Automatic Solution of Richard Stanley's Amer. Math. Monthly Problem #11610 and ANY Problem of That Type

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Preamble

Suppose you toss a (fair) coin n times. If n is large, the *law of large numbers* promises you that (with high probability) you would *roughly* get as many Heads as Tails. But what is the *exact* probability that you would have **exactly** as many Heads as Tails? If n is odd, the answer is easy (**you do it!**). If n is even, then it is almost as easy, and there is a *nice*, "closed-form" formula for that probability, namely $n!/((n/2)!^2 2^n)$.

Richard Stanley [St1] proposed the problem of finding, $a(n)$, the number of n-letter words in the alphabet $\{H, T\}$ where there are as many occurrences of "HT" (i.e. Head immediately followed by Tail) as there are occurrences of "TT" (two Tails in a row). He didn't give a "closed form" formula, but he gave something almost as good, an *explicit* formula as an (*algebraic*, as it turned out, in fact quadratic) formal power series for the (ordinary) generating function $P(t) := \sum_{n=0}^{\infty} a(n)t^n$.

The fact that the generating function, $P(t)$, is an *algebraic* generating function is not at all surprising! This can be seen in (at least) two ways.

One way is to show that the "language" of words with as many occurrences of "HT" as "HH" is *context-free* (type 2) with an *unambiguous grammar*, and hence its *weight-enumerator* is *algebraic*. It is possible to (*automatically*!) generate its grammar, and then *automatically* generate a system of algebraic equations one of whose unknowns is the desired generating function, and solving that system would (presumbly, we didn't do it) yield Stanley's proposed expression.

A better way is to find (automatically, of course!), the *rational generating function* $F(t; z[HT], z[TT])$ that is the *weight-enumerator* of all words in the alphabet $\{H, T\}$ according to the weight $Weight(w) = t^{length(w)} z[HT]^{\#HT(w)} z[TT]^{\#TT(w)}$. This can be done in several ways, including the *Goulden-Jackson method*, beautifully surveyed in [NZ], and efficiently implemented in the Maple package

`http://www.math.rutgers.edu/~zeilberg/tokhniot/DAVID_IAN`

accompanying that article.

Having done that, the desired generating function, $P(t)$, is the coefficient of s^0 (i.e. *the constant term*) in $F(t; s, 1/s)$. Hillel Furstenberg[F] promises us that $P(t)$ is an algebraic formal power series in t, and his proof implies a (rather awkward and inefficient) algorithm (using Cauchy's integral

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formula and residues) for computing it. This should yield a second *rigorous* derivation of Stanley's proposed solution.

But since we know *a priori* (by "general nonsense") that the desired sequence belongs to the *algebraic ansatz* (see [Z1] and the **wonderful** new book by Manuel Kauers and Peter Paule[KP], that should be *required reading* to *any* mathematics student (and professional!)) a *semi-rigorous* derivation would be to crank out the first 40 (or even fewer) terms of Stanley's sequence (a quick way would be to find the first 40 terms in the expansion of the constant term, in s, of $F(t; s, 1/s)$ above), and then use a *guessing* program, e.g. `listtoalgeq` in the Maple package *gfun*([SaZ]) (but *please* enlarge the very small default values of the parameters) that now is part of Maple, or procedure `Empir` in our own Maple package `http://www.math.rutgers.edu/~zeilberg/tokhniot/SCHUTZENBERGER` .

In order to make the above *semi-rigorous* derivation *fully rigorous* (for those obtuse people who desire it), one would need to derive *a priori* bounds on the degree (in t and $P(t)$) of the defining equation $F(t, P(t)) = 0$ for the desired generating function $P(t)$. Unlike the C-finite ansatz (see [Z2] and [KP]) where finding these upper bounds is trivial, we don't know how to do it in the present case. But there is **another** way to make everything fully rigorous. Via the *holonomic ansatz*!

Using the *Continuous Almkvist-Zeilberger Algorithm*[AlZ], that is implemented in procedure `AZc` of the Maple package `http://www.math.rutgers.edu/~zeilberg/tokhniot/EKHAD`, one can obtain a *differential equation* (and its *proof* (a certain *certificate*)), and then verify that the above "conjectured" algebraic expression for $P(t)$ satisfies that very same differential equation, and check that the initial conditions match.

The general case

The beauty of *algorithmic* mathematics is that it is not much harder to write a *general* program to handle a whole class of problems rather than just solve *one* problem. The above discussion applies equally to any (finite) *alphabet* (not just a two-lettered one) and any two *distinguished* substrings, w_1 and w_2 not just HT and TT.

The Maple package RPS

Since we require procedures from four different Maple packages (`DAVID_IAN`, `SCHUTZENBERGER`, `EKHAD` and `AsyRec`), we conveniently assembled all the necessary procedures, together with new "interfacing code" needed to solve problems of the above type. The result is the Maple package `RPS` (named after Richard Peter Stanley), available free of charge from:

`http://www.math.rutgers.edu/~zeilberg/tokhniot/RPS` .

This Maple package does much more! It computes *holonomic representations* (or as Richard Stanley [St2] would say, *P-recursive* ones), that are used, in turn, to derive *asymptotic expressions* using procedures borrowed from

`http://www.math.rutgers.edu/~zeilberg/tokhniot/AsyRec` .

Hence we have "three-quarters" of the Kauers-Paule "concrete tetrahedron": generating function, recurrence, and asymptotics. The last one "definite sum" could also be obtained, but we would (usually) get complicated and ugly *multi-sums* with many sigmas, so it would be stupid to look for these.

Out of sheer laziness we have only programmed the case where the two distinguished words, w_1, w_2, have the same length.

Precomputed Output of the Maple package RPS

The "front" of this article, the webpage

`http://www.math.rutgers.edu/~zeilberg/mamarim/mamarimhtml/rps.html` ,

contains links to several "webbooks" that systematically states (proved!) (algebraic) generating functions, recurrence equations, and asymptotics for analogs of Stanley's problem for *all* possible pairs of words (up to trivial images under permutations of the letters) of the same length (let's call it k) for an m-letter alphabet for the following cases.

• $m = 2, k = 2$: `http://www.math.rutgers.edu/~zeilberg/tokhniot/oRPS22` (containing 3 propositions)

• $m = 2, k = 3$: `http://www.math.rutgers.edu/~zeilberg/tokhniot/oRPS23` (containing 11 propositions)

• $m = 2, k = 4$: `http://www.math.rutgers.edu/~zeilberg/tokhniot/oRPS24` (containing 38 propositions)

• $m = 3, k = 2$: `http://www.math.rutgers.edu/~zeilberg/tokhniot/oRPS32` (containing 6 propositions)

• $m = 3, k = 3$: `http://www.math.rutgers.edu/~zeilberg/tokhniot/oRPS32` (containing 40 propositions)

• $m = 4, k = 2$: `http://www.math.rutgers.edu/~zeilberg/tokhniot/oRPS42` (containing 7 propositions)

• $m = 4, k = 3$: `http://www.math.rutgers.edu/~zeilberg/tokhniot/oRPS43` (containing 63 propositions)

• $m = 5, k = 2$: `http://www.math.rutgers.edu/~zeilberg/tokhniot/oRPS52` (containing 7 propositions)

• $m = 5, k = 3$: `http://www.math.rutgers.edu/~zeilberg/tokhniot/oRPS53` (containing 69 propositions)

• $m = 6, k = 2$: `http://www.math.rutgers.edu/~zeilberg/tokhniot/oRPS62` (containing 7 propositions)

• $m = 6, k = 3$: `http://www.math.rutgers.edu/~zeilberg/tokhniot/oRPS63` (containing 70 propositions)

For Neil Sloane's sake, we have also computed the first 50 terms of each of the considered enumerating sequences. All the sequences for $m = 2$ and $k = 2, 3, 4$ have already been entered to OEIS by R.H. Hardin, for example `http://oeis.org/A164147`. Some of the pages for these sequences come with conjectured recurrences. The present webbooks supply rigorous proofs to all them, and supplies proved recurrences for the remaining ones.

The Maple Package RPSplus

With hardly any more (programming) effort, one can consider the enumerating sequences of words for which, for three given positive integers a_1,a_2 and r,

"a_1 times [the numer of occurrences of w_1]" **minus** a_2 times "[the numer of occurrences of w_2] " **equals** r.

Once again the generating functions are guaranteed to be algebraic and everything goes through. See the procedures listed in `ezraG();` in the more general Maple package `RPSplus`, available from

`http://www.math.rutgers.edu/~zeilberg/tokhniot/RPSplus` .

Readers are welcome to generate their own output.

What About Several Distinguished Words?

The more general case where one has a finite alphabet of, say, m letters, and s, say, distinguished words $w_1, \dots, w_s$, and v diophantine affine linear relations between the quantities "number of occurrences of w_i", then we leave the *algebraic ansatz* and enter the *holonomic* ansatz. By WZ theory we are *guaranteed* that the enumerating sequence, in each case, is holonomic (alias P-recursive), and we are justified, semi-rigorously, just to *guess* the holonomic description, using `gfun`'s `listtorec`, or procedure `Findrec` in the Maple package `RPS`.

For those obtuse people who insist on a *rigorous* proof, they are welcome to use the Maple package

`http://www.math.rutgers.edu/~zeilberg/tokhniot/MultiAlmkvistZeilberger` ,

that is one of the Maple packages accompanying the seminal article [ApZ]. Alas, it may take them quite some time, and frankly, for us, a *semi-rigorous* proof suffices. But so far, we ran out of steam, and we do not even have an implementation of the semi-rigorous, pure guessing, version.

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