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<u>Sign-reversing involutions + identities involving signs</u>

Some identities w/ ± signs can be proven like this:

<u>Prop.</u> Given a set X with a <u>sign function</u> $\mathrm{sgn}: X \to \{\pm 1\}$
a <u>weight function</u> $\mathrm{wt}: X \to R$ (abelian gp.)

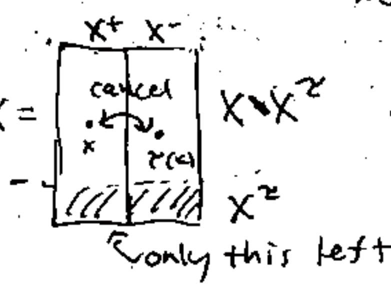
and a <u>sign-reversing</u>, <u>weight-preserving</u>, <u>involution</u>
($\mathrm{sgn}(\tau(x)) = -\mathrm{sgn}(x)$ if $\tau(x) \neq x$) ($\mathrm{wt}(\tau(x)) = \mathrm{wt}(x)$) ($\tau^2 = \mathrm{id}$)

$\tau: X \longrightarrow X$,

then $\displaystyle\sum_{x \in X} \mathrm{sgn}(x) \cdot \mathrm{wt}(x) = \sum_{x \in X^\tau} \mathrm{sgn}(x) \cdot \mathrm{wt}(x)$.

$X^\tau := \{x \in X : \tau(x) = x\}$

<u>Proof:</u> $X =$



$\mathrm{sgn}(x) \cdot \mathrm{wt}(x) + \underbrace{\mathrm{sgn}(\tau(x))}_{-\mathrm{sgn}(x)} \cdot \underbrace{\mathrm{wt}(\tau(x))}_{\mathrm{wt}(x)} = 0$

for all $x \in X \setminus X^\tau$ ▨

<u>Examples</u>

① (Warm-up) $\displaystyle\sum_{k=0}^{n} \binom{n}{k} (-1)^k = 0$ for $n \geq 1$

$\displaystyle = \sum_{\text{subsets } S \subseteq [n]} (-1)^{\#S}$

$\mathrm{sgn}: X = 2^{[n]} \to \{\pm 1\}$
$S \mapsto (-1)^{\#S}$

$\mathrm{wt}: X = 2^{[n]} \to \mathbb{Z}$
$S \mapsto 1$

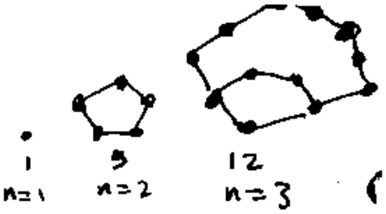
$\tau: \overset{2^{[n]}}{\overset{\shortparallel}{X}} \longrightarrow X$

$S \mapsto \begin{cases} S - \{1\} & \text{if } 1 \in S \\ S \cup \{1\} & \text{if } 1 \notin S \end{cases}$

is sign-reversing, weight-preserving with no fixed points.

<u>Rmk.</u> This was key identity in pf. of P.I.E.

Pentagonal numbers:



② Recall Thm (Euler's "Pentagonal Number Theorem")

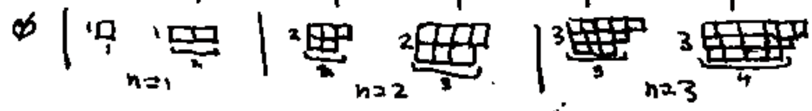
$$\prod_{j\geq 1}(1-q^j) = 1 + \sum_{n\geq 1}(-1)^n\left(q^{\frac{n(3n-1)}{2}} + q^{\frac{n(3n+1)}{2}}\right)$$

$$= 1 - q - q^2 + q^5 + q^7 - q^{12} - q^{15} + \cdots$$

Franklin's (1881) Proof of Euler's P.N.T.:

$$\underline{LHS} = (1-q)(1-q^2)\cdots = \sum_{\substack{X := \text{ partitions} \\ \lambda=\lambda_1>\lambda_2>\cdots>\lambda_\ell>0 \\ \text{into distinct parts}}} \overbrace{(-1)^{\ell(\lambda)}}^{\mathrm{sgn}(x)}\, \overbrace{q^{|\lambda|}}^{\mathrm{wt}(x)}$$

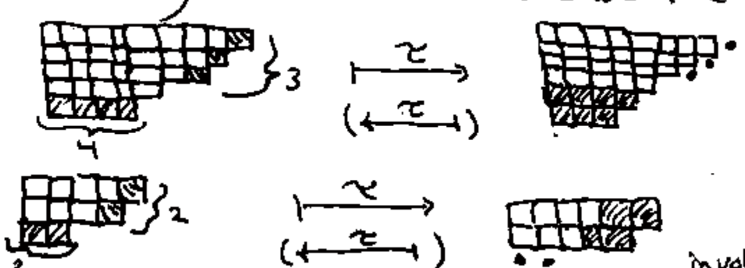
$$\underline{RHS} = 1 - q - q^2 + q^5 + q^7 - q^{12} - q^{15} + \cdots$$



Franklin defined $\tau : X := \{\lambda \text{ w/ distinct parts}\} \to X$ by comparing

• smallest part and • longest initial run $\lambda_1, \lambda_1 - 1, \lambda_1 - 2, \ldots$

and moving the smaller one onto the bigger one:



(or smallest part onto longest run if they are the same size)

When one can do this, check $\tau^2 = id$, $\ell(\tau(\lambda)) = \ell(\lambda) \pm 1$, $|\lambda| = |\tau(\lambda)|$

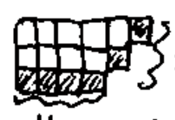
involution, sign-reversing, wt-preserving

One cannot do this if:

• smallest part + run have the same size and overlap

$n=3$, $|\lambda| = \frac{3n(n-1)}{2}$

• or run is 1 smaller + they overlap



$n=3$, $|\lambda| = \frac{3n(n+1)}{2}$

So τ implies only these shapes contribute to LHS $\Rightarrow$ LHS = RHS. ∎

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③ <u>Theorem</u> (Kirchoff's Matrix-Tree Theorem)

The number of spanning <u>trees</u> in a <u>multigraph</u> $G = (V, E)$ $\quad V = [n] = \{1, \ldots, n\}$

(multiple/parallel edges allowed)

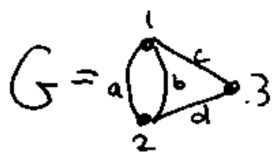
for any i

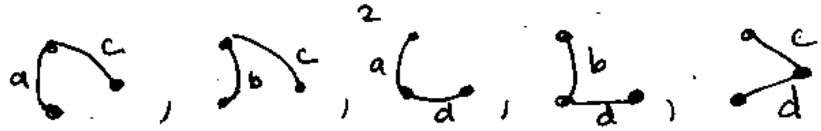
is $\det\left(\overline{L(G)}^{\,i,i}\right)$, where $\overline{A}^{\,i,i}$ means A w/ row + column i removed,

and $L(G)$ is the $n \times n$ <u>Laplacian matrix</u> of G:

$$L(G)_{v,w} := \begin{cases} \deg(v) & \text{if } v = w \\ -\#\text{edges from } v \text{ to } w & \text{if } v \neq w \end{cases}$$

<u>Note</u>: A spanning tree T of G is a subgraph of G that's a tree and which contains all the vertices V.

<u>Example</u> $G =$  has 5 spanning trees:



and
$$L(G) = \begin{array}{c|ccc} & 1 & 2 & 3 \\ \hline 1 & 3 & -2 & -1 \\ 2 & -2 & 3 & -1 \\ 3 & -1 & -1 & 2 \end{array}$$

so $\det\left(\overline{L(G)}^{\,1,1}\right) = \det\left(\begin{bmatrix} 3 & -1 \\ -1 & 2 \end{bmatrix}\right) = 6 - 1 = 5$ ✓

and $\det\left(\overline{L(G)}^{\,3,3}\right) = \det\left(\begin{bmatrix} 3 & -2 \\ -2 & 3 \end{bmatrix}\right) = 9 - 4 = 5$ ✓

<u>Example</u> Recall Cayley's formula n^{n-2} for # of (labeled) trees on n vertices. These are the ...

Spanning trees of the complete graph K_n on $[n]$.

e.g. $n=5$  $$\overline{L(K_n)}^{n,n} = \begin{array}{c|c} & \begin{array}{cccc} 1 & 2 & \cdots & n \end{array} \\ \begin{array}{c} 1 \\ 2 \\ \vdots \\ n \end{array} & \begin{bmatrix} n-1 & -1 & -1 & \cdots \\ -1 & n-1 & -1 & \cdots \\ \vdots & & \ddots & \\ -1 & \cdots & & \end{bmatrix} \end{array} = n\underbrace{I_{n-1}}_{\substack{(n-1)\times(n-1)\\ \text{identity matrix}}} - \underbrace{\mathbb{1}_{n-1}}_{\substack{\text{all 1's matrix}\\ \begin{bmatrix} 1 & \cdots & 1 \\ 1 & \cdots & 1 \end{bmatrix}}}$$

What are eigenvalues of $\mathbb{1}_{n-1}$? It has rank $=1$, so $(n-2)$ eigenvalues $=0$

Also $\mathbb{1}_{n-1}\cdot\begin{bmatrix}1\\ \vdots\\ 1\end{bmatrix} = (n-1)\begin{bmatrix}1\\ \vdots\\ 1\end{bmatrix}$, so one eigenvalue $=(n-1)$.

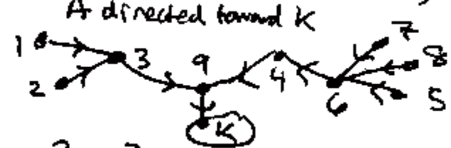
$\mathbb{1}_{n-1}$ has eigenval's $(\overbrace{0,0,\dots,0}^{n-2},n-1) \Rightarrow \overline{L(K)}^{n,n}$ has eigenval's $(\overbrace{n,n,\dots,n}^{n-2},1)$

$$\Rightarrow \det(\overline{L(K)}^{n,n}) = n^{n-2} \Rightarrow \text{Cayley's formula} \checkmark$$

In fact, let's prove a weighted, directed version of Kirchoff:

Thm If $$L = \begin{array}{c|c} & \begin{array}{ccccc} 1 & 2 & & \cdots & n \end{array} \\ \begin{array}{c} 1 \\ 2 \\ \vdots \\ n \end{array} & \begin{bmatrix} * & -a_{12} & -a_{13} & \cdots & -a_{1n} \\ -a_{21} & * & -a_{23} & \cdots & -a_{2n} \\ \vdots & & \ddots & & \\ -a_{n1} & \cdots & & & * \end{bmatrix} \end{array}$$ has $L_{ij} = \begin{cases} -a_{ij} & \text{if } i\neq j \\ a_{i1}+a_{i2}+\cdots+\widehat{a_{ii}}+\cdots+a_{in} & \text{if } i=j \end{cases}$

then $$\det(\overline{L}^{k,k}) = \sum_{\substack{\text{arborescences}\\ A \text{ directed toward } k}} \prod_{\text{arcs } i\to j \text{ in } A} a_{ij},$$ where a_{ij} are formal parameters.



Note: $\Rightarrow$ Kirchoff by setting $a_{ij} = \#$ edges $i\to j$ in G

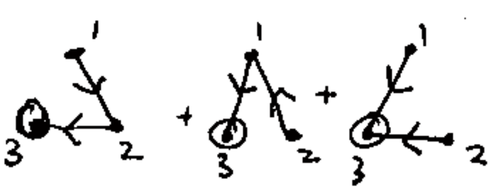
e.g. $n=3$

$$L = \begin{array}{c|c} & \begin{array}{ccc} 1 & 2 & 3 \end{array} \\ \begin{array}{c} 1 \\ 2 \\ 3 \end{array} & \begin{bmatrix} a_{12}+a_{13} & -a_{12} & -a_{13} \\ -a_{21} & a_{21}+a_{23} & -a_{23} \\ -a_{31} & -a_{32} & a_{31}+a_{32} \end{bmatrix} \end{array} \Rightarrow \det(\overline{L}^{3,3}) = \det\begin{bmatrix} a_{12}+a_{13} & -a_{12} \\ -a_{21} & a_{21}+a_{23} \end{bmatrix}$$

$$= (a_{12}+a_{13})(a_{21}+a_{23}) - (-a_{12})(-a_{21})$$

$$= a_{12}a_{23} + \cancel{a_{12}a_{21}} + a_{13}a_{21} + a_{13}a_{23} - \cancel{a_{12}a_{21}}$$

$\|$



$$a_{12}a_{23} \quad a_{13}a_{21} \quad a_{13}a_{23} = a_{12}a_{23} + a_{13}a_{21} + a_{13}a_{23} \checkmark$$

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Proof of Thm:

$$L = \begin{bmatrix} R_1 - a_{11} & -a_{12} & \cdots & -a_{1n} \\ -a_{21} & R_2 - a_{22} & \cdots & \\ \vdots & & \ddots & \\ -a_{n1} & \cdots & & R_n - a_{nn} \end{bmatrix} \text{ where } R_i = a_{i1} + a_{i2} + \cdots + a_{ii} + \cdots + a_{in} = \sum_{j=1}^{n} a_{ij}$$

$$= (R_i \cdot \delta_{ij} - a_{ij})_{\substack{i=1,\dots,n \\ j=1,\dots,n}}$$

$\boxed{\text{Recall: } \operatorname{sgn}(w) = (-1)^{\operatorname{inv}(w)}}$

$$\Rightarrow \det(L^{n,n}) \underset{\text{"Leibniz formula"}}{=} \sum_{w \in S_{n-1}} \operatorname{sgn}(w) \prod_{i=1}^{n-1} L_{i,w(i)}$$

$$= \sum_{\substack{S \subseteq [n-1] \\ \text{(fixed by } w)}} \prod_{i \in S} (R_i - a_{ii}) \sum_{\substack{w \in S_{[n-1] \setminus S} \\ \text{a derangement}}} \operatorname{sgn}(w) \prod_{i \in [n-1] \setminus S} (-a_{i,w(i)})$$

$$= \sum_{S \subseteq [n-1]} \sum_{T \subseteq S} \prod_{i \in T} R_i \prod_{i \in S \setminus T} (-a_{ii}) \sum_{\substack{w \in S_{[n-1] \setminus S} \\ \text{derang.}}} \operatorname{sgn}(w) \cdot \prod_{i \in [n-1] \setminus S} (-a_{i,w(i)})$$

Important property of sign of permutation: $\operatorname{sgn}(v \cdot w) = \operatorname{sgn}(v) \cdot \operatorname{sgn}(w)$

$$= \sum_{T \subseteq [n-1]} \underbrace{\prod_{i \in T} (a_{i1} + a_{i2} + \cdots + a_{in})}_{= \sum_{f: T \to [n]} \prod_{i \in T} a_{i,f(i)}} \cdot \sum_{w \in S_{[n-1] \setminus T}} \operatorname{sgn}(w) \prod_{i \in [n-1] \setminus T} (-a_{i,w(i)})$$

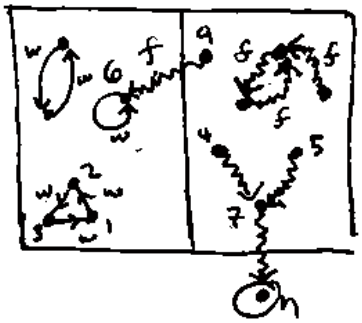
$$= \sum_{(T,f,w)} \underbrace{(-1)^{\#[n-1] \setminus T} \cdot \operatorname{sgn}(w)}_{\operatorname{sgn}(x)} \cdot \underbrace{\prod_{i \in T} a_{i,f(i)} \prod_{i \in [n-1] \setminus T} a_{i,w(i)}}_{\operatorname{wt}(x)}$$

$$\mathcal{X} := \begin{cases} (T, f, w) \\ T \subseteq [n-1] \\ f: T \to [n] \\ w \in S_{[n-1] \setminus T} \end{cases}$$

We will evaluate this signed, weighted sum using a sign-reversing involution ...

Picture of (T, f, w):

$[n-1] \setminus T$ $\quad$ T



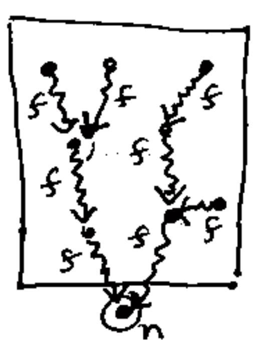
We can define an involution $\tau : \mathcal{X} \to \mathcal{X}$, that swaps the cycle containing the smallest index $i \in [n-1]$ from w to f or back from f to w!

Check that τ
- is an involution (clear)
- is wt-preserving (preserves arcs)
- is sign-reversing (sgn of a k-cycle is $(-1)^{k+1}$ ✓)

What are the fixed points $\mathcal{X}^{\tau}$?

No cycles in w or f $\Rightarrow$ $[n-1] \setminus T$ is empty, i.e., $T = [n-1]$ and $f : [n-1] \to [n]$ has no cycles

$T = [n-1]$



(easy) Lemma.
This forces f to be an arborescence directed toward n (and conversely, any arborescence is such an f).

Hence, $$\det(L^{n,n}) = \sum_{\substack{\text{arborescences} \\ f \text{ on } [n] \text{ directed} \\ \text{toward } n}} \prod_{i \in [n-1]} a_{i,f(i)}.$$ ▨

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The transfer matrix method (Stanley §4.7, Ardila §3.1.2)

Another tool from linear algebra for counting walks in graphs

Thm Let G be a graph w/ vertex set $V=[n]$, and let $A_G=(a_{ij})_{\substack{i=1,\dots,n\\ j=1,\dots,n}}$ be its adjacency matrix: $a_{ij} = \#\text{edges from } i \text{ to } j$.

Then (a) # of walks of length ℓ $i=i_0 \to i_1 \to \cdots \to i_\ell = j$ $= (A_G^\ell)_{i,j}$ for all $\ell \geq 0$.

(b) # of closed walks of length ℓ $i=i_0\to\cdots\to i_\ell=i$ (for all i) $=\lambda_1^\ell+\lambda_2^\ell+\cdots+\lambda_n^\ell$, where $\lambda_1,\lambda_2,\dots,\lambda_n$ are the eigenvalues of A_G.

Pf: (a) is just definition of matrix multiplication:

$$(A_G^\ell)_{i,j} = \sum_{i_1=1}^n \sum_{i_2=1}^n \cdots \sum_{i_{\ell-1}=1}^n a_{i,i_1}a_{i_1,i_2}\cdots a_{i_{\ell-1},j} = \text{LHS of (a)} \checkmark$$

For (b), from (a) it follows that

$$\#\text{closed walks of length } \ell = \sum_{i=1}^n (A_G^\ell)_{i,i} = \operatorname{trace}(A_G^\ell).$$

Since A_G is real + symmetric, it can be diagonalized, i.e., $\exists P$ s.t. $PA_GP^{-1} = \begin{pmatrix}\lambda_1 & & 0\\ & \ddots & \\ 0 & & \lambda_n\end{pmatrix}$. Thus,

$\boxed{\text{Recall: } tr(AB) = tr(BA)}$

$$\operatorname{trace}(A_G^\ell) = \operatorname{trace}\left(\left(P^{-1}\begin{pmatrix}\lambda_1 & & \\ & \ddots & \\ & & \lambda_n\end{pmatrix}P\right)^\ell\right)$$
$$= \operatorname{trace}\left(P^{-1}\begin{pmatrix}\lambda_1 & & 0\\ & \ddots & \\ 0 & & \lambda_n\end{pmatrix}^\ell P\right) = \operatorname{trace}\begin{pmatrix}\lambda_1^\ell & & \\ & \ddots & \\ & & \lambda_n^\ell\end{pmatrix} = \lambda_1^\ell+\cdots+\lambda_n^\ell. \quad \blacksquare$$

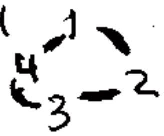
Example Let $f(n,k)$ = # proper vertex-colorings of C_n (no adjacent vertices w/ same color) w/ k-colors. ← cycle graph

eg. $n=2$ $\binom{1}{2}$ $f(2,k) = k(k-1)$

color 1 first in k ways; color 2 second in $k-1$ ways

$n=3$ $f(3,k) = k(k-1)(k-2)$

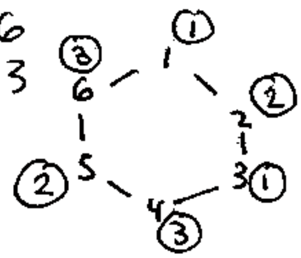
color 1, color 2, color 3

$\underline{n=4}$ 

$$f(4,k) = \underbrace{\overset{\text{color 1}}{k}\,\overset{\text{color 2}}{(k-1)}\,\overset{\text{color 3}}{(k-2)}\,\overset{\text{color 4}}{(k-3)}}_{\text{2+4 have different colors}} + \underbrace{\overset{\text{color 1}}{k}\,\overset{\text{color 2+4 same}}{(k-1)}\,\overset{\text{color 3}}{(k-1)}}_{\text{2+4 have same color}}$$

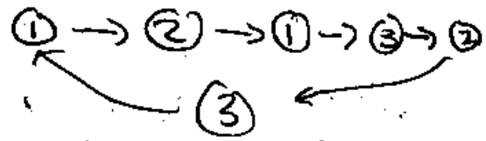
<u>Note</u>: $\{$proper k-colorings of $C_n\} \leftrightarrow \{$closed walks of length n in <u>complete graph</u> $K_k\}$

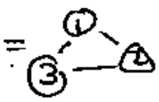
<u>e.g.</u> $n=6$, $k=3$



proper 3-coloring of C_6

$\longleftrightarrow$



a closed walk in $K_3 =$  of length 6.

So taking
$$A_{K_k} = \begin{array}{c|c} & \begin{matrix} ① & ② & \cdots & ⓚ \end{matrix} \\ \begin{matrix} ① \\ ② \\ \vdots \\ ⓚ \end{matrix} & \begin{bmatrix} 0 & 1 & \cdots & 1 \\ 1 & 0 & \cdots & 1 \\ \vdots & & & \vdots \\ 1 & 1 & \cdots & 0 \end{bmatrix} \end{array} = \mathbb{1}_k - I_k,$$

which has eigenvalues $(\lambda_1, \ldots, \lambda_k) = (k-1, \overbrace{-1, -1, \ldots, -1}^{k-1 \text{ terms}})$

(since we saw earlier that $\mathbb{1}_k$ has eigen's $(k, \overbrace{0, 0, \ldots, 0}^{k-1})$)

we find that
$$\begin{aligned} f(n,k) &= \lambda_1^n + \cdots + \lambda_n^n \\ &= (k-1)^n + (-1)^n + \cdots + (-1)^n \\ &= (k-1)^n + (k-1)(-1)^n \\ &= (k-1)\left((k-1)^{n-1} + (-1)^n\right). \end{aligned}$$

<u>e.g.</u>
$$\begin{aligned} f(2,k) &= (k-1)(k-1+1) = (k-1)k \\ f(3,k) &= (k-1)((k-1)^2 - 1) = (k-1)(k^2-2k) \\ f(4,k) &= (k-1)((k-1)^3 + 1) = (k-1)(k^3 - 3k^2 + 3k) \end{aligned}$$