Spectral
11/10/09

Fiedler's Thm

Generalized Laplacians

Throughout $G=(V,E)$ unweighted & undirected

Def $Q^{n \times n}$ is a generalized Laplacian

if:
1) Real symmetric
2) $Q_{ij} < 0$ if $(i,j) \in E$
3) $Q_{ij} = 0$ if $i \neq j$ & $(i,j) \notin E$
4) Q_{ii} no constraint

Note $\lambda(Q)$ are real say

$\lambda_1 \cdots \lambda_n$

$x_1 \cdots x_n$

When needed we can set $\lambda_2 = 0$

ie $(Q - \lambda_2 I)$

Lemma A G connected then $\lambda_1(Q)$ is simple and eigenvector X_1 can be picked $X_1 > 0$.

pf Pick c s.t. $(-Q + cI) \geq 0$ ie

Digonal $(Q - cI) \leq 0$

By Perron-Frobenius $\lambda_n(-Q + cI)$ is simple & can be picked positive.

Def $X : V \to \mathbb{R}$ is an valuation.

Positive support of $X = \{v \in V \mid X(v) > 0\} = \mathrm{Supp}_+(X)$.

Negative " $\quad$ " $< 0\} = \mathrm{Supp}_-(X)$.

<u>Def</u> <u>Positive nodal domain</u> $\equiv$

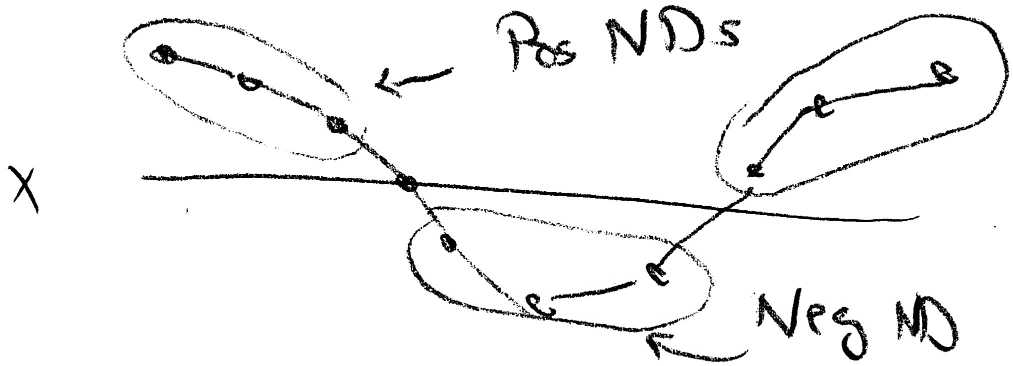
Connected component of induced subgraph on $\mathrm{Supp}_+(x)$

<u>Negative ND</u> $\equiv$

<u>Nodal Domain</u> $\equiv$ Positive or Neg ND.

Goal: Better understand ND.

<u>EG</u> Valuation x for P_n



<u>Def</u> Y is a ND of x.

$$(x_Y)_i = \begin{cases} |x_i| & \text{if } i \in Y \\ 0 & \text{o.w.} \end{cases}$$

<u>Lemma</u> $Qx = \lambda x \wedge$ Pos ND Y of x then
$(Q - \lambda I)\, x_Y \leq 0$ ie $Q x_Y \leq \lambda x_Y$

<u>pf</u>

Write $x = \begin{pmatrix} y \\ \bar{y} \\ z \end{pmatrix} \begin{array}{l} \leftarrow V(Y) \\ \leftarrow \text{other Pos NDs} \\ \leftarrow \text{Neg NDs \& zeros} \end{array}$

Write Q as

$$\left(\begin{array}{c|c|c} Q_Y & A_Y & B_Y \\ \hline A_Y^T & & \\ \hline B_Y^T & & \end{array}\right) \begin{pmatrix} y \\ \bar{y} \\ z \end{pmatrix} = \lambda \begin{pmatrix} y \\ \bar{y} \\ z \end{pmatrix}$$

<u>Note</u> $A_Y \equiv 0$ & $B_Y \leq 0$ & $z \leq 0$

<u>Thus</u> $Q_Y y + B_Y z = \lambda y$

Since $B_y z \geq 0 \Rightarrow Q_Y y \leq \lambda y$

$A_y^T = 0 \Rightarrow A_Y^T y = 0$

$B_Y^T \leq 0 \Rightarrow B_Y^T y \leq 0$

<u>Thus</u> $Q \begin{pmatrix} y \\ 0 \\ 0 \end{pmatrix} \leq \lambda \begin{pmatrix} y \\ 0 \\ 0 \end{pmatrix}$

Cor $Qx = \lambda x$ & $\mathcal{U} = \{ x_Y \mid Y \text{ Pos ND of } x \}$

$u \in \mathcal{U} \Rightarrow u^T (Q - \lambda I) u \leq 0$

<u>pf</u> $u \in \mathcal{U} \Rightarrow u = \sum_{Y \in PND} \alpha_Y x_Y$

<u>note</u> $Y = Y' \Rightarrow x_Y^T Q x_{Y'} = 0$ & $x_Y^T x_Y = 0$

$u^T (Q - \lambda I) u = \sum_{Y \in PND} \alpha_Y^2 x_Y^T (Q - \lambda I) x_Y \leq 0$

<u>Def</u> $\text{support}(x) = \{v \mid x(v) \neq 0\}$

<u>If</u> $Ax = \lambda x$ then x has <u>minimal support</u>
if $\forall y$ s.t. $Ay = \lambda y \Rightarrow \text{Support}(x) \subseteq \text{support}(y)$.

<u>Main Thm</u> Q gen Lap of G, G connected, $Qx = \lambda_2 x$, and x has minmal support then $\text{supp}_+(x)$ & $\text{supp}_-(x)$ induce connected subgraphs.

Pf by contradiction

Suppose $Qv = \lambda_2 v \wedge$ PND Y & Z of v.

Lemma A $\Rightarrow \exists x > 0$ st $Qx = \lambda_1 x$.

$v_Y^T v_Z = 0 \Rightarrow \dim \langle v_Y, v_Z \rangle = 2$

$\Rightarrow \exists u \in \langle v_Y, v_Z \rangle$ st $u^T x = 0$

But $u^T x = 0 \Rightarrow \frac{u^T Q u}{u^T u} \geq \lambda_2$ ie $u^T(Q - \lambda_2 I)u \geq 0$

By Cor $u^T(Q - \lambda_2 I)u \leq 0$

Thus $u^T(Q - \lambda_2 I)x = 0$

By Corrant-Fischer

$u^T x = 0$ & $\frac{u^T Q u}{u^T u} = \lambda_2 \Rightarrow Qu = \lambda_2 u$

$\text{Support}(u) = V(Y) \cup V(Z) \subsetneq \text{Support}(v)$

But v was minimal! contra!

Def Going from v to u we call the Fiedler Flip.

Note We can add Fiedler Flip to an iterative algorithm without increasing $\frac{v^T Q v}{v^T v}$.

Applications of ND thm.

Lemma G is a 3-connected embedded planar, $Qx = \lambda_2 x$ then no 3 vertices of a face are zero.

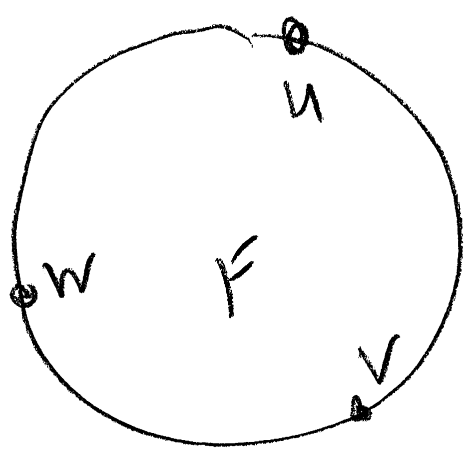
Pf by contradiction.

We give idea first:

Suppose 1) $x(u) = x(v) = x(w) = 0$

2) x has minimal support

3) $p \in Supp_+(x)$ & $q \in Supp_-(x)$

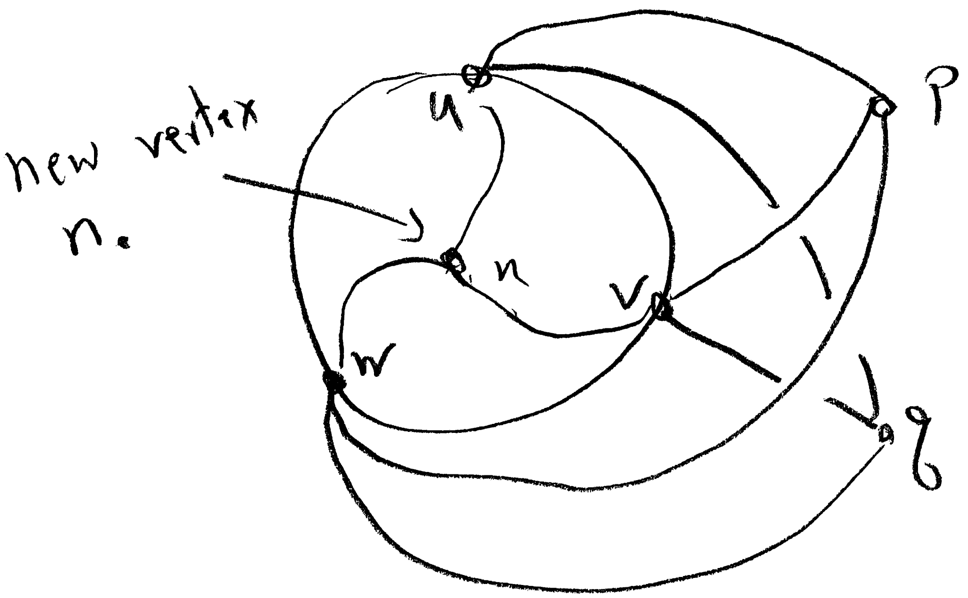


By Menger's Thm

$\exists$ 3 vertex disjoint paths from u, v, w to p

" " " q

If paths to p & to q are also disjoint then



This is $K_{3,3}$ contra!.

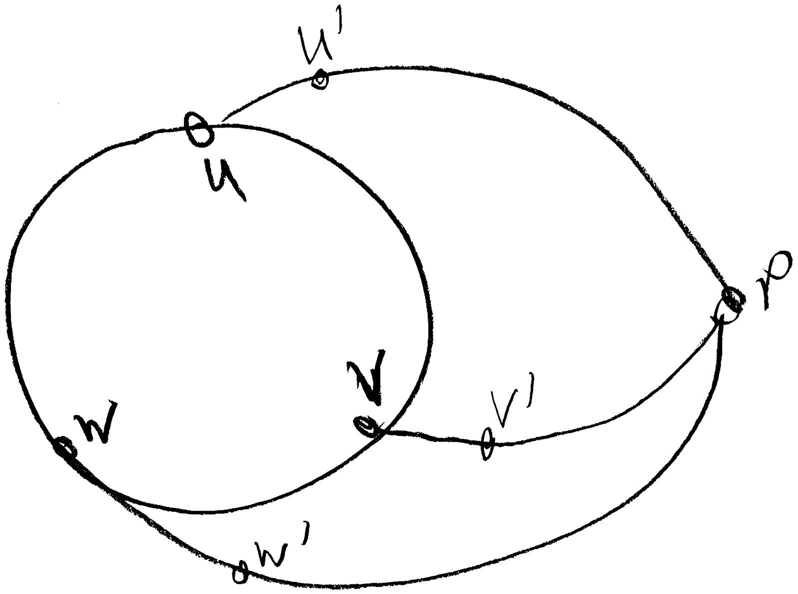
Full pf

Note if $x(v)=0$ & $\exists$ Neig$(v)=v'$ & $x(v')>0$

then $\exists$ Neig$(v)=v''$ s.t $x(v'')<0$

pf $Qx=\lambda x \Rightarrow x(v)$ convex comb of neigs.

consider vertex disj paths to p



Let u' be first $u' \in$ Path(u,p) st

$x(u')=0$ & $x(\text{Next}(u')) \neq 0$

P_u = path from u to u'. Sim define P_v, P_w.

Contract $Supp_+(x)$, $Supp_-(x)$, P_u, P_v, P_w

this gives $K_{3,2}$ contra!

<u>Cor</u> G 3-con & planar $\Rightarrow \lambda_2(Q)$ has multiplicity ≤ 3.

<u>pf</u> by contra!

Suppose 1) mult ≥ 4 with ind vectors $x_1\ x_2\ x_3\ x_4$.

2) Vertices u, v, w on face F.

<u>Claim</u> $\exists x \in \lambda_2(Q), x \neq 0$, zero on u, v, w.

$$\begin{array}{c|c|c|c|c|} & x_1 & x_2 & x_3 & x_4 \\ \hline u & a_1 & a_2 & & a_4 \\ \hline v & b_1 & & & \\ \hline w & c_1 & & & \\ \hline \end{array} \begin{pmatrix} \alpha_1 \\ \\ \\ \alpha_4 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$$

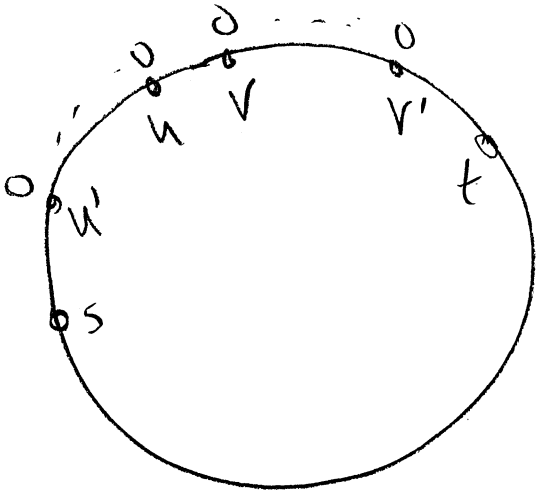
$\exists \alpha \neq 0$ contra!

Lemma G is 2-con embedded planar graph $\wedge$ $Qx = \lambda_2 x$ $\wedge$ x of minimal support if $(u,v) \in E$ of Face F s.t $x(u) = x(v) = 0$ then $x(F) \geq 0$ or $x(F) \leq 0$.

pf G 2-con $\Rightarrow$ F is a simple cycle

assume $(u,v) \in E \subseteq F$ & $x(u) = x(v) = 0$

add $\exists p, q \in F$ s.t $x(p) > 0$ & $x(q) < 0$

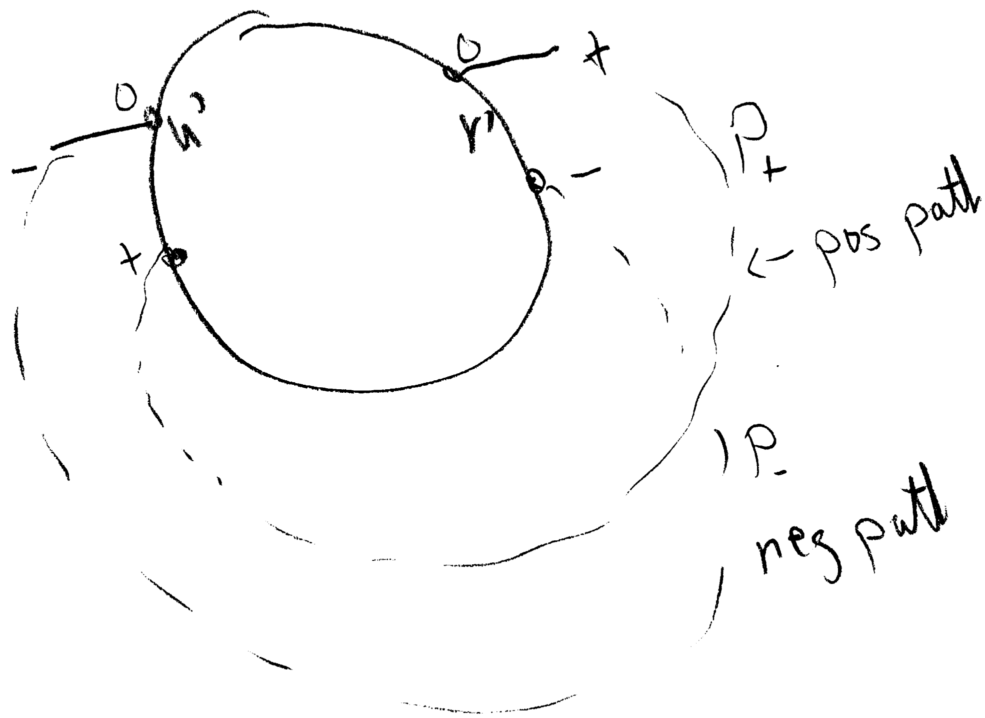


Interval $\langle u', v' \rangle$ is a maximal zero interval of x

u', v' have both pos & neg neigh.

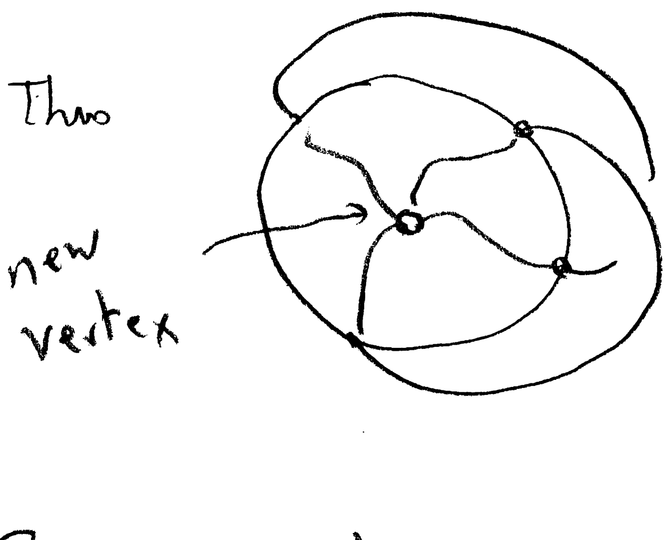
Case 1 $x(s) > 0$ $x(t) < 0$

Case 1



<u>Claim</u> $\exists$ subpaths of P_+, P_- disjoint from F that "interlace".

Thus

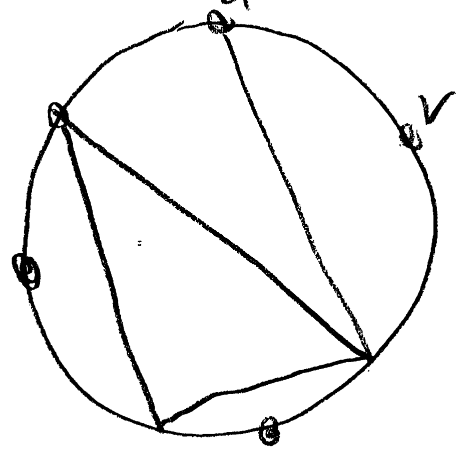


This is K_5 a contra!

Case 2 similiar.

Cor G is 2-conn & outerplanar then $\mathrm{mult}(\lambda_2(Q)) \leq 2$.

pf by contra.



Assuming mult ≥ 3 then $\exists x \in \lambda_2(Q)$

st $x(u) = x(v) = 0$

$\Rightarrow x \geq 0$ & $x^T x_1 = 0$ contra!