Restricted or Ported Tutte Decomposion and Analogs of All-Minors Laplacian Expansions

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What is a Strong Tutte function?

Some history. Zaslavsky (1992) in "Strong Tutte Functions of Matroids and Graphs" showed what happens with Tutte equations (on a field), with 4 parameters (or weights) (Different notation!) g_e, r_e, $i_{\mathbf{loop(e)}}$ and $i_{\mathbf{coloop(e)}}$ for element e:

1. For all $\mathbf{N}$ with separator (neither loop nor coloop) $e \in S(\mathbf{N})$,

$$F(\mathbf{N}) = g_e F(\mathbf{N}/e) + r_e(\mathbf{N} \backslash e)$$

2. When $\mathbf{N} = \mathbf{N_1} \oplus \mathbf{N_2}$,

$$F(\mathbf{N}) = F(\mathbf{N_1})F(\mathbf{N_2})$$

3. When $\mathbf{N}$ is a loop or coloop on e, an initial value is given:

$$F(\mathbf{N}) = i_{\mathbf{N}}$$

   (Z.'s term: Point values.) This means there are two parameters (besides g_e, r_e) for each e, so

$$F(\mathbf{loop(e)}) = i_{\mathbf{loop(e)}} \text{ and } F(\mathbf{coloop(e)}) = i_{\mathbf{coloop(e)}}$$

What happens?

Those equations might not have a solution!

For (typically *lots of*) equations involving a common *function* F, for them "to have a solution" MEANS there exists a function F on some domain of matroids so all the equations are satisfied with that F.
This MEANS $F(\mathbf{N})$ is what is computed by applying Tutte equations *in any order they are applicable*.

Z.'s result

Strong Tutte functions are classified into seven types, each given by conditions on the weights and the initial values.
Amazingly, the conditions for there to be a solution are all derived by requiring all Tutte decompositions of **2 or 3 point matroids** in the domain to compute *the same value*.

Maybe more history

All things matroids and Tutte polynomial were around Zaslavsky and the rest of the 1970's MIT gang.
After a couple of years, I tried my hand at drawing algorithms for planar graphs, and was led to Tutte's "How to draw a graph", and Brook, Smith, Stone and Tutte's "Dissecting a square into squares." Both inverted submatrices of a graph's Laplacian; both had the Matrix Tree Theorem to prove this was possible. Harmonic functions on vertices were used to place vertices (after fixing places of some) and to find sizes of squares so they tiled a square in a given combinatorial pattern.

Solving electrical problems by counting trees

Very shocking fact-Maxwell's or Kirchhoff's rule

The equivalent resistance R_{uv} between nodes u and v of a resistor network N with edge conductances g_e ($= r_e^{-1}$ is

$$R_{uv} = \frac{\sum_{F \text{ a spanning tree in } N/(uv) \text{ with } u,v \text{ identified}} \prod_{e \in F} g_e}{\sum_{F \text{ a spanning tree in } N} \prod_{e \in F} g_e}$$

So weighted tree enumeration don't just tell us some matrices are invertable.

Thinking matroids, $N/(uv)$ is N with a different kind of edge, an interface edge $p = uv$ added. Then,

Numerator is $\sum g_F$ over F bases in N/p.
Denominator is $\sum g_F$ over F bases in $N \backslash p$.
BOTH of these sums are weighted Tutte functions.

Why call (uv) a port?

from "The Tutte Polynomial of a Ported Matroid" sdc 1989

We have been motivated by electrical network considerations where the branches used to connect the network to other networks are distinguished from the branches or variables associated with devices such as resistors or capacitors..

Ported/Set Pointed/Relative Tutte Functions

Definition (sdc 1989)

(easily updated with weights and oriented matroids) Let $M(E, P)$ be a P-ported oriented matroid with rank function ρ. The P-ported weighted rank generating function $r_P(M)$ is

$$r_P(M) = \sum_{A \subseteq E} [M/A|P] g_A r_{\overline{A}} x^{\rho(M) - \rho(M/A|P) - \rho(A)} y^{|A| - \rho(A)}$$

Here $S(M) = P(M) \coprod E(M)$, and r_e, g_e are weights for each $e \in E$.

For any oriented matroid M for which $E(M) = \emptyset$, $[\emptyset] = 1$ and

$$[M] = [M_1][M_2] \cdots [M_k]$$

where $M = M_1 \oplus M_2 \cdots M_k$ and each M_i is connected. These bracket *oriented* matroid symbols comprise, with (the well-known) Tutte Polynomial variables x and y, the variables in $r_P(M)$.

P-ported parametrized Tutte Equations

They are the usual, except deletion/contraction of e is forbidden when $e \in P$.

Definition

An oriented matroid $M(P, E)$ is P-ported when its ground set $S(M) = P \coprod E$. A function F on oriented matroids is a P-ported weighted Tutte function if

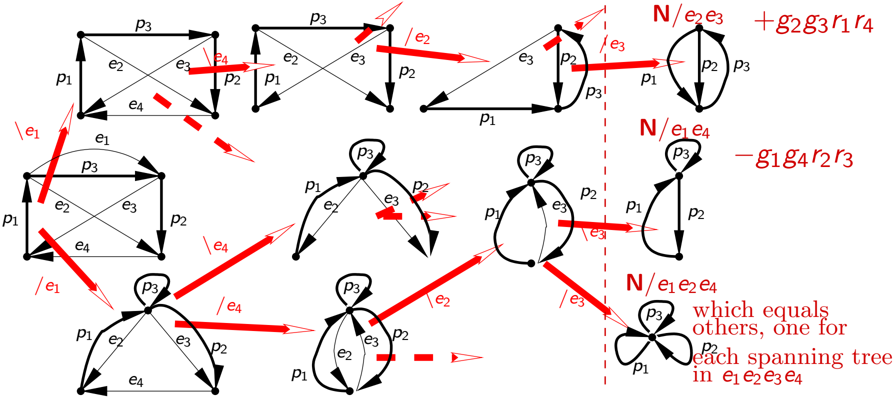
- Whenever $e \in E(M)$, and e is a non-separator in M, $F(M) = g_e F(M/e) + r_e F(M \backslash e)$.
- Whenever $M = M_1 \oplus M_2$, $F(M) = F(M_1)F(M_2)$.

Theorem

r_P defined above is (such) a Tutte function.

Ported Tutte Decomposition (not all of it)

The decomposition ends with minors $\mathbf{N}/F\overline{F}$.
We show component $\mathbf{L}_E(\mathbf{N}\ \mathbf{N})[p_{\alpha 1}p_{\beta 1}p_{\alpha 3}]$:



Zaslavsky 1992: It doesn't all work. r_P is not universal.

$$r_P(\textbf{loop(e)}) = g_e y + r_e$$
$$r_P(\textbf{coloop(e)}) = r_e x + g_e$$

The two Tutte decompositions of the circuit U^1_{ef} on e, f to compute a prospective Tutte function F give

$$e \text{ first } F(U^1) = g_e F(loop(f)) + r_e F(coloop(f))$$
$$f \text{ first } F(U^1) = g_f F(loop(e)) + r_f F(coloop(e))$$

We still need those 4 point values, and they can't be chosen independently of the 4 weights. Zaslavsky called the class where there are arbitrary x, y values and the point values are $g_e y + r_e$ and $r_e x + g_e$ *normal Tutte functions*.

Related work.

- $|P| = 1$ and series/parallel connections on pointed matroids (Brylawsky (1971)), extended to unions and dual-unions over P (also sdc 1989).
- Matroids called set-pointed on P encoded by products of many variables (Las Vergnas 1975).
- Weighs/colors/parameters (Zaslavsky 1992, Bollobás and Riordan 1999, Ellis-Monaghan and Traldi 2006. Much motivation from maps on surfaces and knot theory.
- Dao and Hetyei (2012) named carried out BRZs classfication program, called the matroids relative. Motivated by knots with ports for virtual crossings. Easy to see this extends to oriented matroids.

What this talk is about.

Some ways determinants make Tutte functions.
How the graph and other Laplacians ACTUALLY ARE Tutte functions, not just a partcular determinant.
Ported Tutte functions are needed to tell this story.
The only Tutte function I know valued in a **non-commutative ring** (the signed commutative exterior algebra).
Only normal Tutte functions are relevant, and we only need them with $x = y = 0$ (which does P-subbasis enumeration).

Tutte Functions using determinants: Our setup

- Matrices N_α, $N_\beta^\perp$; full row rank, columns indexed by $P \coprod E$.
  $\text{rank}(N_\alpha) + \text{rank}(N_\beta^\perp) = |E| + |P|$.
  $P_\alpha, P_\beta \leftrightarrow P$, $P_\alpha \cap P_\beta = \emptyset$.
- Weight (parameter) matrices
  $G = \text{diag}\{g_e\}_{e \in E}$, $R = \text{diag}\{r_e\}_{e \in E}$.
- Matrix with columns $P_\alpha \coprod P_2 \coprod E$

$$L = L\begin{pmatrix} N_\alpha \\ N_\beta^\perp \end{pmatrix} = \left[\begin{array}{c|c|c} N_\alpha(P) & 0 & N_\alpha(E)G \\ \hline 0 & N_\beta^\perp(P) & N_\beta^\perp(E)R \end{array}\right]$$

Define

$$F(L) = \left(\left(\binom{2p}{p}\right)\right) - \text{tuple of determinants } L[Q_\alpha \overline{Q_\beta} E (\text{all of } E)]$$

indexed by length $p = |P|$ sequences $Q_\alpha \overline{Q_\beta} \subseteq P_\alpha P_\beta$ where $Q_\alpha \subseteq P_\alpha$ and $\overline{Q_\beta} \subseteq P_\beta$.

Column e of L when $e \notin P$ is

$$\begin{bmatrix} N_{\alpha,1,e} g_e \\ N_{\alpha,2,e} g_e \\ \dots \\ N_{\alpha,r_1,e} g_e \\ N^{\perp}_{\beta,1,e} r_e \\ N^{\perp}_{\beta,2,e} r_e \\ \dots \\ N^{\perp}_{\beta,r_2,e} r_e \end{bmatrix} = \begin{bmatrix} N_{\alpha,1,e} \\ N_{\alpha,2,e} \\ \dots \\ N_{\alpha,r_1,e} \\ 0 \\ 0 \\ \dots \\ 0 \end{bmatrix} g_e + \begin{bmatrix} 0 \\ 0 \\ \dots \\ 0 \\ N^{\perp}_{\beta,1,e} \\ N^{\perp}_{\beta,2,e} \\ \dots \\ N^{\perp}_{\beta,r_2,e} \end{bmatrix} r_e$$

So, for all $e \in E$, that is $e \notin P$:

$$F(L)_{Q_\alpha \overline{Q_\beta}} = L[Q_\alpha \overline{Q_\beta} E] =$$

$$g_e L \begin{pmatrix} N_\alpha / e \\ N^{\perp}_\beta \backslash e \end{pmatrix} [Q_\alpha \overline{Q_\beta} E] + r_e L \begin{pmatrix} N_\alpha \backslash e \\ N^{\perp}_\beta / e \end{pmatrix} [Q_\alpha \overline{Q_\beta} E].$$

Since deletion and contraction are done only for $e \notin P$

we get a **Ported** (sdc) or **Set-pointed** (Las Vergnas) or **relative** (Dao and Hetyei) Tutte Function.

$|Q_\alpha \overline{Q_\beta}| = p$, so $\binom{2p}{p}$ determinants $L[Q_\alpha \overline{Q_\beta} E]$ make the tuple:

$$F(L) = g_e FL \begin{pmatrix} N_\alpha / e \\ N_\beta^\perp \backslash e \end{pmatrix} + r_e FL \begin{pmatrix} N_\alpha \backslash e \\ N_\beta^\perp / e \end{pmatrix}$$

where

N/e means remove the g_e or r_e but otherwise keep column e

$N \backslash e$ means replace column e by 0.

Plücker coordinates

These determinants can be considered an *affine* version of the (projective) Plücker coordinates for the row space of L projected into $K^{P_\alpha \coprod P_\beta}$. We need affine so Tutte's $+$ identity makes sense.

$$FL\begin{pmatrix} N_\alpha \\ N_\beta^\perp \end{pmatrix} = g_e FL\begin{pmatrix} N_\alpha/e \\ N_\beta^\perp \backslash e \end{pmatrix} + r_e FL\begin{pmatrix} N_\alpha \backslash e \\ N_\beta^\perp/e \end{pmatrix} \qquad (*)$$

Real deletion/contraction removes e from the ground set of the matroid or other object, but $N/e, N\backslash e$ still have column e. But (*) holds for all $e \in E$, so Laplace's expansion is a basis expansion:

$$L[Q_\alpha \overline{Q_\beta} E] = \sum_{A \subseteq E} g_A r_{\overline{A}} N_\alpha[Q_\alpha A] N_\beta^\perp[\overline{Q_\beta A}]\epsilon(Q_\alpha A, \overline{Q_\beta A})$$

The A term is $\neq 0$ iff $Q_\alpha A$ is a column basis for N_α and $\overline{Q_\beta A}$ is a column basis for $N_\beta^\perp$. So, for each $Q_\alpha \overline{Q_\beta}$

$$L[Q_\alpha \overline{Q_\beta} E] = \pm \sum_{A \subseteq E} g_A r_{\overline{A}} N_\alpha[Q_\alpha A] N_\beta^\perp[\overline{Q_\beta A}]\epsilon(A, \overline{A})$$

(The non-zero terms all have $|A| = \mathrm{rank}(N_\alpha) - |Q_\alpha|$.)

Quick and dirty fix

1. Drag column e to the far right.
   Changes sign of $F(L)$ by $\epsilon(E'e)$.
2. Left multiply by a determinant 1 matrix that sends the last column to $(0, \ldots, 1g_e, 0, \ldots, 1r_e)^{\mathbf{t}}$ (if the top or bottom submatrix has just 1 row, do the hack: $\mathbf{N}/e$ is number $\mathbf{N}_{1,e}$ that acts like a matrix with columns E' and no rows.)
3. Drag the row with the $1g_e$ to the bottom.
   Changes sign of $F(L)$ by $(-1)^{\mathsf{r}\mathbf{N}_\beta^\perp}$
4. With e deleted/contracted from the $\mathbf{N}$s defining L, define F by $FL_{Q_\alpha \overline{Q_\beta}} = L[Q_\alpha \overline{Q_\beta} E']$

Result

$$FL\begin{pmatrix} N_\alpha \\ N_\beta^\perp \end{pmatrix} = \epsilon(E'e)\left(g_e(-1)^{\mathsf{r}(N_\beta^\perp)} FL\begin{pmatrix} N_\alpha/e \\ N_\beta^\perp \backslash e \end{pmatrix} + r_e FL\begin{pmatrix} N_\alpha \backslash e \\ N_\beta^\perp / e \end{pmatrix}\right)$$

Simplify calculations /w minors via Exterior Algebra

Full r-row minors of matrix N with columns indexed by S:

$$
\begin{array}{ccc}
(e_1) & (e_2) & (e_3) \\
a_1 & a_2 & a_3 \\
b_1 & b_2 & b_3 \\
\hline
\multicolumn{3}{c}{\mathbf{N}[e_1 e_3] = (a_1 b_3 - a_3 b_1)}
\end{array}
$$

Coefficients when the exterior product of N's row vectors $\mathbf{N}$ are expressed in basis $\{\mathbf{e}_{i_1} \wedge \mathbf{e}_{i_2} \cdots \mathbf{e}_{i_r} | i_1 < i_2 \cdots < i_r\}$:

$$
\begin{array}{cc}
 & (a_1\mathbf{e}_1 + a_2\mathbf{e}_2 + a_3\mathbf{e}_3) \\
\wedge & (b_1\mathbf{e}_1 + b_2\mathbf{e}_2 + b_3\mathbf{e}_3) \\
\hline
\multicolumn{2}{c}{((a_1 b_3 - a_3 b_1)\mathbf{e}_1\mathbf{e}_3 + \cdots)}
\end{array}
$$

We sometimes omit the $\wedge$ and we can always write:

$$(\text{Exterior product})\mathbf{N} = \sum_{A \subseteq S; |E|=r} \mathbf{N}[A]\mathbf{A}$$

Each subset A is ordered $a_1 a_2 \ldots a_r$ **arbitrarilly** but $\mathbf{A}$ denotes the exterior product of (row coordinate vectors) **in the same order**

$$\mathbf{A} = \mathbf{a_1 a_2 \ldots a_r}$$

Catalogs of Oriented Matroid operations on the OM of matrix N and on $\mathbf{N} = \wedge(\text{rows}(N))$

domain D of operations:	chirotopes	exterior products
D is which functions:	$\pm\chi : B \mapsto \text{sign}(N[B])$	$\mathbf{N} : B \mapsto \mathbf{N}[B]$
type of fun. value	sign $\in \{0, +, -\}$	**field value; number**
deletion $\bullet\backslash A$	$\pm\chi' : B \mapsto \chi(B)$	$\mathbf{N}\backslash A : B \mapsto \mathbf{N}[B]$
contraction $\bullet/A$	$\pm\chi' : B \mapsto \chi(BA)$	$\mathbf{N}/A : B \mapsto \mathbf{N}[BA]$
duality $\bullet^\perp$	$\pm\chi^\perp : B \mapsto \chi(\overline{B})\epsilon(\overline{B}B)$	$\mathbf{N}^\perp : B \mapsto \mathbf{N}[\overline{B}]\epsilon(\overline{B}B)$

We must choose some global orientation ϵ in order to define duality as an exterior alg. operation!
ϵ is an alternating sign function on all finite sequences of elements.

This implies commutations

$$(\mathbf{N}\backslash X)^\perp = \epsilon(S')\epsilon(S'X)(\mathbf{N}^\perp/X)$$

$$(\mathbf{N}/X)^\perp = \epsilon(S')\epsilon(S'X)(-1)^{|X|r\mathbf{N}^\perp}(\mathbf{N}^\perp\backslash X)$$

Our setup - again

- Matrices N_α, $N_\beta^\perp$; full row rank, columns indexed by $P \coprod E$. $\mathrm{rank}(N_\alpha) + \mathrm{rank}(N_\beta^\perp) = |E| + |P|$. $P_\alpha, P_\beta \leftrightarrow P$, $P_\alpha \cap P_\beta = \emptyset$.
- Weight (parameter) matrices $G = \mathrm{diag}\{g_e\}_{e \in E}$, $R = \mathrm{diag}\{r_e\}_{e \in E}$.
- Matrix with columns $P_\alpha \coprod P_2 \coprod E$

$$L \begin{pmatrix} N_\alpha \\ N_\beta^\perp \end{pmatrix} = \left[\begin{array}{c|c|c} N_\alpha(P) & 0 & N_\alpha(E)G \\ \hline 0 & N_\beta^\perp(P) & N_\beta^\perp(E)R \end{array} \right]$$

Define

$$F(L) = ((\binom{2p}{p})) - \text{tuple of determinants } L[Q_\alpha \overline{Q_\beta} E])$$

indexed by sequences $Q_\alpha \overline{Q_\beta} \subseteq P_\alpha P_\beta$ where $Q_\alpha \subseteq P_\alpha$, $\overline{Q_\beta} \subseteq P_\beta, |Q_\alpha \overline{Q_\beta}| = p = |P|$.

$$L\begin{pmatrix} N_\alpha \\ N_\beta^\perp \end{pmatrix} = \left[\begin{array}{c|c|c} N_\alpha(P) & 0 & N_\alpha(E)G \\ \hline 0 & N_\beta^\perp(P) & N_\beta^\perp(E)R \end{array}\right] \qquad F(L) = \text{tuple } (L[Q_\alpha \overline{Q_\beta} E])$$

Translate into exterior algebra definitions:

$$\mathbf{L}\begin{pmatrix} \mathbf{N}_\alpha \\ \mathbf{N}_\beta^\perp \end{pmatrix} := (\iota(\mathbf{N}_\alpha)(P_\alpha) + \iota_G(\mathbf{N}_\alpha(E))) \wedge (\upsilon(\mathbf{N}_\beta^\perp)(P_\beta) + \upsilon_R(\mathbf{N}_\beta^\perp)(E))$$
$$= (\iota_G(\mathbf{N}_\alpha) \wedge \upsilon_R(\mathbf{N}_\beta^\perp))$$

$$\mathbf{F}_E(\mathbf{L}) := \mathbf{L}/E = \sum_{Q_\alpha, \overline{Q_\beta}} \mathbf{L}[Q_\alpha \overline{Q_\beta} E]\mathbf{Q}_\alpha \overline{\mathbf{Q}_\beta}$$
$$= ((\iota(\mathbf{N}_\alpha)\backslash e(\text{no } \mathbf{e}) + g_e(\iota(\mathbf{N}_\alpha)/e) \wedge \mathbf{e})$$
$$\wedge (\upsilon(\mathbf{N}_\beta^\perp)\backslash e(\text{no } \mathbf{e}) + r_e(\upsilon(\mathbf{N}_\beta^\perp)/e) \wedge \mathbf{e}))/E$$

$$\text{2 of 4 terms} = \Big(r_e \qquad \iota(\mathbf{N}_\alpha)\backslash e \wedge (\upsilon(\mathbf{N}_\beta^\perp)/e) \wedge \mathbf{e}$$
$$\text{vanish} \quad + g_e(-1)^{r(\mathbf{N}_\beta^\perp)}(\iota(\mathbf{N}_\alpha)/e) \wedge (\upsilon(\mathbf{N}_\beta^\perp)\backslash e) \wedge \mathbf{e}\Big)/E$$

$$L\begin{pmatrix} N_\alpha \\ N_\beta^\perp \end{pmatrix} = \left[\begin{array}{c|c|c} N_\alpha(P) & 0 & N_\alpha(E)G \\ \hline 0 & N_\beta^\perp(P) & N_\beta^\perp(E)R \end{array}\right] \qquad F(L) = \text{tuple } (L[Q_\alpha \overline{Q_\beta} E])$$

$$\mathbf{F}_E(\mathbf{L}) = \mathbf{L}/E = \Big(r_e \qquad \iota(\mathbf{N}_\alpha \backslash e) \wedge (\upsilon(\mathbf{N}_\beta^\perp / e)) \wedge \mathbf{e}$$

$$+ g_e(-1)^{r(\mathbf{N}_\beta^\perp)} (\iota(\mathbf{N}_\alpha / e)) \wedge (\upsilon(\mathbf{N}_\beta^\perp \backslash e)) \wedge \mathbf{e} \Big)/E$$

$$= r_e \left(\mathbf{L} \begin{pmatrix} \mathbf{N}_\alpha \backslash e \\ \mathbf{N}_\beta^\perp / e \end{pmatrix} \wedge \mathbf{e}/E \right) + g_e(-1)^{r(\mathbf{N}_\beta^\perp)} \left(\mathbf{L} \begin{pmatrix} \mathbf{N}_\alpha / e \\ \mathbf{N}_\beta^\perp \backslash e \end{pmatrix} \wedge \mathbf{e}/E \right)$$

$$(\mathbf{N}\backslash e)^\perp = \epsilon(S')\epsilon(S'e)(\mathbf{N}^\perp / e) \; ; \; (\mathbf{N}/e)^\perp = \epsilon(S')\epsilon(S'e)(-1)^{|\{e\}| r \mathbf{N}^\perp} (\mathbf{N}^\perp \backslash e)$$

Result

$$= \epsilon(S)\epsilon(S'e)(r_e \left(\mathbf{L} \begin{pmatrix} \mathbf{N}_\alpha \backslash e \\ (\mathbf{N}_\beta \backslash e)^\perp \end{pmatrix} \wedge \mathbf{e}/E \right) + g_e \left(\mathbf{L} \begin{pmatrix} \mathbf{N}_\alpha / e \\ (\mathbf{N}_\beta / e)^\perp \end{pmatrix} \wedge \mathbf{e}/E \right))$$

With $\mathbf{L}(\mathbf{N}_\alpha \;\; \mathbf{N}_\beta) = \mathbf{L}\begin{pmatrix} \mathbf{N}_\alpha \\ \mathbf{N}_\beta^\perp \end{pmatrix}$, and more sign calculations:

Definition

For E, P sets written as ordered sequences,

$$\mathbf{F}_E(\mathbf{N}_\alpha \;\; \mathbf{N}_\beta) = \mathbf{L}(\mathbf{N}_\alpha \;\; \mathbf{N}_\beta)/E$$

Theorem

$$\begin{aligned} &\epsilon(PE)\mathbf{F}_E(\mathbf{N}_\alpha \;\; \mathbf{N}_\beta) = \\ &\qquad \epsilon(PE')\left(g_e\mathbf{F}_{E'}(\mathbf{N}_\alpha/e \;\; \mathbf{N}_\beta/e) + r_e\mathbf{F}_{E'}(\mathbf{N}_\alpha\backslash e \;\; \mathbf{N}_\beta\backslash e)\right)\end{aligned}$$

Corollary

$\mathbf{F} = \mathbf{F}_E(\mathbf{N}_\alpha \;\; \mathbf{N}_\beta) = \pm \sum_{H \subset E} g_H r_{\overline{H}} \mathbf{F}_\emptyset(\mathbf{N}_\alpha / H \backslash \overline{H} \;\; \mathbf{N}_\beta / H \backslash \overline{H})$

Applying the Tutte Polynomial

- THEREFORE: We can obtain $\mathbf{F}$ by doing a ported Tutte decomposition, keeping track of the contraction and deletion order H,$\overline{H}$. Then, when we get nodes with no more $e \in E$, substitute the exterior product $\mathbf{F}_\emptyset(\mathbf{N}_\alpha / H \backslash \overline{H} \mathbf{N}_\beta / H \backslash \overline{H})$ which is $\mathbf{N}_\alpha / H | P \wedge \mathbf{N}_\beta / H | P$
- When the $\mathbf{N}_\alpha = \mathbf{N}_\beta$ represent regular matroids by unimodular matrices, we can do the familiar substition of the Tutte function value(s) $F([M/H|P])$ for the matroid variable (product) $[M/H|P]$. (More research needed to develop how to make sure proper $\pm$ signs are maintained everywhere.)

Corollary

1. *Componentwise,* $\sum_{Q_\alpha, Q_\beta} \mathbf{F}_E[Q_\alpha \overline{Q}_\beta]\mathbf{Q}_\alpha \overline{\mathbf{Q}_\beta} =$
$$= \pm \sum_{Q_\alpha, Q_\beta} \sum_{H \in E} g_H r_{\overline{H}} \mathbf{N}_\alpha[Q_\alpha H] \mathbf{N}_\beta^\perp[\overline{Q_\beta H}]$$
$$= \pm \sum_{Q_\alpha, Q_\beta} \sum_{H \in E} g_H r_{\overline{H}} \mathbf{N}_\alpha[Q_\alpha H] \mathbf{N}_\beta[Q_\beta H]$$
2. *Two expr. for products of numbers* $\mathbf{N}_\alpha[Q_\alpha H]\mathbf{N}_\beta[Q_\beta H]$*:*
$$(\mathbf{N}_\alpha/Q_\alpha)[H] \cdot (\mathbf{N}_\beta/Q_\beta)[H] = (\mathbf{N}_\alpha/H)[Q_\alpha] \cdot (\mathbf{N}_\beta/H)[Q_\beta]$$
3. *It's non-zero iff H is a common basis (in the matroids of)* $\mathbf{N}_\alpha/Q_\alpha$ *and* $\mathbf{N}_\beta/Q_\beta$
iff Q_α is a basis in $\mathbf{N}_\alpha/H$ and Q_β is a basis in $\mathbf{N}_\beta/H$

Weighted Laplacian-like matrices

Generalize a graph's incidence matrix: Make P label the rows, E the columns of any matrices A_α, A_β. Take all $r_e \neq 0$. Then, $N_\alpha = (I(P) \;\; A_\alpha(E))$ and $N_\beta = (I(P) \;\; A_\beta(E))$, and

$$L\begin{pmatrix} N_\alpha \\ N_\beta^\perp \end{pmatrix} = \left[\begin{array}{c|c|c} I & 0 & A_\alpha G \\ \hline 0 & -A_\beta^t & IR \end{array}\right] = L\left(N_\alpha \quad N_\beta\right). \text{ Do row ops:}$$

$$\begin{pmatrix} I & -A_\alpha G R^{-1} \\ 0 & R^{-1} \end{pmatrix} L = \begin{pmatrix} I & A_\alpha G R^{-1} A_\beta^t & 0 \\ 0 & -R^{-1} A_\beta^t & I \end{pmatrix}, \text{ and therefore}$$

$$\epsilon(Q_\alpha \overline{Q_\alpha}) \mathbf{F}_E(\mathbf{L})[Q_\alpha \overline{Q_\beta}] = \frac{1}{r_E} \sum_{B \in E} g_B r_{\overline{B}} A_\alpha[\overline{Q_\alpha} B] A_\beta[\overline{Q_\beta} B]$$

is the Cauchy-Binet expansion of any minor $(\overline{Q_\alpha}, \overline{Q_\beta})$ of the weighted graph Laplacian-like matrix $A_\alpha G R^{-1} A_\beta^t$.
(Note $\frac{1}{r_E} r_{\overline{B}} = (r^{-1})_B$.)

Examples

$N_\alpha = N_\beta = N; A =$ graph's incidence matrix w/ columns $(0, ..0, 1, 0, .., -1, 0, .., 0)^t$ for each edge; reps. graphic matroid.

The all-minors Matrix Tree Theorem for weighted undirected graphs

A_α, N_α as above. $A_\beta =$ only the $+1$ entries of A for a directed graph, so $+1$ is for an edge head on a vertex.

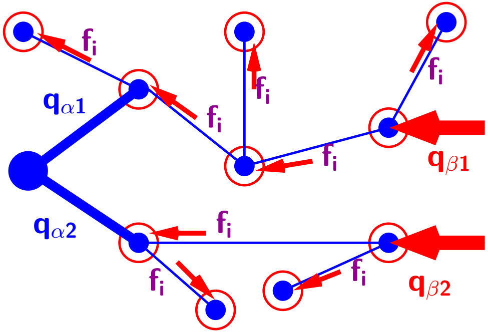
The all-minors Matrix Tree Theorem for weighted directed graphs

$N_\alpha = N_\beta = N; A =$ gain graph's incidence matrix w/ columns $(0, .., 0, 1, 0, .., -\gamma_e, 0, .., 0)^t$ for e with gain $\gamma_e \in \mathbf{C}$.

All-minors expansions of a signed, genr. gain graph's Laplacian

NB: Edge Gains γ_e are DIFFERENT ATTRIBUTES from weights/parameters g_e, r_e

All-Minors Digraph Matrix Tree Theorem Example

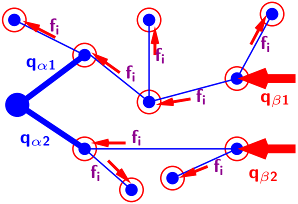


This contributes the term

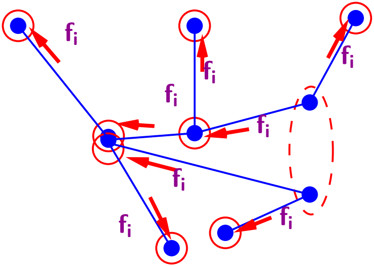
$g_F r_{\overline{F}} \mathbf{N}_\alpha[Q_\alpha F] \mathbf{N}_\beta[Q_\beta F]$.

The $\mathbf{q}_{\alpha 1}, \mathbf{q}_{\alpha 2}$ port edges $\cup$ the f_i elements as edges in the graphic matroid comprise a spanning tree.

The $\mathbf{q}_{\beta 1}, \mathbf{q}_{\beta 2}$ port arrows $\cup$ the f_i elements as arrows in a partition matroid comprise a basis. Each part (a red cirle) of the partition is the set of arrows incident to a vertex, except the star vertex.



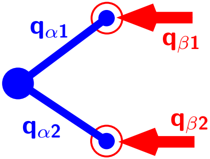
Contract the ports.



Count the bases in common.

$g_F r_{\overline{F}} \mathbf{N}_\alpha / Q_\alpha[F] \mathbf{N}_\beta / Q_\beta[F]$.

Contract the non-ports.



α and β ports are bases in the contracted N_α and N_β matroids.

$g_F r_{\overline{F}} \mathbf{N}_\alpha / F[Q_\alpha] \mathbf{N}_\beta / F[Q_\beta]$.

Resistive Network style problems Solved by Tutte Functions

With the $\binom{2p}{p}$ tuple of $(p+n) \times (p+n)$ minors of $\mathbf{L}(\mathbf{N} \;\; \mathbf{N})$ all including columns E, every electrical style problem can be analyzed.

Input

Choose $1 \leq k \leq p$, and choose from among the set of $2p$ variables $\{v_1, \ldots, v_p; i_1, \ldots, i_p\}$ these 4 subsets:

- k "source" variables $S = \{s_1, \ldots, s_k\}$.
- $p - k$ "zero" variables $Z = \{z_1, \ldots, z_{p-k}\}$ so $S \cap Z = \emptyset$, ie. $|S \cup Z| = p$.
- k' "response" variables $R = \{r_1, \ldots, r_{k'}\}$
- $p - k'$ "don't care" variables $D = \{d_1, \ldots, d_{p-k}\}$

Question and Answer

Does there exist a $k' \times k$ matrix Ξ for all source values s_i,

$$\Xi(s_1, \ldots, s_k)^t = (r_1, \ldots, r_{k'})^t \text{ is the unique solution in}$$

$$\{(r_1, \ldots, r_{k'}) | L(\mathbf{N} \quad \mathbf{N})(v_1, \ldots, v_p; i_1, \ldots, i_p)^t = 0,$$

$$s_i \text{ are given }, z_i = 0,$$

$$\text{and there exist } d_1, \ldots, d_{p-k'}\}??$$

Answer for S, Z, R, D

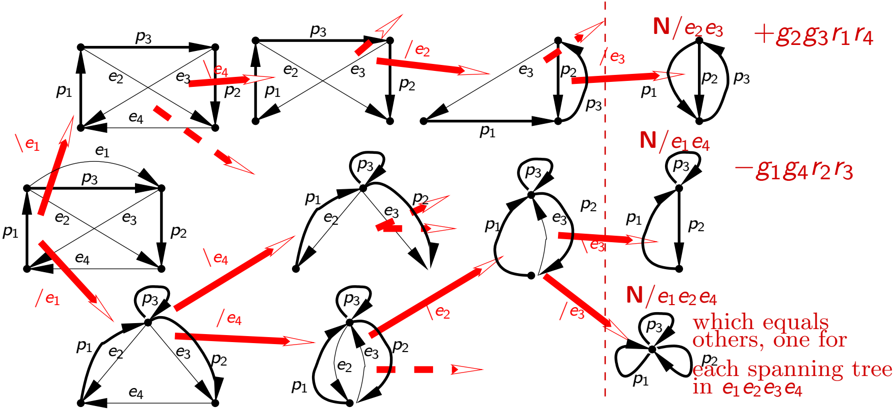
- If $\mathbf{F}_E(\mathbf{N} \quad \mathbf{N})[SZ] \neq 0$, then Ξ exists.
- If so, every minor of Ξ is, for some $Q_{\text{Num1}}, Q_{\text{Num2}}, Q_{\text{Den1}}, Q_{\text{Den2}} \subset P_\alpha P_\beta$

$$\frac{\sum_{F \subseteq E} \mathbf{N}[Q_{\text{Num1}} F] \mathbf{N}[Q_{\text{Num2}} F] g_F r_{\overline{F}}}{\sum_{F \subseteq E} \mathbf{N}[Q_{\text{Den1}} F] \mathbf{N}[Q_{\text{Den2}} F] g_F r_{\overline{F}}}$$

Remember, each (field valued) sum, being a component of $\mathbf{F}_E(\mathbf{N} \quad \mathbf{N})$, IS A TUTTE FUNCTION.

Ported Tutte Decomposition (incomplete)

The decomposition ends with minors $\mathbf{N}/F\overline{F}$.
We show component $\mathbf{L}_E(\mathbf{N}\ \mathbf{N})[p_{\alpha 1}p_{\beta 1}p_{\alpha 3}]$:



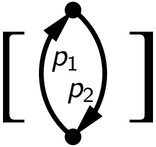
Conditions (what sets F are enumerated by one det. C_i)

The **conditions ...** are on the rank, nullity of F and, WHAT ORIENTED MINOR is $G/F \setminus (E \setminus F)$, the minor with ONLY PORT EDGES from contracting F and deleting the other resistor edges, leaving the ports.

The conditions for a given C_k *sometimes* make all the signs the same (eg: C_i and C_j in 1-port equivalent resistance $R = C_i/C_j$)

Othertimes, the oriented **P-minors** in the completed Tutte decomposition of C_k determine some $+$ and some - signs.

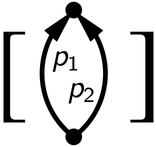
When $[G/F|P]$ is



the term is

$+g_F r_{E\setminus F}$

When $[G/F|P]$ is



the term is

$-g_F r_{E\setminus F}$

Known to EEs: Linear electrical networks with IDEAL AMPLIFIERS

$N_\alpha i(P, E) = 0$ expresses Kirchhoff's current law on currents i_e in the network edges (along edge direction) and currents i_p into vertices from external connections.

$N_\beta^\perp v(P, E) = 0$ expresses Kirchoff's voltage law: The voltage rise along a network edge $v_e = v_h - v_t$ is the difference of the head and tail vertex potentials. (Sometimes the vertex potentials are imposed by external connections.)

$N_\alpha = N_\beta$ in ordinary resistor networks.

Different Graphs for N_α and N_β

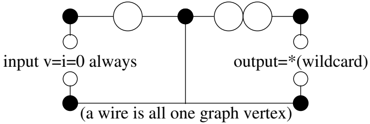
W. K. Chen models networks with ideal amplifiers by N_α by one graph on (P, E) called the **Current Graph** and another graph also on (P, E) called the **Voltage Graph**.

Voltage and Current graphs G_V, G_I

"Voltage graph" G_V (EEs Hasler and Neirynck 1986, not Gross, et. al.) $\mathbf{v} \in$ Coboudaries W/ SOME $v_e \equiv 0$

"Current graph" G_I represents KCL $\mathbf{i} \in$ Cycles WITH SOME FLOWS $\equiv 0$

- They are EQUAL GRAPHS for resistor networks.
- For networks with idealized amplifiers, they are not equal.



The output voltage and current are whatever makes the input voltage and current BOTH BE zero.

- (More) realistic amp. model = idealized amp. + resistors.

open

$G_v = G \backslash e$

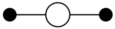
$G_I = G \backslash e$

short

$G_v = G / e$

$G_I = G / e$

nullator



$G_v = G / e$

$G_I = G \backslash e$

norator

$G_v = G \backslash e$

$G_I = G / e$

Chain Complexes View (Alg. Topology, Homological Alg.)

A graph is a k-dim simplicial complex X with $k = 1$.
In general, for us, the k-chains $C_k = Z[P \coprod E] = \{\sum_{x \in P \coprod E} c_e e\}$ are the free abelian group with basis $P \coprod E$.
The k-cochains $C^k = \mathrm{Hom}(C_k, \mathbb{R})$ is the $\mathbb{R}$-module of linear maps from C_k to a coefficient ring $\mathbb{R}$.
The k-complex $X = \coprod_{j=0}^{k} X_j$ (X_j is the set of j-simplices) determines, (or the chain complex might just be subspaces given with) **boundary maps** $\partial_j : C_j \to C_{j-1}$ for $j = 0, ..., k$ that satisfy $\partial_{j-1} \circ \partial_j = 0$ for each j.
The dual $\delta^j : C^{j-1} \to C^j$ is defined by $(\delta^j(u^*))(v) = u^*(\partial_j(v))$.

In the case $N_\alpha = N_\beta$, generalizing:

- $\mathbf{N}$ ($\wedge$ of the rows on N_α) represents the k-coboundary group $B^k = \mathrm{img}(\delta_k)$.
- The equation $N_\alpha \begin{pmatrix} I \\ G \end{pmatrix} (J_P \;\; X_E)^t = 0$ says $\begin{pmatrix} I \\ G \end{pmatrix} (J_P \;\; X_E) \in Z_1$, is a k-cycle. (Electrically, a flow of currents in edges.)
- $\mathbf{N}^\perp$ ($\wedge$ of the rows of $N^\perp$) represents the k-cycle group $Z_k = \ker(\partial_k)$.
- The equation $N^\perp \begin{pmatrix} I \\ R \end{pmatrix} (V_P \;\; X_E)^t = 0$ says $\begin{pmatrix} I \\ R \end{pmatrix} (V_P \;\; X_E) \in Z_1$, is a k-coboundary $\delta_k \psi$. (Electrically, $\delta_1 \psi$ maps each edge (1-simplex) to the difference of electrical potential assigned to vertices (a 1-cochain) $\delta_1(\psi)(v_0 v_1) = \psi(v_1) - \psi(v_0)$.

Electribraic Topology–Happy Birthday, have fun Tom.

The left edge is a port containing an electric source.
Red:1-coboundary Diffs of a potential ψ (0-cobdy). Coeffs v_e are ≥ 0 for the edge $e = u_0 u_1$ dirs indicated, so $v_e = \psi(u_1) - \psi(u_0)$.
Blue:1-cycle Current (charge flow), ≥ 0 with arrow. In resistor edge w/ conductance g_e, $c_e = g_e(-(\psi(u_1) - \psi(u_0)))$.
In the port, either the pot. diff. or the current is set by the source. Other coefficents are determined by Kirchhoff's and Ohm's laws.