Connectivity

A separating set (or vertex cut) of a graph G is a set $S \subseteq V(G)$ such that $G - S$ has more than one component. For $G \neq K_n$, the connectivity of G is $\kappa(G) := min\{|S| : S \text{ is a vertex cut}\}$. By definition, $\kappa(K_n) := n - 1$. A graph G is k-connected if there is no vertex cut of size $k - 1$. (i.e. $\kappa(G) \geq k$)

Examples. $\kappa(K_{n,m}) = \min\{n, m\}$
$\kappa(Q_d) = d$

Extremal problem: What is the minimum number of edges in a k-connected graph?

Theorem. For every n, the minimum number of edges in a k-connected graph is $\lceil kn/2 \rceil$.

Proof:

$$\begin{aligned} \text{min} &\geq \lceil kn/2 \rceil, \text{ since } k \leq \kappa(G) \leq \delta(G) \\ \text{min} &\leq \lceil kn/2 \rceil; \text{ Example: Harary graphs } H_{k,n}. \end{aligned}$$

Edge-connectivity

A disconnecting set of a multigraph G is a set $F \subseteq E(G)$ of edges such that $G - F$ has more than one component. The edge-connectivity of G is

$$\kappa'(G) := \min\{|F| : F \text{ is a disconnecting set}\}.$$

A graph G is k-edge-connected if there is no disconnecting set of size $k-1$ (i.e. $\kappa'(G) \geq k$).
An edge cut is an edge-set of the form $[S, \bar{S}]$, where $\emptyset \neq S \neq V(G)$ and $\bar{S} = V(G) \setminus S$.

For $S, T \subseteq V(G)$, $[S, T] := \{xy \in E(G) : x \in S, y \in T\}$.

Implications.	edge cut	$\Rightarrow$	disconnecting set
	edge cut	$\not\Leftarrow$	disconnecting set
	edge cut	$\Leftarrow$	*minimal* disconnecting set

Theorem. (Whitney, 1932) If G is a simple graph, then $\kappa(G) \leq \kappa'(G) \leq \delta(G)$.

Homework. Example of a graph G with $\kappa(G) = k$, $\kappa'(G) = l$, $\delta(G) = m$, for any $0 < k \leq l \leq m$.

Theorem. G is 3-regular $\Rightarrow \kappa(G) = \kappa'(G)$.

Characterization of 2-connected graphs

Theorem. (Whitney,1932) Let G be a graph, $n(G) \geq 3$. Then G is 2-connected iff for every $u, v \in V(G)$ there exist two internally disjoint u, v-paths in G.

Theorem. Let G be a graph with $n(G) \geq 3$. Then the following four statements are equivalent.

- (i) G is 2-connected
- (ii) For all $x, y \in V(G)$, there are two internally disjoint x, y-path.
- (iii) For all $x, y \in V(G)$, there is a cycle through x and y.
- (iv) $\delta(G) \geq 1$, and every pair of edges of G lies on a common cycle.

Expansion Lemma. Let G' be a supergraph of a k-connected graph G obtained by adding one vertex to $V(G)$ with at least k neighbors.
Then G' is k-connected as well.

Menger's Theorem

Given $x, y \in V(G)$, a set $S \subseteq V(G) \setminus \{x, y\}$ is an x, y-separator (or an x, y-cut) if $G - S$ has no x, y-path.
A set $\mathcal{P}$ of paths is called pairwise internally disjoint (p.i.d.) if for any two path $P_1, P_2 \in \mathcal{P}$, P_1 and P_2 have no common internal vertices.
Define

$$\begin{aligned} \kappa(x, y) &:= \min\{|S| : S \text{ is an } x, y\text{-cut,}\} \text{ and} \\ \lambda(x, y) &:= \max\{|\mathcal{P}| : \mathcal{P} \text{ is a set of p.i.d. } x, y\text{-paths}\} \end{aligned}$$

Local Vertex-Menger Theorem (Menger, 1927) Let $x, y \in V(G)$, such that $xy \notin E(G)$. Then

$$\kappa(x, y) = \lambda(x, y).$$

Corollary (Global Vertex-Menger Theorem) A graph G is k-connected iff for any two vertices $x, y \in V(G)$ there exist k p.i.d. x, y-paths.

Proof: **Lemma.** For every $e \in E(G)$, $\kappa(G - e) \geq \kappa(G) - 1$.

Edge-Menger

Given $x, y \in V(G)$, a set $F \subseteq E(G)$ is an x, y-disconnecting set if $G - F$ has no x, y-path. Define

$$\kappa'(x,y) := \min\{|F| : F \text{ is an } x,y\text{-disconnecting set,}\}$$
$$\lambda'(x,y) := \max\{|\mathcal{P}| : \mathcal{P} \text{ is a set of p.e.d.}^* \ x,y\text{-paths}\}$$

* p.e.d. means pairwise edge-disjoint

Local Edge-Menger Theorem For all $x, y \in V(G)$,

$$\kappa'(x,y) = \lambda'(x,y).$$

Proof. Apply Menger's Theorem for the line graph of G', where $V(G') = V(G) \cup \{s, t\}$ and $E(G') = E(G) \cup \{sx, yt\}$.

The line graph $L(G)$ of a graph G is defined by
$V(L(G)) := E(G)$,
$E(L(G)) := \{ef : e \text{ and } f \text{ share an endpoint}\}$.

Corollary (Global Edge-Menger Theorem) Multigraph G is k-edge-connected iff there is a set of k p.e.d.x, y-paths for any two vertices x and y.