

CO 342

Graph Theory I

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1.

Connectivity

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1.1 Basic Graph Terminology

Graph

Def'n 1.1 A **graph** $G = (V, E)$ is an ordered pair such that

- (a) V is a set; and *vertex set*
- (b) E is a set of unordered pairs of elements of V . *edge set*

The elements of V are called the **vertices** of G and the elements of E are called the **edges** of G . Given $u, v \in V$, we denote uv to denote an edge **joining** u, v . Note that $uv = vu$ for every $u, v \in V$. For simplicity, we assume that

- (a) G does not have any **loop** (i.e. $vv \notin E$ for every $v \in V$);^a
- (b) G has at least one vertex; and
- (c) G is **finite** (i.e. V is a finite set).

^aNote that, since we defined E to be a set of unordered pairs of elements of V , if $e, f \in E$ join the same vertices, then $e = f$. In other words, we do not allow **multiple edges**.

$V(G), E(G)$

Notation 1.2 Let G be a graph. We write $V(G)$ to denote the vertex set and write $E(G)$ to denote the edge set of G .

Subgraph of a Graph

Def'n 1.3 Let G be a graph. We say H is a **subgraph** of G if $V(H) \subseteq V(G)$, $E(H) \subseteq E(G)$, and all edges in $E(H)$ have both endpoints in $V(H)$. In particular,

- (a) when $V(H) = V(G)$, we say H is a **spanning** subgraph; and
- (b) if there exists $S \subseteq V(G)$ such that $V(H) = S$ and that

$$E(H) = \{e \in E(G) : \exists v, u \in S [e = vu]\},$$

then we say H is the subgraph **induced** by S , denoted as $G[S]$.

Degree of a Vertex

Def'n 1.4 Let G be a graph. The **degree** of $v \in V(G)$, denoted as $d_G(v)$, is the number of edges incident to v . Moreover, we write $\delta(G)$ to denote

$$\delta(G) = \min \{d_G(v) : v \in V(G)\}$$

and write $\Delta(G)$ to denote

$$\Delta(G) = \max \{d_G(v) : v \in V(G)\}.$$

Connected Graph

Def'n 1.5 Let G be a graph. We say G is **connected** if for every $u, v \in V(G)$, there is a u, v -path in G . A **component** of G is a maximally connected subgraph of G .

Proposition 1.1

Let G be a graph. The following are equivalent.

- (a) G is connected.
- (b) There exists $v \in V(G)$ such that for every $u \in V(G)$, there exists a u, v -path in G .

Notation 1.6

$G - F, G - e, G - U, G - v$

Let G be a graph.

- (a) Given $F \subseteq E(G)$, we write $G - F$ to denote the graph such that $V(G - F) = V(G)$, $E(G - F) = E(G) \setminus F$.
- (b) In case $F = \{e\}$ for some $e \in E$, we simply write $G - e$ to denote $G - \{e\}$.
- (c) Similarly, given $U \subseteq V(G)$, we write $G - U$ to denote the graph such that $V(G - U) = V(G) \setminus U$ and that

$$E(G - U) = \{e \in E(G) : \exists u, v \in V(G) \setminus U [e = uv]\}.$$

In other words, we remove every vertex in U from G and every edge in G that is incident to at least one vertex in U .

- (d) In case $U = \{v\}$ for some $v \in V$, we simply write $G - v$ to denote $G - \{v\}$.

Def'n 1.7

Contraction of a Graph

Let G be a graph. For any $e \in E(G)$, the G **contract** e , denoted as G/e , is defined by *removing* e from G and *identifying* u, v as the same vertex.

1.2 Edge Connectivity

Def'n 1.8

k -edge-connected Graph

We say a graph G is **k -edge-connected** if $G - F$ is connected for every $F \subseteq E(G)$ such that $|F| < k$. The **edge connectivity** of G , denoted as $\kappa'(G)$, is the largest $k \in \mathbb{N}$ for which G is k -edge-connected.

Def'n 1.9

Cut-edge of a Graph

Let G be a graph. We say $e \in E(G)$ is a **cut-edge** if $G - \{e\}$ is disconnected.

(1.1)

Let G be a graph.

- (a) $\kappa'(G) = 1$ if and only if G has a cut-edge. Equivalently, G is 2-edge connected if and only if G is connected with no cut-edges.
- (b) If G is disconnected, then we define $\kappa'(G) = 0$ and say G is 0-edge-connected.
- (c) The **trivial graph** $(\{v\}, \emptyset)$ cannot be disconnected; we define its edge-connectivity to be 0.

Proposition 1.2

Let G be a graph. Then

$$\kappa'(G) \leq \delta(G).$$

Proof. If $\delta(G) = 0$, then there is an isolated vertex $v \in V(G)$, which means G is disconnected. So $\kappa'(G) = 0$, meaning $\delta(G) = 0 \leq 0 = \kappa'(G)$. Now assume $\delta(G) \geq 1$ and let $v \in V(G)$ be such that $d_G(v) = \delta(G)$. Let $F = \{e \in E(G) : \exists u \in V(G) [uv = e]\}$, the set of all edges incident with v . Then $G - F$ is disconnected, since v is not adjacent to any other vertices in G , which in turn exist since $\delta(G) \geq 1$. It follows that $\kappa'(G) \leq |F| = \delta(G)$. ■

Def'n 1.10

Cut Induced by a Subset

Let G be a graph and let $S \subseteq V(G)$. We define the **cut** induced by S , denoted as $\delta_G(S)$, to be the set of all edges with exactly one end in S :

$$\delta_G(S) = \{e \in E(G) : \exists v \in V(G) \setminus S, u \in S [e = vu]\}.$$

We say $\delta_G(S)$ is **nontrivial** if $S \neq \emptyset$ and $S \neq V(G)$.

Proposition 1.3

Let G be a graph. Then the following are equivalent.

- (a) G is connected.
- (b) Every nontrivial cut of G is nonempty.

(1.2)

Say we have a graph and a cut $C \subseteq E(G)$. Then it is easy to see that $G - C$ is disconnected when C is nontrivial. It follows that the size of any nontrivial cut is an upper bound on $\kappa'(G)$.

Proposition 1.4

Let G be a graph and let $F \subseteq E(G)$. If $G - F$ is disconnected, then F contains a nontrivial cut.

Proof. Suppose $G - F$ is disconnected and let H be a component of $G - F$. Since $G - F$ is disconnected, $V(H) \neq \emptyset$ and $V(H) \neq V(G)$. Consider $\delta_G(V(H))$. Since H is maximally connected in $G - F$, none of the edges in $\delta_G(V(H))$ can be in $G - F$. Hence, all edges in $\delta_G(V(H))$ must be in F . Hence F contains a nontrivial cut $\delta_G(V(H))$, as required. ■

Corollary 1.4.1

Let G be a graph. Then $\kappa'(G)$ is the size of a minimum nontrivial cut.

Def'n 1.11

Bond of a Graph

A **bond** is a minimal nonempty cut.

Proposition 1.5

Characterization of a Bond

Let $F = \delta_G(S)$ be a cut in a connected graph G , where $S \subseteq V(G)$. Then the following are equivalent.

- (a) F is a bond.
- (b) $G - F$ has exactly 2 components.

Proof.

- (\implies) Suppose $G - F$ has at least 3 components. Assume, without loss of generality, that (at least) 2 of the components are contained in $G[S]$ and let H be one of them. Then $\delta_G(V(H)) \subset F$, so F is not minimal and hence not a bond.
- Suppose $G - F$ has exactly 2 components and suppose further F is not a bond, for the sake of contradiction. Then there is a nonempty cut $\delta_G(S)$ that is a proper subset of F . Then the two components of G_F are linked by some edge in F . It follows that $G - \delta_G(S)$ is connected, contradicting the fact that $\delta_G(S)$ is a cut. ■

Proposition 1.6

Every cut is a disjoint union of bonds.

Def'n 1.12

Symmetric Difference of Two Sets

Let S, T be sets. Then the **symmetric difference** of S, T , denoted as $S \triangle T$, is defined as

$$S \triangle T = (S \cup T) \setminus (S \cap T).$$

Lemma 1.6.1

Let G be a graph and let $S, T \subseteq V(G)$. Then

$$\delta_G(S) \triangle \delta_G(T) = \delta_G(S \triangle T).$$

Proof of Proposition 1.6. We proceed inductively on the number of edges in F . If $|F| = 0$, then F is a disjoint union of no bonds, so we are done. Now assume that F is any nonempty cut (where the inductive hypothesis is that any cut with a smaller size than F is a disjoint union of bonds). We may assume F is not a bond. Then F contains a nonempty cut F_1 by the definition of a bond. Now define

$$F_2 = F \setminus F_1,$$

where we note that $F \setminus F_1 = (F \cup F_1) \setminus (F \cap F_1) = F \triangle F_1$. Hence by Lemma 1.6.1, F_2 is a cut. Since F_1, F_2 are nonempty, both F_1, F_2 have fewer edges than F . It follows that F_1, F_2 are disjoint union of bonds by the inductive hypothesis. Thus $F = F_1 \cup F_2$ is also a disjoint union of bonds, as required. ■

1.3 Vertex Connectivity

Def'n 1.13

Separating Set, Cut-vertex of a Graph

Let G be a graph.

- (a) If $S \subseteq V(G)$ is such that $G - S$ is disconnected, then we say S is a **separating set**.
- (b) If $v \in V(G)$ is such that $G - v$ has more components than G , then we say v is a **cut-vertex**.

Def'n 1.14

Connectivity of a GraphLet G be a graph.

- (a) We say G is **k -connected**, where $k \in \mathbb{N} \cup \{0\}$, if G has at least $k + 1$ vertices and does not have a separating set of size at most $k - 1$.
- (b) The **connectivity** of G , denoted as $\kappa(G)$, is the largest $k \in \mathbb{N} \cup \{0\}$ for which G is k -connected.

(1.3)

- (a) The complete graph K_n ($n \in \mathbb{N}$) has no separating sets. Hence $\kappa(K_n) = n - 1$. In particular, K_n is the smallest $(n - 1)$ -connected graph: any $(n - 1)$ -connected graph has at least n vertices.
- (b) Let G be a graph. If there exists a separating set of size $k \in \mathbb{K}$, then $\kappa(G) \leq k$.

Theorem 1.7

Expansion Lemma

Let G be a k -connected graph and let G' be obtained from G by adding a new vertex v and adding at least k edges joining v to at least k distinct vertices of G . Then G' is k -connected.

Proof. To show that G' is k -connected, we show that there is no separating set of size $k - 1$. To do so, let $X \subseteq V(G')$ have $k - 1$ vertices. We now have 2 cases.

- *Case 1. Suppose $v \in X$. Then $G' - X = G - (X \setminus \{v\})$. Since G is k -connected and $|X \setminus \{v\}| = k - 2$, so $G - (X \setminus \{v\})$ is connected. Hence $G' - X$ is connected, implying that X is not a separating set.*
- *Case 2. Suppose $v \notin X$. Then $X \subseteq V(G)$. Since $|X| = k - 1$ and G is k -connected, $G - X$ is connected. Moreover, v has at least k neighbors by definition, so at least one of them, say w , is not in X . Then given any $u \in V(G - X)$, note that there is a u, w -path in $G - X$ by the connectedness of $G - X$, so by the fact that w, v are neighbors in $G' - X$, there is a u, v -path in $G' - X$. Hence $G' - X$ is connected and X is not a separating set.*

Thus G' is k -connected, as required. ■

Theorem 1.8

Whitney's Theorem

Let G be a graph. Then

$$\kappa(G) \leq \kappa'(G) \leq \delta(G).$$

Proof. We showed the second inequality in Proposition 1.2. We now prove $\kappa(G) \leq \kappa'(G)$. Note that we have the following two special cases.

- *Case 1. Suppose G is complete, say $G = K_n$ for some $n \in \mathbb{N}$. Then $\kappa(G) = \kappa'(G) = n - 1$.*
- *Case 2. Suppose G is disconnected. Then $\kappa(G) = \kappa'(G) = 0$.*

Hence, we may assume G is connected and not complete. Let F be a minimum nontrivial cut in G , so that $|F| = \kappa'(G)$. Then F is a bond, since every minimum nontrivial cut is clearly minimal. So by Proposition 1.5, $G - F$ has exactly 2 components, say H_1, H_2 . We break into two cases.

- *Case 3. Suppose there exists a vertex $v \in V(G)$ that is not incident to any edge in F . Without loss of generality, say v is in H_1 . Let S be the set of all vertices in H_1 incident with some edge in F . Then $|S| \leq |F|$. Also, S is a separating set, since it separates v from all the vertices in H_2 . So*

$$\kappa(G) \leq |S| \leq |F| = \kappa'(G),$$

as required.

- *Case 4. Suppose all vertices are incident with some edge in F .* Since G is not complete, there exist two vertices u, v that are not adjacent. Without loss of generality, say $u \in H_1$. Let S be the set of all neighbors of u . Now observe that $v \notin S$, so S is a separating set as it separates u from v . We now count the size of S . To do so, we show that every vertex in S corresponds to a distinct edge in F .
 - *Case 4.1. Say $y \in H_1$.* Then y is incident to some edge in F , say e , (since we assumed that all vertices are incident with some edge in F), and clearly u is not incident to e , since both y, u are in H_1 .
 - *Case 4.2. Say $y \in H_2$.* Then $uy \in F$.

In other words, if $y \in H_1$, then y corresponds to an edge in F that is incident to y but not incident to u . If $y \in H_2$, then y corresponds to uy . And it is immediate from the definition that these correspondences are distinct.¹ It follows that $|S| \leq |F|$, which means

$$\kappa(G) \leq |S| \leq |F| = \kappa'(G).$$

This completes the proof. ■

1.4 Menger's Theorem

(1.4) So far we have looked at the connectivity of graphs via *destructive* methods: that is, we remove, or *destroy*, few edges or vertices and see what happens. We now change our perspective to *constructive* methods: finding disjoint paths between vertices. We first do this in a *local* point view (i.e. given two vertices, we ask: how well connected are they?). Later, we extend this to a *global* description, using paths.

(1.5) Let us reiterate what we said in (1.4). Suppose that x, y are two nonadjacent vertices of a graph G . There are two ways to measure connectivity between x, y .

- (a) How many vertices do we need to remove to disconnect x from y ? *destructive*
- (b) How many *internally disjoint* paths are there from x to y ? *constructive*

Note that for (a) we want the *minimum* number of such vertices, whereas for (b) we want the *maximum* number of such paths. In fact, we can ask the following question: between (a), (b), which one should be larger?

Answer-ish. Suppose there are k paths from x to y . In order to disconnect x from y , we have to remove at least one vertex from each path. In other words, (a) is at least (b). ◁

Surprisingly, *Menger's theorem* shows that this inequality always holds with equality. Let us first define notions that we need.

Def'n 1.15 X, Y-separating Set
 Let G be a graph and let $X, Y \subseteq V(G)$. We say $S \subseteq V(G) \setminus (X \cup Y)$ is an ***X, Y-separating set*** if there is no path from any vertex in X to any vertex in Y in $G - S$. In case $X = \{x\}, Y = \{y\}$, we say S is an ***x, y-separating set***.

¹That is, we just informally described an injection from S to F .

Def'n 1.16 **Internally Disjoint x, y -paths**
 Let G be a graph and let $x, y \in V(G)$. We say x, y -paths are **internally disjoint** (or **i.d.**), if no two of them share any vertices other than x, y .

Note that, from our previous observations, if S is an x, y -separating set and P is a set of internally disjoint x, y -paths, then $|S| \geq |P|$.

Theorem 1.9
 Menger's Theorem

Let x, y to nonadjacent distinct vertices of a graph G . Then the minimum size of an x, y -separating set is equal to the maximum size of a set of internally disjoint x, y -paths.

Notation 1.17 **G/X**
 Let G be a graph and let $X \subseteq V(G)$. We denote G/X to be the graph obtained from G by removing all edges in $G[X]$ and identifying all vertices in X into one new vertex.

(1.6)
 Wrong Approach to
 Menger's Theorem

Here is a *wrong*, but useful, approach to the Menger's theorem. We proceed inductively on the number of edges of the graph. Let S be a minimum x, y -separating set, and say $k = |S|$. Let X, Y be the components containing x, y in $G - S$, respectively. Then we *shrink* X by taking G/X , and get k i.d. x, y -paths by induction. Similarly, we *shrink* Y by taking G/Y , and get k i.d. x, y -paths by induction. Combining these paths results in k i.d. x, y -paths in G .

(1.7)
 Proof Outline of Menger's
 Theorem

Here is why (1.6) is wrong: the induction works only when $G/X, G/Y$ have *fewer* edges than G . But if $X = \{x\}$ or $Y = \{y\}$, this is not the case, and the induction fails. Hence, much of the work of the upcoming proof is done to ensure that X, Y has at least 2 vertices, a vertex besides x, y , respectively. Here is an outline.

Proof Outline. We begin by assuming that a minimum x, y -separating set, say S , has size k . We desire to build k i.d. x, y -paths by using induction on $|E(G)|$. We break our proof into three cases.

- *Case 1. Suppose every edge is incident with x, y .* This case is relatively easy.

After we are done with Case 1, we may assume that there are vertices $u, v \in V(G) \setminus \{x, y\}$ that are adjacent. The vertices u, v will be the extra vertices we need in X, Y . Let $e = uv$.

- *Case 2. Suppose a minimum x, y -separating set has size k in $G - e$.* Then by applying induction we obtain k i.d. x, y -paths.
- *Case 3. Suppose a minimum x, y -separating set S has size at most $k - 1$ in $G - e$.* This is arguably the hardest case. For Case 3, we first show that any minimum x, y -separating set indeed has size $k - 1$ in $G - e$. Afterwards, we show that $S \cup \{u\}$ is a minimum x, y -separating set of size k in G/Y , and since G/Y has fewer edges than G , by applying induction we obtain k i.d. x, y -paths. Similarly, we obtain k i.d. x, y -paths in G/X . Combining these paths gives us k i.d. x, y -paths in G . \triangleleft

Proof of Menger's Theorem. We prove by inducting on the number of edges on G . When there are no edges, a minimum x, y -separating set has size 0, and there are 0 x, y -paths. We now assume G has at least one edge, and that the theorem holds for any graph with less than $|E(G)|$ edges. Let k be the size of a minimum x, y -separating set, where the goal is to find k internally disjoint x, y -paths. We have few cases.

- *Case 1. Suppose every edge of G is incident with x or y .* Let S be the set of all vertices adjacent to both x, y . Then the only x, y -paths are those of length 2 going through S , and they are internally disjoint. So there are $|S|$ internally disjoint x, y -paths. But S is a x, y -separating set, so $|S| = k$, as required.

We now assume there exists some edge uv that is not incident to x nor y . Let $H = G - uv$ and let S be a minimum x, y -separating set in H .

- *Case 2. Suppose $|S| = k$.* Since H has fewer edges than G , by induction there exists a set of k internally disjoint x, y -paths in H . These paths are also in G since $H \subseteq G$, and the result follows.
- *Case 3. Suppose $|S| < k$.*

· *Claim 1. We claim that $S \cup \{u\}$ is an x, y -separating set in G .*

Proof. Note $G - (S \cup \{u\}) = H - (S \cup \{u\})$. Also, $S \cup \{u\}$ is an x, y -separating set in H , since H is an x, y -separating set in H . It follows that $S \cup \{u\}$ is an x, y -separating set in G . \triangleleft

But any x, y -separating set in G has size at least k , so $|S \cup \{u\}| \geq k$. Therefore, $|S| \geq k - 1$, which means $|S| = k - 1$. Now write

$$S = \{v_i\}_{i=1}^{k-1}$$

for convenience. Let X, Y be the vertices of the components of $H - S$ containing x, y , respectively. Since $|S| = k - 1 < k$, $G - S$ does not separate x, y . So there is an x, y -path in $G - S$. This path does not exist in $H - S$, so uv must be on this path. In fact, e must join a vertex in X with a vertex in Y . Without loss of generality, say $u \in X, v \in Y$. This means X, Y has at least two vertices, $X \supseteq \{x, u\}, Y \supseteq \{y, v\}$. We now consider G/Y , and let y^* be the new vertex.

· *Claim 2. Any x, y^* -separating set in G/Y is an x, y separating set in G .*

Proof. Let T be any x, y^* -separating set in G/Y . Then any x, y -path in G that does not use T corresponds to an x, y^* -path in G/Y that does not use T , which does not exist. Therefore, T is an x, y -separating set in G . \triangleleft

Claim 2 in particular means any x, y^* -separating set in G/Y has size at least k . But $S \cup \{u\}$ is an x, y^* -separating set in G/Y , with size k . Therefore, a minimum x, y^* -separating set in G/Y has size exactly k . Since Y has at least 2 vertices, $G[Y]$ has at least one edge, so G/Y has fewer edges than G , so by induction there is a set of k internally disjoint x, y^* -paths in G/Y . In particular, each path must use a distinct vertex in $S \cup \{u\}$. Now for each $i \in \{1, \dots, k - 1\}$, let P_i be the parts of the paths from x to v_i , and let P_k be the part of the path from x to u . We can make the same argument for G/X , and find k paths: Q_1, \dots, Q_{k-1} from v_1, \dots, v_{k-1} to y , Q_k from v to y . Then,

$$\{P_i + Q_i\}_{i=1}^{k-1} \cup \{P_k + uv + Q_k\}$$

is a set of k internally disjoint x, y -paths, as required. \blacksquare

(1.8)

There are many variations and corollaries of Menger's theorem.

Corollary 1.9.1

Characterization of k -connectedness

Let G be a graph. The following are equivalent.

- (a) G is k -connected.
- (b) There exist k internally disjoint x, y -paths for any distinct $x, y \in V(G)$.

Proof.

- (a) \implies (b): Let $x, y \in V(G)$. We break into 2 cases.

· *Case 1. Suppose x, y are not adjacent.* Since G is k -connected, any x, y -separating set has size at least k , so by Menger's theorem, there exist at least k internally disjoint x, y -paths in G .

- *Case 2. Suppose x, y are adjacent.* Then $G - xy$ is $(k - 1)$ -connected. So any x, y -separating set in $G - xy$ has size at least $k - 1$. By Menger's theorem, there exist at least $k - 1$ internally disjoint x, y -paths in $G - xy$. Together with the path $(\{x, y\}, \{xy\})$, we have at least k internally disjoint x, y -paths in G .

- (a) \iff (b): Let X be any set of $k - 1$ vertices and let $x, y \in V(G) \setminus X$. By assumption, there exist k internally disjoint x, y -paths in G . So removing $k - 1$ vertices leaves at least one such path: there exists an x, y -path in $G - X$ for any vertices x, y in $G - X$. Hence $G - X$ is connected, which means G is k -connected. ■

Fan

Def'n 1.18

Let G be a graph. Let $v \in V(G)$ and let $X \subseteq V(G) \setminus \{v\}$. A **k -fan** from v to X is a set of k internally disjoint paths that start with v and end with distinct vertices in X , and no internal vertices are in X .

Corollary 1.9.2

Fan Lemma

Let G be a k -connected graph. Let $v \in V(G)$ and let $X \subseteq V(G) \setminus \{v\}$ where $|X| \geq k$. Then there exists a k -fan from v to X .

Proof. Let H be the graph obtained from G from adding a vertex x^* and edges xx^* for all $x \in X$. Then observe that H is k -connected by the Expansion lemma (Theorem 1.7), so by Corollary 1.9.1, there are k internally disjoint v, x^* -paths, say P_1, \dots, P_k . Now for each $i \in \{1, \dots, k\}$, write P_i as

$$P_i = (\{v, u_1, \dots, u_{l_i}, x^*\}, \{vu_1, u_1u_2, \dots, u_{l_i-1}u_{l_i}, u_{l_i}x^*\})$$

and let $j_i \in \{1, \dots, l_i\}$ be the smallest index such that $u_{j_i} \in X$. It follows that $\{Q_i\}_{i=1}^k$ by

$$Q_i = (\{v, u_1, \dots, u_{j_i}\}, \{vu_1, u_1u_2, \dots, u_{j_i-1}u_{j_i}\})$$

for all $i \in \{1, \dots, k\}$ is a k -fan from v to X . ■

Corollary 1.9.3

Let G be a k -connected graph with $k \geq 2$ and let $X \subseteq V(G)$ be such that $|X| = k$. Then there exists a cycle in G with all vertices in X .

Proof. We proceed inductively on k . Suppose $k = 2$ and let $X = \{u, v\}$. Then by Corollary 1.9.1, there exist 2 internally disjoint u, v -paths in G ; they form a cycle containing u, v . Now assume $k \geq 3$ and let $X \subseteq V(G)$ with $|X| = k$. Then G is also $(k - 1)$ -connected. Choose $v \in X$. Then $X \setminus \{v\}$ has $k - 1$ vertices, so there is a cycle in G that has all vertices in $X \setminus \{v\}$. If C also has v , then we are done. So assume C does not have v . The $k - 1$ vertices of $X \setminus \{v\}$ are on the cycle C , say they are in order v_1, \dots, v_{k-1} . These $k - 1$ vertices partitions C into $k - 1$ internally disjoint paths, or segments. We now have 2 cases.

- *Case 1. Suppose C has at least k vertices.* Since G is k -connected and $|V(G)| \geq k$, there exists a k -fan from v to $V(C)$ by the Fan lemma. Since there are $k - 1$ segment on C , by the pigeonhole principle, there is a segment S on C that contains the endpoints of 2 paths, say P_1, P_2 , in the fan. Say P_1, P_2 end with vertices $w_1, w_2 \in V(C)$, respectively. Let P_3 be the w_1, w_2 -path contained in S . Then no internal vertex of P_3 is in X , so $C - P_3 + P_1 + P_2$ is a cycle that contains X .
- *Case 2. Suppose C has exactly $k - 1$ vertices.* Then there is a $(k - 1)$ -fan from v to $V(C)$, ending in all vertices in C . By removing any edge from C and adding 2 paths ending at the endpoints of the edge, we obtain a cycle containing X . ■

Disjoint X, Y -paths

Def'n 1.19

Let G be a graph and let $X, Y \subseteq V(G)$. We say paths in G are **disjoint X, Y -paths** if

- (a) each join a vertex in X with a vertex in Y ;
- (b) no other vertices are in X nor Y ; and
- (c) no two paths share any vertex, including the endpoints.

Note that we *allow* X, Y to have a nonempty intersection in Def'n 1.15 and 1.18, and an X, Y -separating set could include vertices in X or Y . In fact, X and Y are X, Y -separating sets.

Theorem 1.10

Menger's Theorem, Set Version

Let G be a graph and let $X, Y \subseteq V(G)$. Then the minimum size of an X, Y -separating set is equal to the maximum size of a set of disjoint X, Y -paths.

Proof. First observe that any size of X, Y -separating set must be at least the size of any set of disjoint X, Y -paths, since we need to remove at least one vertex from each path. It remains to show that there exist an X, Y -separating set and a set of disjoint X, Y -paths of the same size. To do so, we shall utilize Menger's theorem. Let H be the graph obtained from G by adding 2 new vertices, say x^*, y^* , and adding edges x^*x, y^*y for all $x \in X, y \in Y$. Since x^*, y^* are not adjacent, by Menger's theorem, any minimum x^*, y^* -separating set S has the same size as a maximum set of internally disjoint x, y -paths \mathcal{P} .

- *Claim 1. S is an X, Y -separating set in G .*

Proof. Suppose S is not an X, Y -separating set, for the sake of contradiction. Then there exists an X, Y -path Q from $x \in X$ to $y \in Y$ in $G - S$. Then $(V(Q) \cup \{x^*, y^*\}, E(Q) \cup \{x^*x, y^*y\})$ is an x^*, y^* -path in $H - S$, contradicting the fact that S is an x^*, y^* -separating set. ◁

We now obtain a set of disjoint X, Y -paths \mathcal{P}' from \mathcal{P} as follows. Say a path

$$(\{x^*, v_1, \dots, v_l, y^*\}, \{x^*v_1, v_1v_2, \dots, v_{l-1}v_l, v_ly^*\}) \in \mathcal{P}$$

is given. Let $i \in \{1, \dots, l\}$ be the largest index such that $v_i \in X$, and let $j \in \{1, \dots, l\}$ be the smallest index at least i such that $v_j \in Y$. We put the path $(\{v_i, \dots, v_j\}, \{v_iv_{i+1}, \dots, v_{j-1}v_j\})$ in \mathcal{P}' . We see that each path in \mathcal{P}' joins a vertex in X with a vertex in Y with no other vertices in X or Y , and paths in \mathcal{P}' do not share any vertices since \mathcal{P} is internally disjoint. Then $|S| = |\mathcal{P}| = |\mathcal{P}'|$, we have a set of disjoint X, Y -paths \mathcal{P}' of the same size as an X, Y -separating set S . ■

Edge-disjoint x, y -paths

Def'n 1.20

Let G be a graph and let $x, y \in V(G)$. We say x, y -paths are **edge-disjoint** if no 2 paths share an edge.

Theorem 1.11

Menger's Theorem, Edge Version

Let x, y be distinct vertices of a graph G . Then the minimum size of a cut that disconnects x from y is equal to the maximum size of a set of edge-disjoint x, y -paths.

Line Graph of a Graph

Def'n 1.21

Let G be a graph. Then the **line graph** of G , denoted as $L(G)$, is the graph whose vertex set is $\{v_e : e \in E(G)\}$ and $v_e v_f$ is an edge of $L(G)$ if and only if e, f have a common endpoint in G .

Corollary 1.11.1

Characterization of
 k -edge-connectedness

Let G be a graph. The following are equivalent.

- (a) G is k -edge-connected.
- (b) There exist k edge-disjoint x, y -paths for any distinct $x, y \in V(G)$.

1.5 2-connected Graphs

Proposition 1.12

Cycle Characterizations of
2-connectedness

Let G be a graph with at least 3 vertices. The following are equivalent.

- (a) G is 2-connected.
- (b) For any distinct $u, v \in V(G)$, there is a cycle C such that $u, v \in V(C)$.
- (c) $\delta(G) \geq 1$ and for any distinct $e, f \in E(G)$, there is a cycle C such that $e, f \in E(C)$.

Proof.

- (b) \implies (a) This follows immediately from Corollary 1.9.1.
- (a) \implies (c) Assume G is 2-connected. Since G is connected with at least 3 vertices, no isolated vertex exists, so $\delta(G) \geq 1$. Moreover, let $e, f \in E(G)$ be distinct and let $u, v, x, y \in V(G)$ be such that $e = uv, f = xy$. Let $A = \{u, v\}, B = \{x, y\}$. Since G is 2-connected, any A, B -separating set has size at least 2. Hence by the set version of Menger's theorem (Theorem 1.10), there exist 2 disjoint A, B -paths, P_1, P_2 . In particular, both endpoints of e, f are on distinct paths. So

$$C = P_1 + f + P_2 + e$$

is a cycle which has e, f .

- (c) \implies (b) Let $u, v \in V(G)$ be distinct. Since $\delta(G) \geq 1$, both u, v are incident to at least one edge.
 - *Claim 1.* There exist distinct edges e, f that are incident to u, v , respectively.

Proof. For the sake of contradiction, suppose $e \in E(G)$ is the only edge incident to u, v . Then $e = uv$. But this means

$$H = (\{u, v\}, \{uv\})$$

is a component of G , since no edge other than $e = uv$ is incident to u, v . Since G has at least 3 vertices, there is $w \in V(G) \setminus \{u, v\}$. But then there is $f \in E(G)$ that is incident to w , and $f \neq e$. Since H is a component, it follows that there is no cycle of G that has e, f , contradicting (c). \triangleleft

By Claim 1, choose distinct e, f that are incident to u, v , respectively. Then by (c), there exists a cycle C which has e, f , which means C also has u, v . ■

Def'n 1.22

Ear Decomposition of a Graph

Let F be a subgraph of G .

- (a) An **ear** of F in G is a nontrivial path in G where only the two endpoints of the path are in F .
- (b) An **ear decomposition** of G is a sequence of graphs $(G_0)_{i=0}^k$ where

- (i) G_0 is a cycle in G ; *starting cycle*
- (ii) for each $r \in \{0, \dots, k-1\}$,
- $$G_{i+1} = G_i + P_i$$
- where P_i is an ear of G_i ; and *intermediate cycles*
- (iii) $G_k = G$.

Proposition 1.13

Characterization of 2-connectedness
by Ear Decompositions

Let G be a graph. The following are equivalent.

- (a) G is 2-connected.
- (b) G has an ear decomposition.

Proof.

- (\implies) Let G be 2-connected and let G_0 be any cycle in G . For $i \in \mathbb{N} \cup \{0\}$, we inductively construct G_{i+1} from G_i as follows.

- (a) If $G_i = G$, then we are done.
- (b) Otherwise, there exists an edge $e \in E(G) \setminus E(G_i)$, say $e = uv$ for some $u, v \in V(G)$. Then by the set version of Menger's theorem, there exist 2 disjoint $\{u, v\}$, G_i -path in G , say Q_1, Q_2 . Then observe that

$$P_i = Q_1 + uv + Q_2$$

is an ear of G_i . We then set $G_{i+1} = G_i + P_i$.

Note that the above process terminates since we add at least one edge of G each time. At termination, say after k step, $(G_i)_{i=1}^k$ is an ear decomposition of G .

- (\impliedby) Suppose $(G_i)_{i=1}^k$ is an ear decomposition of G . We proceed inductively to prove each G_i is 2-connected, thereby proving that G is also 2-connected. Since G_0 is a cycle, G_0 is 2-connected. Now suppose that G_i is 2-connected, where $i \in \mathbb{N} \cup \{0\}$ and let P_i be an ear of G_i such that

$$G_{i+1} = G_i + P_i.$$

We claim that every distinct vertices x, y in G_{i+1} are in a cycle, so that we can use Proposition 1.12. Suppose that the two endpoints of P_i are u, v and let $x, y \in V(G_{i+1})$. We have 3 cases.

- *Case 1.* Suppose $x, y \in V(G_i)$. Then since G_i is 2-connected, there is a cycle C in G_i , hence in G_{i+1} , which has x, y .
- *Case 2.* Suppose $x, y \in V(P_i)$. Since G_i is connected, there exists a u, v -path Q in G_i . It follows that $P_i + Q$ is a cycle which has x, y .
- *Case 3.* Suppose exactly one of x, y is in G_i . Without loss of generality, say $x \in V(G_i), y \in V(P_i)$. Since G_i is 2-connected, there exist 2-fan from x to $\{u, v\}$ by the fan lemma. Then 2-fan combined with P_i is a cycle which has x, y .

Hence every 2 distinct vertices in G_{i+1} are in a cycle, and by Proposition 1.12 G_{i+1} is 2-connected. Thus G_k is 2-connected, as required. ■

Corollary 1.13.1

Let G be a graph.

- (a) If G is 2-connected, then any cycle in G can be the starting cycle in the ear decomposition.*
- (b) If G admits an ear decomposition, then each intermediate graph in the ear decomposition is 2-connected.*

Proposition 1.14

Let G be a graph. If G admits an ear decomposition $(G_i)_{i=0}^k$, then $k = |E(G)| - |V(G)|$.