The Number of 1...d-Avoiding Permutations of Length d+r for SYMBOLIC d but Numeric r

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Dedicated to Ira Martin GESSEL (b. April 9, 1951), on his millionth$_2$ birthday

Preface: How many permutations are there of length googol+30 avoiding an increasing subsequence of length googol?

This number is way too big for our physical universe, but the number of permutations of length googol+30 that *contain* at least one increasing subsequence of length googol is

376998762881590564385292152564610566414683382362199480145699135711350293678127053805471904803967527
076919335437172135000152461057809770004597279282389729095962420389610198195292964080517012928207388
474001880757114753409122995124943591314917179530259231247745609127781232195621280220478557859802025
562500880285083845558625740294725684838064718147999322256642002590867910691700434807781242826151024
634017630058539751799003239303665395130492458648996865080978929229148927096871099480967705017659675
072595620235075084137609502404639684496851124349478416201488179533783552862614280815007311110128336
098070157193795282413679642501722463619685399595058794325904368743165392292784057286439610508519022
258279906781037838989063519632242566746733515889050082012876833175085546996305032243297319447233194
098982593446969607934472305367900113003366782752496603466178206485106821418245473136574341348672973
063105544412772593001379283651538485070234679729840680304923014569743356700481155598415837861112589
014576890134872555072603752766981262635326683768503739740886276708201823957939266302413179210540728
478872084061851446346503539210388439498120200783472411009444711661343912875828504426947180850208327
662937424792852150178683940985328774075857005623085373846252737453470964173545848756081694936561648
069562691302969992264810209161552994941494064858804883648537275877580874323136561745951532919097239
707454394641557872843999430607127965404514643237955754135840897815686317298041972083929276102526175
680587662659016326579559224817866468163098089382158768841381520660921608251498378788338697722607142
216491477289935925789614221777002944825967409939865193572469599306681465050852707144755611501137472
208878700477533581773162062633569279557294587546865506444326346876802820279764027727724838361171054
481456115092281545104720004041306146397809264171373299397324657220146805649028399308243068349204145
138747536000552520920011368145713293845873255824684878872443952952455854191886467927642528321599620
694116495443721310532353874394468754346987937351214127964002369657325844846872199828983551459802919
862692344861359731125642502470072391352803557757122679547260190338937713787627774236691965752951745
964525876697257261448327403717828223080061705319100992656781414836225171440141077162170100983838399
845078045902447206674065939295641345915478057936344685239344543289067567587012097654715148805723707
090843317362163022890751771618064020890838899894673342933665767554237388450995526282792699371769155
594278358704445398006444800528216309223317799370232286563052729741599319773650648178493618609094453
081201405774366900071407015705994841768610474610528267747448992467466669092645780670762439234530885
966987780692177671943829413657321120394128797135319915983176756825054398454246256004382250769731165
491302133085147997288307646371721290040656119074756104017130087909728914090203626587419465098918321
770166766700600120961099890938038201086500388522077756553170113354321858833072097085269435882648189

3775738149186073685934586558285596632901636818878886042883326839132327059391308990152857750191809743
3487912142476276560621310123468845009650614775925658273562207923751954793994347093016618292164580401
1254279814338864116761417830119059817479387880694430162532210993791275528220779177902246600447925840
2446294959276134988131654342203869918382647352510707580950827477809341316822096398440902856636229390
4021541588241935864951867435541480109504741382604082456634512978942603922184208879705298143957373660
5022330793088649449089550661242226637700975872048802255877951342510043234892643042766512594498769305
4224575112270628402898275433738688545939162654357055516205161266436378837328045722669166090867956953
2716308156251990403004593327493174233201870456895707500259180589455710602937342719975864491923386963
5903842897776980002129651552219483587717759774043798881299174958483572178675529350262014933898703123
3251822518408158990271446362436501824274759908263581759373772458033768880934255069534236693503642534
9188091443537667487643227020476441406556138221242510025369533668010935357887804140526277263813912479
8321640648394196028626519959966325451252664262353889631883841776653646129270593661149306259085397801
1862926623393421168173669371424135263438461510848532070094781148761874414915822566817516932438525928
5563436340937294481843784242150745917626033404675889463006327603959116662310009262655062833600709070
4341332664779779937712263184388203605477211162014805937750522978535620225925004722918738657674699944
4740534790765914361805057941708749765216546018547704334563663220497822600180042427352634146022024254
6837287991790650300830294945144509055317250899679032932909355008745485393391787351940856948821074863
7988337458525082077728767764580028044307669916606263760676379777023540421219334461005282376299007211
7830708202345451414808988746374861068938167745982146640071560388867319753842572023825 .

Hence the number of permutations of length googol+30 *avoiding* an increasing subsequence of length googol is $(googol + 30)!$ *minus* the above small number.

Counting the "Bad Guys"

Recall that thanks to Robinson-Schensted ([Rob][Sc]), the number of permutations of length n that do **not** contain an increasing subsequence of length d is given by

$$G_d(n) := \sum_{\substack{\lambda \vdash n \\ \#rows(\lambda) < d}} f_\lambda^2 \quad ,$$

where λ denotes a typical *Young diagram*, and f_λ is the number of *Standard Young tableaux* whose *shape* is λ.

Hence the number of permutations of length n that **do** contain an increasing subsequence of length d is

$$B_d(n) := \sum_{\substack{\lambda \vdash n \\ \#rows(\lambda) \geq d}} f_\lambda^2 \quad .$$

Since the total number of permutations of length n is $n!$ ([B]), if we know how to find $B_d(n)$, we would know immediately $G_d(n) = n! - B_d(n)$, at least if we leave $n!$ alone as a factorial, rather than spell it out.

Recall that the *Hook Length formula* (see [Wiki]) tells you that if λ is a Young diagram then

$$f_\lambda = \frac{n!}{\prod_{c \in \lambda} h(c)} \quad ,$$

where the product is over all the n cells of the Young diagram, and the *hook-lenght*, $h(c)$, of a cell $c=(i,j)$, is $(\lambda_i - i) + (\lambda'_j - j) + 1$, where λ' is the *conjugate* diagram, where the rows become columns and vice-versa.

Let r be a fixed integer, then for *symbolic* d, valid for $d \geq r-1$, any Young diagram with at least d rows, and with $d+r$ cells, can be written, for some Young diagram $\mu = (\mu_1, \ldots, \mu_r)$, with $\leq r$ cells, (where we add zeros to the end if the number of parts of μ is less than r) as

$$\lambda = (1+\mu_1, \ldots, 1+\mu_r, 1^{d-r+r'}) \quad ,$$

where $r' = r - |\mu|$. For such a shape λ, with *at least* d rows,

$$\prod_{c\in\lambda} h(c) = \left(\prod_{c\in\mu} h(c) \right) \cdot ((d+r'+\mu_1)(d+r'-1+\mu_2)\cdots(d+r'-r+1+\mu_r)) \cdot (d-r+r')! \quad .$$

Hence f_λ, that is $(d+r)!$ divided by the above, is a certain specific number times a certain polynomial in d. Since, for a specific, *numeric*, r, there are only *finitely* many Young diagrams with at most r cells, the computer can find all of them, compute the polynomial corresponding to each of them, square it, and add-up all these terms, getting an *explicit* **polynomial** expression, in the variable d, for $B_d(d+r)$, the number of permutations of length $d+r$ that *contain* an increasing subsequence of length d. As we said above, from this we can find $G_d(d+r) = (d+r)! - B_d(d+r)$, valid for *symbolic* $d \geq r-1$.

$\mathbf{B_d(d+r)}$ for r from 0 to 30

$$B_d(d) = 1 \quad ,$$

$$B_d(d+1) = d^2 + 1 \quad ,$$

$$B_d(d+2) = \frac{1}{2}\,d^4 + d^3 + \frac{1}{2}\,d^2 + d + 3 \quad ,$$

$$B_d(d+3) = \frac{1}{6}\,d^6 + d^5 + \frac{5}{3}\,d^4 + \frac{2}{3}\,d^3 + \frac{19}{6}\,d^2 + \frac{31}{3}\,d + 11 \quad ,$$

$$B_d(d+4) = \frac{1}{24}\,d^8 + \frac{1}{2}\,d^7 + \frac{25}{12}\,d^6 + \frac{19}{6}\,d^5 + \frac{29}{24}\,d^4 + 9\,d^3 + \frac{247}{6}\,d^2 + \frac{395}{6}\,d + 47 \quad ,$$

$$B_d(d+5) = \frac{1}{120}\,d^{10} + \frac{1}{6}\,d^9 + \frac{31}{24}\,d^8 + \frac{14}{3}\,d^7 + \frac{823}{120}\,d^6 + \frac{67}{30}\,d^5 + \frac{653}{24}\,d^4 + \frac{959}{6}\,d^3 + \frac{10459}{30}\,d^2 + \frac{3981}{10}\,d + 239 \quad .$$

For $B_d(d+r)$ for r from 6 up to 30, see
`http://www.math.rutgers.edu/~zeilberg/tokhniot/oGessel64a` .

Sequences

The sequence $G_3(n)$ is the greatest *celeb* in the kingdom of combinatorial sequences [the subject of an entire book([St]) by Ira Gessel's illustrious *academic father*, Richard Stanley], the super-famous **A000108** in Neil Sloane's legendary database ([Sl]). $G_4(n)$, while not in the same league as the Catalan sequence, is still moderately famous, **A005802**. $G_5(n)$ is **A047889**, $G_6(n)$ is

A047890, $G_7(n)$ is **A052399** , $G_8(n)$ is **A072131**, $G_9(n)$ is **A072132**, $G_{10}(n)$ is **A072133**, $G_{11}(n)$ is **A072167**, but $G_d(n)$ for $d \geq 12$ are absent (for a good reason, one must stop somewhere!). Also the *flattened version* of the *double-sequence*, $\{G_d(n)\}$, for $1 \leq d \leq n \leq 45$ is **A047887**. Using the polynomials $B_d(d+r)$, we computed the first $2d+1$ terms of $G_d(n)$ for $d \leq 30$. See
`http://www.math.rutgers.edu/~zeilberg/tokhniot/oGessel64b` .

But this method can only go up to $2d+1$ terms of the sequence $G_d(n)$, and of course, the first $d-1$ terms are trivial, namely $d!$ (and the d-th term is $d!-1$). Can we find the first 100 terms (or whatever) for the sequences $G_d(n)$ for d up to 20, and beyond, **efficiently?**

Encore: Efficient Computer-Algebra Implementation of Ira Gessel's AMAZING Determinant Formula

Recall Ira Gessel's [G] famous expression for the generating function of $G_d(n)/n!^2$, *canonized* in the *bible* ([W], p. 996, Eq. (5)). Here it is:

$$\sum_{n \geq 0} \frac{G_d(n)}{n!^2}\, x^{2n} = \det(I_{|i-j|}(2x))_{i,j=1,\ldots,d} \quad ,$$

in which $I_\nu(t)$ is (the modified Bessel function)

$$I_\nu(t) = \sum_{j=0}^{\infty} \frac{(\frac{1}{2}\, t)^{2j+\nu}}{j!(j+\nu)!} \quad .$$

Can we use this to compute the first 100 terms of, say, $G_{20}(n)$?

While computing *numerical* determinants is very fast, computing *symbolic* ones is a different story. First, do not get scared by the "infinite" power series. If we are only interested in the first N terms of $G_d(n)$, then it is safe to truncate the series up to t^{2N}, and take the determinant of a $d \times d$ matrix with *polynomial entries*. If you use the *vanilla* determinant in a computer-algebra system such as Maple, it would be very inefficient, since the degree of the determinant is much larger than $2N$. But a little cleverness can make things more efficient. The Maple package `Gessel64`, available free of charge from

`http://www.math.rutgers.edu/~zeilberg/tokhniot/Gessel64` ,

accompanying this article, has a procedure `SeqIra(k,N)` that computes the first N terms of $G_k(n)$, using a division-free algorithm (see [Rot]) over an appropriate ring to compute the determinant in Gessel's famous formula.

```
SeqIra:=proc(k,N) local ira,t,i,j, R:

  R := table():

  R[‘0‘] := 0:

  R[‘1‘] := 1:
```

```
  R[`+`] := `+`:

  R[`-`] := `-`:

  R[`*`] := proc(p, q): return add(coeff(p*q, t, i)*t**i, i=0..2*N): end:

  R[`=`] := proc(p, q): return evalb(p = q): end:

  ira:=expand(LinearAlgebra[Generic][Determinant][R](Matrix([seq([seq(Iv(abs(i-j),t,2*N),
                                                                    j=1..k-1)],
                                                                 i=1..k-1)]))):

  [seq(coeff(ira,t,2*i)*i!**2,i=1..N)]:

end:
```

In the above code, procedure `Iv(v,t,N)` computes the truncated modified Bessel function that shows up in Gessel's determinant, and it is short enough to reproduce here:

```
Iv:=proc(v,t,N) local j:  add(t**(2*j+v)/j!/(j+v)!,j=0..trunc((N-v)/2)+1):  end:
```

.

Using this procedure, the first-named author computed (in 4507 seconds) the first 100 terms of each of the sequences $G_d(n)$ for $3 \leq d \leq 20$, and could have gone much further.

See `http://www.math.rutgers.edu/~zeilberg/tokhniot/oGessel64c` .

HAPPY 64th BIRTHDAY, IRA!

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