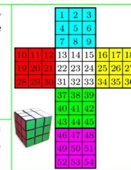
Abstract. What's the hardest math I've ever used in real life? Me, myself, directly - not by using a cellphone or a GPS device that somebody else designed? And in "real life" — not while studying or teaching mathematics?
I use addition and subtraction daily, adding up bills or calculating change. I use percentages often, though mostly it is just "add 15 percents". I seldom use multiplication and division: when I buy in bulk, or when I need to know how many tiles I need to replace my kitchen floor. I've used powers twice in my life, doing calculations related to mortgages. I've used a tiny bit of geometry and algebra for a tiny bit of non-math-related computer graphics I've played with. And for a long time, that was all. In my talk I will tell you how recently a math topic discovered only in the 1800s made a brief and modest appearance in my non-mathematical life. There are many books devoted to that topic and a lot of active research. Yet for all I know, nobody ever needed the actual formulas for such a simple reason before.
Hence we'll talk about the motion of movie cameras, and the fastest way to go from A to B subject to driving speed limits that depend on the locale, and the "happy segway principle" which is a the heart of the least action principle which in itself is at the heart of all of modern physics, and finally, about that funny discovery of Janos Bolyai's and Nikolai Ivanovich Lobachevsky's, that the famed axiom of parallels of the ancient Greeks need not actually be true.

Dror Bar-Natan: Talks: Mathcamp-0907:

Non-Commutative Gaussian Elimination and Rubik's Cube

Joint study with Itai Bar-Natan

The Problem. Let $G = \langle g_1, \dots, g_\alpha \rangle$ be a subgroup of S_n, with $n = O(100)$. Before you die, understand G:
1. Compute $|G|$.
2. Given $\sigma \in S_n$, decide if $\sigma \in G$.
3. Write a $\sigma \in G$ in terms of $g_1, \dots, g_\alpha$.
4. Produce *random* elements of G.

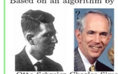


The Commutative Analog. Let $V = \mathrm{span}(v_1, \dots, v_\alpha)$ be a subspace of $\mathbb{R}^n$. Before you die, understand V.
Solution: Gaussian Elimination. Prepare an empty table,

1	2	3	4	…	n−1	n

Space for a vector $u_4 \in V$, of the form $u_4 = (0,0,0,1,*,\dots,*)$; $1 :=$ "the pivot".

Based on an algorithm by



Otto Schreier Charles Sims

See also *Permutation Group Algorithms* by Ákos Seress.

Feed $v_1, \dots, v_\alpha$ in order. To feed a non-zero v, find its pivotal position i.
1. If box i is empty, put v there.
2. If box i is occupied, find a combination v' of v and u_i that eliminates the pivot, and feed v'.

Non-Commutative Gaussian Elimination
Prepare a mostly-empty table,

(1,1) I				
(1,2)	(2,2) I			
(1,3)	(2,3)	(3,3) I		
⋮		(i,j)	⋱	
(1,n)	(2,n)	(3,n)	…	(n,n) I

Space for a $\sigma_{i,j} \in S_n$ of the form $(1,2,\dots,i-2,i-1,j,*,*,\dots,*)$. So $\sigma_{i,j}$ fixes $1,\dots,i-1$, sends "the pivot" i to j and goes wild afterwards, and $\sigma_{i,j}^{-1}$ "does sticker j".

Feed $g_1, \dots, g_\alpha$ in order. To feed a non-identity σ, find its pivotal position i and let $j := \sigma(i)$.
1. If box (i,j) is empty, put σ there.
2. If box (i,j) contains $\sigma_{i,j}$, feed $\sigma' := \sigma_{i,j}^{-1}\sigma$.

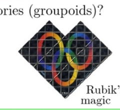
The Twist. When done, for every occupied (i,j) and (k,l), feed $\sigma_{i,j}\sigma_{k,l}$. Repeat until the table stops changing.
Claim. The process stops in our lifetimes, after at most $O(n^6)$ operations. Call the resulting table T.
Claim. Anything fed in T is a monotone product in T:
f was fed $\Rightarrow f \in M_1 := \{\sigma_{1,j_1}\sigma_{2,j_2}\cdots\sigma_{n,j_n} : \forall i, j_i \geq i \ \& \ \sigma_{i,j_i} \in T\}$

Homework Problem 1. Can you do cosets?

www.powerstrike.net/puzzles/

Homework Problem 2. Can you do categories (groupoids)?

7	9	2	5
1	4	8	3
6	10	11	12
13	14	15	



Rubik's magic

The Generators

```
In[1]:= gs = {
  purple = P[18,27,36,4,5,6,7,8,9,3,11,12,13,14,15,16,17,
   45,2,20,21,22,23,24,25,26,44,1,29,30,31,32,33,34,35,43,
   37,38,39,40,41,42,10,19,28,52,49,46,53,50,47,54,51,48],
  white = P[1,2,3,4,5,6,16,25,34,10,11,9,15,24,33,39,17,
   18,19,20,8,14,23,32,38,26,27,28,29,7,13,22,31,37,35,36,
   12,21,30,40,41,42,43,44,45,46,47,48,49,50,51,52,53,54],
  green = P[1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,
   19,20,21,22,23,24,25,26,27,31,32,33,34,35,36,48,47,46,
   39,42,45,38,41,44,37,40,43,30,29,28,49,50,51,52,53,54],
  blue = P[3,6,9,2,5,8,1,4,7,54,53,52,10,11,12,13,14,15,
   19,20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,
   37,38,39,40,41,42,43,44,45,46,47,48,49,50,51,18,17,16],
  red = P[13,2,3,22,5,6,31,8,9,12,21,30,37,14,15,16,17,
   18,11,20,29,40,23,24,25,26,27,10,19,28,43,32,33,34,35,
   36,46,38,39,49,41,42,52,44,45,1,47,48,4,50,51,7,53,54],
  yellow = P[1,2,48,4,5,51,7,8,54,10,11,12,13,14,3,18,27,
   36,19,20,21,22,23,6,17,26,35,28,29,30,31,32,9,16,25,34,
   37,38,15,40,41,24,43,44,33,46,47,39,49,50,42,52,53,45]
};  Enter
```

Theorem. $G = M_1$. G^{-1} is more fun!
$G = M_1 := \{\sigma_{1,j_1}\sigma_{2,j_2}\cdots\sigma_{n,j_n} : \forall i, j_i \geq i \text{ and } \sigma_{i,j_i} \in T\}$.
Proof. The inclusions $M_1 \subset G$ and $\{g_1,\dots,g_\alpha\} \subset M_1$ are obvious. The rest follows from the following
Lemma. M_1 is closed under multiplication.
Proof. By backwards induction. Let
$$M_k := \{\sigma_{k,j_k}\cdots\sigma_{n,j_n} : \forall i \geq k, j_i \geq i \text{ and } \sigma_{i,j_i} \in T\}.$$
Clearly $M_nM_n \subset M_n$. Now assume that $M_5M_5 \subset M_5$ and show that $M_4M_4 \subset M_4$. Start with $\sigma_{8,j}M_4 \subset M_4$:
$$\sigma_{8,j}(\sigma_{4,j_4}M_5) \overset{1}{=} (\sigma_{8,j}\sigma_{4,j_4})M_5 \overset{2}{\subset} M_4M_5$$
$$\overset{3}{=} \sigma_{4,j_4}(M_5M_5) \overset{4}{\subset} \sigma_{4,j_4}M_5 \subset M_4$$
(1: associativity, 2: thank the twist, 3: associativity and tracing i_4, 4: induction). Now the general case
$$(\sigma_{4,j_4'}\sigma_{5,j_5'}\cdots)(\sigma_{4,j_4}\sigma_{5,j_5}\cdots)$$
falls like a chain of dominos.

Problem Solved!

A Demo Program

```
In[2]:= ($RecursionLimit = 2^16;
 n = 54;
 P /: p_P ** P[a___] := p[[{a}]];
 Inv[p_P] := P @@ Ordering[p];
 Feed[P @@ Range[n]] := Null;
 Feed[p_P] := Module[{i, j},
   For[i = 1, p[[i]] == i, ++i];
   j = p[[i]];
   If[Head[s[i, j]] === P,
     Feed[Inv[s[i, j]] ** p],
   (* Else *) s[i, j] = p;
     Do[If[Head[s[k, l]] == P,
       Feed[s[i, j] ** s[k, l]];
       Feed[s[k, l] ** s[i, j]]
     ], {k, n}, {l, n}]
   ]]);  Enter
```

The Results

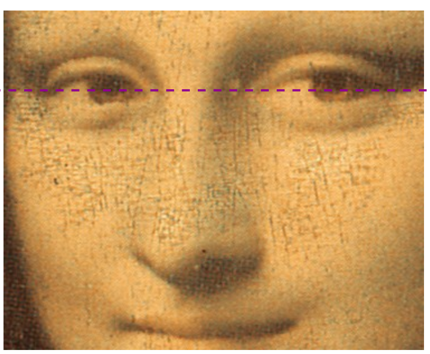
that's cool!

```
In[3]:= (Feed[#]; Product[1 + Length[Select[Range[n], Head[s[i, #]] === P &]], {i, n}]) & /@ gs  Enter
Out[3]= {4, 16, 159993501696000, 21119142223872000, 43252003274489856000, 43252003274489856000}
```

http://www.math.toronto.edu/~drorbn/Talks/Mathcamp-0907/ and links there

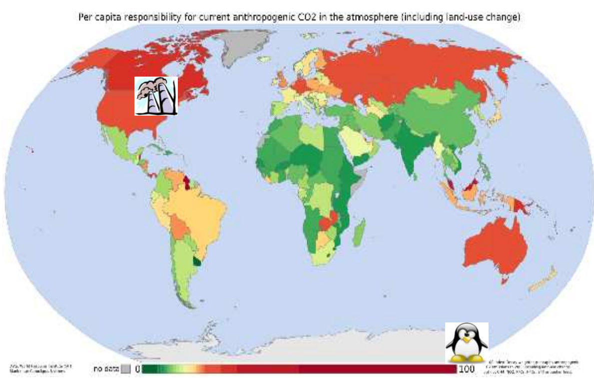
I could be a mathematician ...

...or an art historian...

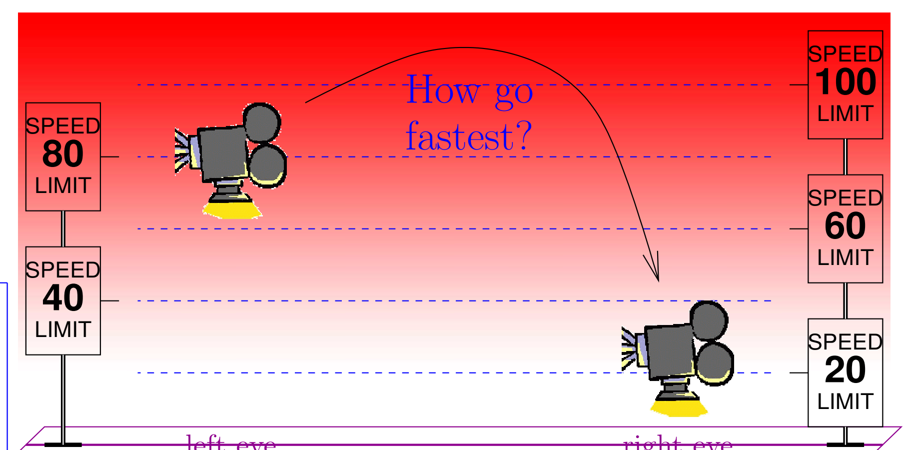


...or an environmentalist.

Al Gore in Futurama, circa 3000AD



Goal. Find the least-blur path to go from Mona's left eye to Mona's right eye in fixed time. Alternatively, fix your blur-tolerance, and find the fastest path to do the same. For fixed blur, our camera moves at a speed proportional to its distance from the image plane:



http://drorbn.net/n16

Video at http://www.math.toronto.edu/~drorbn/Talks/RCI-110213/, more at http://www.math.toronto.edu/~drorbn/Talks/Niagara-1612/