300442\dots$, and $a(n)$ is asymptotic to $(0.50029301491\dots)\,(1.99994300442\dots)^n$.

The second theorem enumerates compositions that do not contain any of the members of $\{252, 343, 424\}$.
It was obtained by typing

```
InfoV( {[2,5,2],[3,4,3],[4,2,4] },x,30):
```

in the Maple package `Compositions.txt` .

Theorem 2: Let $a(n)$ be the number of compositions of n avoiding, as subcompositions, all the three members the set $\{252, 343, 424\}$, then

$$\sum_{n=0}^{\infty} a(n)\, x^n \; =$$

$$-\frac{x^{17}+3\,x^{14}+x^{13}-3\,x^{11}+x^{10}+x^{6}-x^{5}+x^{4}+x^{2}-2\,x+1}{x^{18}+3\,x^{15}+2\,x^{14}-2\,x^{13}-2\,x^{12}+3\,x^{11}-3\,x^{10}+x^{8}+x^{7}-x^{6}+2\,x^{5}-x^{4}-2\,x^{2}+3\,x-1}.$$

The first 31 terms of $a(n)$, starting at $n = 0$, are:

$$1, 1, 2, 4, 8, 16, 32, 64, 128, 255, 505, 998, 1971, 3893, 7697, 15223, 30113, 59575, 117861, 233164,$$

$$461250, 912423, 1804882, 3570257, 7062369, 13970211, 27634848, 54665348, 108135332, 213906125, 423134791.$$

The limit of $a(n + 1)/a(n)$ as n goes to infinity is $1.9781317474\ldots$, and $a(n)$ is asymptotic to $(.54805291269\ldots)\,(1.9781317474\ldots)^n$.

The Cluster Method for Compositions

Our algorithm is an adaptation of the Goulden-Jackson cluster method as described in [NZ].

We will use generating functions. The weight of a composition, C, is defined by

$$Weight(C) := \; x^{Sum(C)} \quad .$$

The weight-enumerator of the set of compositions, as noted above, is $1/(1-(\frac{x}{1-x})) = \frac{1-x}{1-2x}$. Let's reprove this trivial fact, in order to motivate our algorithm.

Any composition is either empty (weight 1) or starts with a **positive integer**. Removing the first entry results in a brand-new composition, i.e.

$$C \;=\; EmptyComposition \quad or \quad C \;=\; i\,C' \quad ,$$

for some positive integer i, and some smaller (possibly empty) composition C'. Let $\mathcal{C}$ be the set of compositions, and $\mathcal{P} = \{1, 2, 3, \ldots\}$ be the set of **strictly positive** integers. We have

$$\mathcal{C} = \{EmptyComposition\} \bigcup \mathcal{P} \times \mathcal{C} \quad .$$

Taking weights on both sides (the weight of a set is the sum of the weights of its members), we have

$$Weight(\mathcal{C}) = Weight(\{EmptyComposition\}) + Weight(\mathcal{P})\, Weight(\mathcal{C}) \quad .$$

Since $Weight(\{EmptyComposition\}) = 1$ and $Weight(\mathcal{P}) = \sum_{i=1}^{\infty} x^i = \frac{x}{1-x}$, we have the *algebraic* equation

$$Weight(\mathcal{C}) = 1 + \frac{x}{1-x} Weight(\mathcal{C}) \quad ,$$

and solving for $Weight(\mathcal{C})$ we get that it indeed equals $1/(1 - \frac{x}{1-x})$.

Our problem is as follows. We are given a finite set of compositions, of the **same length** (that is our simplifying assumption), let's call it A, and we would like to find the weight-enumerator of the set of compositions, let's call it $\mathcal{C}(A)$, that do **not** contain any of the members of A. For simplicity of exposition, let's assume, until further notice, that the set of offenders is a singleton. Later we will describe how to extend it to the case when we want to avoid, by containment, more than one fixed composition.

In other words, we would like to find a way of computing

$$Weight(\mathcal{C}(A))(x) \quad .$$

Being the weight-enumerator of the set $\mathcal{C}(A)$, extracting the coefficient of x^n from its Maclaurin expansion would give us the exact number of compositions of n that do **not** contain any of the members of A.

Rather than counting *good guys*, that is very hard, we will do *signed-weighted counting* of pairs (C, S), where C is *any* composition, and S is a subset of its set of 'crimes', i.e. a subset of its set of offending containments, that in turn, is a certain subest of A (possibly empty, if C is a saint, and possibly the whole of A, if C is an arch-criminal). Let's call this much larger set $\hat{\mathcal{C}}(A)$, and define

$$\overline{Weight}(C, S) := x^{Sum(C)} (-1)^{|S|} \quad .$$

Using the following two extremely deep identities

$$1 + (-1) \; = \; 0 \quad ,$$

and

$$0^a \; = \; \begin{cases} 1 & if \quad a = 0; \\ 0 & if \quad a > 0. \end{cases} \quad ,$$

it follows, just as in the case of Goulden-Jackson, that

$$Weight(\mathcal{C}(A)) \; = \; \overline{Weight}(\hat{\mathcal{C}}(A)) \quad .$$

We are left with the task of computing the right side, $\overline{Weight}(\hat{\mathcal{C}}(A))$.

let's illustrate the method by using a concrete example, where the set of offenders, A, consists of the single composition 232. In other words $A = \{232\}$. How do we compute $\overline{Weight}(\hat{\mathcal{C}}(\{232\}))$? (and hence $Weight(\mathcal{C}(\{232\}))$?

Consider the composition 14542351, whose $Weight$ is $x^{1+4+5+4+2+3+5+1} = x^{25}$. It has a total of three 'crimes'

$$\begin{array}{cccccccc} 1 & 4 & 5 & 4 & 2 & 3 & 5 & 1 \\ - & - & - & - & - & - & - & - \\ & 2 & 3 & 2 & & & & \end{array} \quad , \quad \begin{array}{cccccccc} 1 & 4 & 5 & 4 & 2 & 3 & 5 & 1 \\ - & - & - & - & - & - & - & - \\ & & 2 & 3 & 2 & & & \end{array} \quad , \quad \begin{array}{cccccccc} 1 & 4 & 5 & 4 & 2 & 3 & 5 & 1 \\ - & - & - & - & - & - & - & - \\ & & & & 2 & 3 & 2 & \end{array} \quad .$$

These give rise to 2^3 members of $\hat{\mathcal{C}}(\{232\})$. For example, when $S = \emptyset$:

$$\begin{array}{cccccccc} 1 & 4 & 5 & 4 & 2 & 3 & 5 & 1 \\ - & - & - & - & - & - & - & - \end{array} \quad ,$$

whose weight is $(-1)^0\, x^{25} = x^{25}$. Another example, is when S consists of the violations that start at the 2nd and 3rd entries of the underlying composition $C = 14542351$:

$$\begin{array}{cccccccc} 1 & 4 & 5 & 4 & 2 & 3 & 5 & 1 \\ - & - & - & - & - & - & - & - \\ & 2 & 3 & 2 & & & & \\ & & 2 & 3 & 2 & & & \end{array} \quad ,$$

whose weight is $(-1)^2 x^{25} = x^{25}$. Yet another example, out of the eight possibilities , is when S consists of violations starting at the 2nd and 5th entries of 14542351:

$$\begin{array}{cccccccc} 1 & 4 & 5 & 4 & 2 & 3 & 5 & 1 \\ - & - & - & - & - & - & - & - \\ & 2 & 3 & 2 & & & & \\ & & & & 2 & 3 & 2 & \end{array} \quad ,$$

whose weight is also $(-1)^2\, x^{25} = x^{25}$. Finally, don't forget the case where S is the full set of 'crimes':

$$\begin{array}{cccccccc} 1 & 4 & 5 & 4 & 2 & 3 & 5 & 1 \\ - & - & - & - & - & - & - & - \\ & 2 & 3 & 2 & & & & \\ & & 2 & 3 & 2 & & & \\ & & & & 2 & 3 & 2 & \end{array} \quad ,$$

whose weight is $(-1)^3\, x^{25} = -x^{25}$.

Let's analyze the anatomy of a typical member of $\hat{\mathcal{C}}(A)$, (C, S). We have one of the following three cases

• It is the element $(EmptyComposition, \emptyset)$.

• The first entry of C does not belong to any offenders. This case is isomorphic to $\mathcal{P} \times \hat{\mathcal{C}}(A)$

• The first entry belongs to an offender. This offender may not overlap with any other offenders that start later on, or may. Continuing to examine whether the last offender in the chain overlaps with yet another offender, eventually we will stop, getting a '**pre-cluster**', after which we have

a brand-new (shorter) member of $\hat{\mathcal{C}}(A)$. Let's denote by $\mathcal{M}(A)$ this set of pre-clusters. It is the subset of $\hat{\mathcal{C}}(A)$ where every entry of the underlying composition belongs to at least one offender, and every offender overlaps with at least another offender.

Still using $A = \{232\}$ as our running example, here is a member of $\mathcal{M}(A)$:

$$
\begin{array}{ccccccccc}
5 & 4 & 5 & 4 & 5 & 3 & 5 & 6 & 4 \\
- & - & - & - & - & - & - & - & - \\
2 & 3 & 2 & & & & & & \\
 & & 2 & 3 & 2 & & & & \\
 & & & 2 & 3 & 2 & & & \\
 & & & & & 2 & 3 & 2 & \\
 & & & & & & 2 & 3 & 2
\end{array} \quad .
$$

On the other hand

$$
\begin{array}{ccccccccc}
5 & 4 & 5 & 4 & 5 & 3 & 5 & 6 & 4 \\
- & - & - & - & - & - & - & - & - \\
2 & 3 & 2 & & & & & & \\
 & & & 2 & 3 & 2 & & &
\end{array} \quad ,
$$

is **not** a member of $\mathcal{M}(\{232\})$, since the second offending 232 does not overlap the first one, and hence can be decomposed to

$$
\begin{bmatrix} 5 & 4 & 5 \\ - & - & - \\ 2 & 3 & 2 \end{bmatrix}
\begin{bmatrix} 4 & 5 & 3 & 5 & 6 & 4 \\ - & - & - & - & - & - \\ 2 & 3 & 2 & & & \end{bmatrix} \quad .
$$

We get the following *grammar* for our set $\hat{\mathcal{C}}(A)$.

$$
\hat{\mathcal{C}}(A) = \ \{(EmptyComposition, \emptyset)\} \bigcup \mathcal{P} \times \hat{\mathcal{C}}(A) \bigcup \mathcal{M}(A) \times \hat{\mathcal{C}}(A) \quad .
$$

Applying $\overline{Weight}$, and abbreviating $\overline{Weight}(\hat{\mathcal{C}}(A))$ (our object of desire) to $F(x)$, we have

$$
F(x) \ = 1 + \frac{x}{1-x} F(x) + \overline{Weight}(\mathcal{M}(A))F(x) \quad .
$$

Solving for $F(x)$, and abbreviating $\overline{Weight}(\mathcal{M}(A))$ to $G(x)$, we get

$$
F(x) = \frac{1}{1 - \frac{x}{1-x} - G(x)} \quad .
$$

It remains to compute the $\overline{Weight}$-enumerator of the set of pre-clusters, $\mathcal{M}(A)$, alias $G(x)$.

Let's forget for a second the underlying composition (the top row in the above examples), and focus on the offenders. Let's call this pre-cluster with the top row (underlying composition) removed a **cluster**. We will denote the set of clusters by $\mathcal{N}(A)$.

For example, still using $A = \{232\}$, here is an example of a cluster:

$$
\begin{array}{ccccccccc}
2 & 3 & 2 & & & & & & \\
 & & 2 & 3 & 2 & & & & \\
 & & & 2 & 3 & 2 & & & \\
 & & & & & 2 & 3 & 2 & \\
 & & & & & & 2 & 3 & 2
\end{array} \quad .
$$

Let's call the total number of columns the *width*. In the above example, the width is 9. What compositions may serve as the underlying composition (top row) of such a cluster? Obviously, its number of columns must be equal to the width, and its respective entries, must be $\geq$ to the maximum of the entries of the offenders in the corresponding columns, where we ignore the empties (or replace them by 0, note that every column has at least one non-empty entry, or else it would not be a cluster). In the above example, the maxima of the nine columns are

$$
2\,3\,2\,3\,3\,2\,3\,3\,2 \quad .
$$

We will call this the *Skyline* of the cluster.

For the sake of convenience, let's represent a cluster as matrix, with empties replaced by 0, then the above cluster is written

$$
\begin{array}{ccccccccc}
2 & 3 & 2 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 2 & 3 & 2 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 2 & 3 & 2 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 2 & 3 & 2 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 2 & 3 & 2
\end{array} \quad .
$$

In terms of this associated matrix (where empty spaces are replaced by 0), we get a certain $k \times r$ matrix (k is the number of offenders, and r is the width), the Skyline is defined as follows.

$$
Skyline(L)_j := max(\{L_{ij} \,|\, 1 \leq i \leq k\}) \quad , \quad 1 \leq j \leq r.
$$

Note that the underlying compositions that can be put on top of a cluster L must satisfy $C_j \geq Skyline(L)_j$ for all $1 \leq j \leq r$. The $\overline{Weight}$-enumerator of these is simply $x^{Sum(Skyline(L))}\,(\frac{1}{1-x})^r(-1)^k$.

This leads us to define yet-another weight, this time on clusters, introducing an auxiliary variable t:

$$
Poids(L)(x,t) := x^{Sum(Skyline(L))}\,(-1)^k\,t^r \quad .
$$

We have

$$
G(x) = \overline{Weight}(\mathcal{M}(A)) = Poids(\mathcal{N}(A))(x, \frac{1}{1-x}) \quad .
$$

We are left with the task of computing $Poids(\mathcal{N}(A))(x,t)$.

A natural approach would be to break the set $\mathcal{N}(A)$ into *states*, and relate them to each other. Continuing with the assumption that our set of offenders is a singleton, $\{A\}$, where A is of length

a, say, ($A = 232$ in our example, so $a = 3$), the state of a cluster is the list consisting of the first a entries of its Skyline. For example the state of the cluster

$$\begin{matrix} 2 & 3 & 2 & 0 \\ 0 & 2 & 3 & 2 \end{matrix} \quad ,$$

is 233, while the state of the cluster

$$\begin{matrix} 2 & 3 & 2 & 0 & 0 \\ 0 & 0 & 2 & 3 & 2 \end{matrix} \quad ,$$

is 232. It is readily seen that in this case these are the only states. In general the computer can easily determine the set of states, by generating all the clusters of width $\leq 2a-1$ (recall that a is the width of A), and extracting the first a entries.

For each state, s, let $B_s(x,t)$ be the Poids-enumerator of the set of clusters that belong to state s. Given such a cluster, if it only has one row, then it must be A, and its Poids is $(-1)x^{Sum(A)}t^a$. If it has more than one row, we look at all the possibilities that it can overlap with the second row (i.e. the number of starting zeros (empties) in the second row, and their state). These are the 'children states'. In fact it is much easier, to go the other way. For any state look at the 'parent states', i.e. the one obtained by putting A at the top row in all the $a-1$ possible ways.

For example, for the state 232, we can have

$$\begin{matrix} 2 & 3 & 2 & 0 \\ - & - & - & - \\ 0 & 2 & 3 & 2 \end{matrix} \quad ,$$

whose state is 233, and

$$\begin{matrix} 2 & 3 & 2 & 0 & 0 \\ - & - & - & - & - \\ 0 & 0 & 2 & 3 & 2 \end{matrix} \quad ,$$

whose state is 232. Hence the parents of the state 232 are 233 and 232.

On the other hands for the state 233, we can have

$$\begin{matrix} 2 & 3 & 2 & 0 \\ - & - & - & - \\ 0 & 2 & 3 & 3 \end{matrix} \quad ,$$

whose state is 233, and

$$\begin{matrix} 2 & 3 & 2 & 0 & 0 \\ - & - & - & - & - \\ 0 & 0 & 2 & 3 & 3 \end{matrix}$$

whose state is 232. Hence the parents of the state 233 are also 233 and 232.

Recall that $B_s(x,t)$ is the Poids-enumerator of the clusters with state s. For each state, we need to set-up an equation.

Let's first find an equation for B_{232}. The children of the state 232 are 232 and 233. If the child is 232 then it **must** be as follows

$$\begin{array}{ccccc} 2 & 3 & 2 & 0 & 0 \\ \_ & \_ & \_ & \_ & \_ \\ 0 & 0 & 2 & 3 & 2 \end{array} \quad .$$

Removing the first row costs $2+3=5$ units to the Skyline, and shrinks the width by 2, so the contribution to B_{232} from this scenario (where the child is 232) is $x^5 t^2 (-1) B_{232}$.

If the child is 233 then it **must** be as follows

$$\begin{array}{ccccc} 2 & 3 & 2 & 0 & 0 \\ \_ & \_ & \_ & \_ & \_ \\ 0 & 0 & 2 & 3 & 3 \end{array} \quad .$$

Removing the first row costs $2+3=5$ units to the Skyline, and shrinks the width by 2, so the contribution to B_{232} from this scenario (where the child is 233) is $x^5 t^2 (-1) B_{233}$.

In addition it may be just a one-row cluster, whose Poids is $-x^{2+3+2}\, t^3 = -x^7\, t^3$.

Hence the equation for B_{232} is

$$B_{232} \; = \; -x^7\, t^3 - x^5\, t^2\, B_{232} - x^5\, t^2\, B_{233} \quad .$$

Next, let's find an equation for B_{233}. The children of the state 233 are also 232 and 233. If the child is 232 then it **must** be as follows

$$\begin{array}{cccc} 2 & 3 & 2 & 0 \\ \_ & \_ & \_ & \_ \\ 0 & 2 & 3 & 2 \end{array} \quad .$$

Removing the first row costs $2+3-2=3$ units to the Skyline, and shrinks the width by 1, so the contribution to B_{233} from this scenario (where the child is 232) is $x^3 t (-1) B_{232}$.

If the child is 233 then it **must** be as follows

$$\begin{array}{cccc} 2 & 3 & 2 & 0 \\ \_ & \_ & \_ & \_ \\ 0 & 2 & 3 & 3 \end{array}$$

removing the first row costs 3 units to the Skyline, and shrinks the width by 1, so the contribution to B_{232} from this scenario (where the child is 233) is $x^3 t (-1)\, B_{233}$.

Since 233 is not a violation, we don't have to add its Poids.

Hence the equation for B_{233} is

$$B_{233} \; = \; -x^3\, t\, B_{232} - x^3\, t\, B_{233} \quad .$$

We have to solve the following system of two linear equations with two unknowns $\{B_{232}, B_{233}\}$:

$$\{\, B_{232} \;=\; -x^7\,t^3 - x^5\,t^2\,B_{232} - x^5\,t^2\,B_{233} \quad , \quad B_{233} \;=\; -x^3\,t\,B_{232} - x^3\,t\,B_{233}\,\} \quad .$$

Solving them gives

$$B_{232} \;=\; -\frac{\left(1+tx^3\right)t^3x^7}{1+tx^3+t^2x^5} \quad , \quad B_{233} \;=\; \frac{t^4x^{10}}{1+tx^3+t^2x^5} \quad .$$

Hence

$$Poids(\mathcal{N}(\{232\}))(x,t) = B_{232} + B_{233} = -\frac{t^3x^7}{1+tx^3+t^2x^5} \quad .$$

Hence

$$G(x) = \overline{Weight}(\mathcal{M}(\{232\}) = Poids(\mathcal{N}(\{232\}))(x, \frac{1}{1-x}) = \frac{x^7}{(1-2\,x+x^2+x^3-x^4+x^5)\,(-1+x)} \quad .$$

Finally, our object of desire, $F(x) = \overline{Weight}(\hat{\mathcal{C}}(A))(x)$, alias $Weight(\mathcal{C}(A))$, is

$$F(x) = \frac{1}{1-\frac{x}{1-x}-G(x)} \;=\; -\frac{1-2\,x+x^2+x^3-x^4+x^5}{x^6-x^5+2\,x^4-x^3-2\,x^2+3\,x-1} \quad .$$

Avoiding many compositions (by containment)

The above method can be easily modified to handle multiple offenders. The clusters now can have several violations starting at any location, and the effect of the Skyline on a given state is determined by looking at the Skyline of the subset of violations starting at the same column. The readers are welcome to look at the source code of procedure `GFset(S,x)` in the Maple package `Compositions.txt`, where this case is implemented. So far we only handle sets of offenders all of the same length. Our readers are welcome to extend it to the more general case where the offending compositions may be of different lengths.

Keeping track of the number of occurrences

So far we described how to find the exact number, let's call it $a_S(n)$ of compositions of length n, that **avoid** (i.e. do not contain) any members of the set of compositions $S = \{C_1, ..., C_r\}$. We gave an efficient algorithm, implemented in the Maple package `Compositions.txt`, to explicitly find the generating function, let's call $f_S(x)$

$$f_S(x) \;:=\; \sum_{n=0}^{\infty} a(n)\,x^n \quad .$$

Note that, out of laziness, (so far) we only implemented the case where all the members of the offending set, $S = \{C_1, ..., C_r\}$, are of the same length.

But it is very hard to stay out of trouble. Suppose that you want to find the exact number, let's call it $A_S(n; c_1, \dots, c_r)$ of compositions of n that contain

C_1, c_1 times, C_2, c_2 times, ..., C_r, c_r times.

Of course, our former quantity, $a_S(n)$ is just the special case $c_1 = 0, c_2 = 0, \dots, c_r = 0$, i.e.

$$a_S(n) \; = \; A_S(n; 0, 0, \dots, 0) \quad .$$

All the information about the discrete function $A_S(n; c_1, \dots, c_r)$, with $1 + r$ *discrete* variables, is **encapsulated** in the multi-variable rational function, with $1+r$ '*continuous*' variables $x, X_1, \dots, X_r$

$$F_S(x; X_1, \dots, X_r) \; := \; \sum_{n=0}^{\infty} \sum_{c_1=0}^{\infty} \dots \sum_{c_r=0}^{\infty} A(n; c_1, \dots, c_r) \, x^n {X_1}^{c_1} \cdots {X_r}^{c_r} \quad .$$

Of course $f_S(x) = F_S(x; 0, 0, \dots, 0)$.

The beauty of the cluster method is that a very tiny tweak in the former algorithm yields a way to compute F_S. Rather then use the deep identity $0 = 1 + (-1)$ we use the only slightly deeper identity $X = 1 + (X - 1)$ applied to $X = X_1$, $X = X_2$, ..., $X = X_r$. This entails redefining the *Poids* of a cluster C, to be

$x^{Skyline(C)}$ (as before)

multiplied by $(X_1 - 1)^{NumberOf \, C_1} \quad ,$

multiplied by $(X_2 - 1)^{NumberOf \, C_2} \quad ,$

$\dots \quad ,$

multiplied by $(X_r - 1)^{NumberOf \, C_r} \quad .$

The set of equations is modified accordingly, and Maple solves it. Of course, now it takes much longer, since we have so many more symbols, but the principle is the same.

This is implemented (still under the simplifying assumption of the members of the offending set all of the same length) in the Maple package `CompositionsPlus.txt`, also available from the front of this article, where there are also sample input and output files.

Using the method of [Z], (that have been included in this package) we can do *statistical analysis* of the random variables 'Number of occurrences of C_i', for the various members of S, defined on the sample space of all compositions of n, as well as how they interact.

We do it by using the multi-variable generating function F_S.

By taking partial derivatives, and then setting all the variables X_i to be 1, we find expressions for the expectation, variance, (these are always linear in n) and higher moments (certain polynomials in n).

We can also find mixed moments for any set of such random variables, in particular, the *asymptotic correlation*, and confirm that for any such pair, these random variables are *joint asymptotically normal*, alas (of course) , **not** independently so. Using the asymptotic correlation one can confirm this by computing the mixed moments of the corresponding bi-variate normal distribution with correlation ρ,

$$\frac{1}{2\pi\sqrt{1-\rho^2}}\,e^{-x^2/2-y^2/2+\rho\,x\,y} \quad .$$

Our Maple package does that automatically (to any desired order).

Just to cite one example, typing

```
InfoX2V([2,3,4],[4,3,2],x,X,Y,n,6):
```

in the Maple package `CompositionsPlus.txt`, yields the following theorem.

Theorem 3: The following statements are true.

• Let $a(n)$ be the number of compositions of n that contain neither 234 nor 432, then

$$\sum_{n=0}^{\infty} a(n)\,x^n \;=\; -\frac{x^{16}+x^{15}+x^{12}+2\,x^{10}-x^7+x^5-x^4-x^2+2\,x-1}{x^{17}+x^{16}+x^{13}+2\,x^{11}-x^{10}+x^9-x^8+x^7-2\,x^5+x^4+2\,x^2-3\,x+1} \quad .$$

• $a(n)$ is asymptotic to $(0.548269839581\ldots)\cdot(1.976902834153\ldots)^n$

• Let $A(n;c,d)$ be the number of compositions of n that contain exactly c occurrences of 234 and d occurrences of 432, then

$$\sum_{n=0}^{\infty}\sum_{c=0}^{n-3}\sum_{d=0}^{n-3} A(n;c,d)\,x^n\,X^c\,Y^d \;=\; \frac{Numer(x,X,Y)}{Denom(x,X,Y)} \quad , where$$

$$Numer(x,X,Y) \;=\; -1+x^{12}-2\,x^{11}+x^3+2\,x^5-x^6-x^4-x^7-3\,x^2+x^8+2\,x^{10}-x^{17}+x^{15}X^2-x^{13}X^2$$
$$-x^{12}X-x^{12}Y-x^{13}Y^2+x^{15}Y^2-x^{17}Y^2-x^{17}X^2-2\,x^{15}X-2\,x^{15}Y+2\,x^{11}Y-2\,x^{10}X+2\,x^{13}Y+2\,x^{11}X$$
$$-2\,x^{10}Y+2\,x^{13}X+2\,x^{17}Y+2\,x^{17}X+x^{15}+3\,x+x^7XY-x^{13}+x^6XY-x^8XY+x^4XY+x^{15}X^2Y^2-x^{17}X^2Y^2$$
$$+x^{13}XY^2+x^{13}X^2Y+x^{12}XY-3\,x^{13}XY-2\,x^{11}XY+2\,x^{10}XY-2\,x^{15}X^2Y-2\,x^{15}XY^2$$
$$+4\,x^{15}XY+2\,x^{17}X^2Y-2\,x^5XY-4\,x^{17}XY+2\,x^{17}XY^2 \quad ,$$

and

$$Denom(x,X,Y) \;=\; -1+2\,x^{12}-3\,x^{11}+2\,x^3+3\,x^5-2\,x^6-x^4-x^7-5\,x^2+2\,x^8+2\,x^{10}+2\,x^{16}Y+2\,x^{16}X-2\,x^{18}Y$$
$$-2\,x^{14}X-2\,x^{14}Y-2\,x^{18}X-2\,x^{12}X-2\,x^{12}Y+x^{14}X^2+x^9X+x^{14}Y^2+x^{18}Y^2-x^{16}Y^2+x^{18}X^2+x^9Y-x^{16}X^2$$
$$+3\,x^{11}Y-2\,x^{10}X+x^{13}Y+3\,x^{11}X-2\,x^{10}Y+x^{13}X+4\,x+2\,x^{16}XY^2+x^7XY+4\,x^{18}XY-4\,x^{16}XY$$

$$-x^{13}-2\,x^{18}XY^2+2\,x^6XY-2\,x^{18}X^2Y-2\,x^8XY+2\,x^{16}X^2Y+3\,x^{14}XY+x^4XY+2\,x^{12}XY-2\,x^9+x^{14}$$
$$-x^{13}XY-3\,x^{11}XY+2\,x^{10}XY-x^{14}X^2Y-x^{14}XY^2-x^{16}X^2Y^2+x^{18}X^2Y^2-3\,x^5XY+x^{18}-x^{16} \quad .$$

• The expectation and variance of the random variables 'number of occurrences of 234', and 'number of occurrences of 432', are both (obviously they are the same)

$$\frac{n}{128} \quad , \quad \frac{147}{16384}\,n-\frac{1439}{16384} \quad .$$

• The asymptotic correlation is $\frac{71}{147} = 0.482993197\ldots$, and the joint asymptotic normality (with that correlation) is confirmed up to the sixth mixed moments (not that we had any doubts).

Encore: The asymptotic growth constants for all compositions up that of 6

This is an excerpt from the output file

`http://sites.math.rutgers.edu/~zeilberg/tokhniot/oCompositions4.txt`,

ranking them according to the asymptotic growth constants of the sequences enumerating compositions that do not contain them. We only list one of them in case of ties (due to trivial equivalence).

$n = 2$: 2 (1) .

$n = 3$: 12 (1), 3 (1.6180339887498948482).

$n = 4$: 112 (1), 13 (1.6180339887), 22 (1.7548776662), 4 (1.8392867552) .

$n = 5$: 1112 (1), 113 (1.6180339887), 212 (1.7548776662), 14 (1.83928675521), 23 (1.86676039917), 5 (1.92756197548) .

$n = 6$: 11112 (1), 1113 (1.6180339887), 2112 (1.7548776662), 114 (1.839286755214), 213 (1.866760399), 222 (1.908790738787), 15 (1.92756197548), 24 (1.93318498189952), 33 (1.9417130342786), 6 (1.965948236645).

For the ranking for the compositions of up to 11, see the above output file.

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