# Graph Theory

#### **Chapter 10. Planar Graphs** 10.1. Plane and Planar Graphs—Proofs of Theorems



# Table of contents





#### **Theorem 10.2.** $K_5$ is nonplanar.

**Proof.** ASSUME  $G = K_5$  is planar. Let  $\tilde{G}$  be a planar embedding of  $K_5$ , with points  $v_1, v_2, v_3, v_4, v_5$ . Since  $K_5$  is complete, any two points of  $\tilde{G}$  are joined by a line.

**Theorem 10.2.**  $K_5$  is nonplanar.

**Proof.** ASSUME  $G = K_5$  is planar. Let  $\tilde{G}$  be a planar embedding of  $K_5$ , with points  $v_1, v_2, v_3, v_4, v_5$ . Since  $K_5$  is complete, any two points of  $\tilde{G}$  are joined by a line. The cycle  $C = v_1v_2v_3v_1$  is a simple closed curve in  $\mathbb{R}^2$ , and the point  $v_4$  must lie either in int(C) or in ext(C). Without loss of generality we can suppose  $v_4 \in int(C)$  (or else we can permute the roles of  $v_1, v_2, v_3, v_4$  and get a different cycle C and a different interior point).

**Theorem 10.2.**  $K_5$  is nonplanar.

**Proof.** ASSUME  $G = K_5$  is planar. Let  $\tilde{G}$  be a planar embedding of  $K_5$ , with points  $v_1, v_2, v_3, v_4, v_5$ . Since  $K_5$  is complete, any two points of  $\tilde{G}$  are joined by a line. The cycle  $C = v_1 v_2 v_3 v_1$  is a simple closed curve in  $\mathbb{R}^2$ , and the point  $v_4$  must lie either in int(C) or in ext(C). Without loss of generality we can suppose  $v_4 \in int(C)$  (or else we can permute the roles of  $v_1, v_2, v_3, v_4$  and get a different cycle C and a different interior point). Then the edges  $v_1 v_4, v_2 v_4, v_3 v_4$  all lie entirely in int(C) (apart from their end points  $v_1, v_2, v_3$ ):

**Theorem 10.2.**  $K_5$  is nonplanar.

**Proof.** ASSUME  $G = K_5$  is planar. Let  $\tilde{G}$  be a planar embedding of  $K_5$ , with points  $v_1, v_2, v_3, v_4, v_5$ . Since  $K_5$  is complete, any two points of  $\tilde{G}$  are joined by a line. The cycle  $C = v_1 v_2 v_3 v_1$  is a simple closed curve in  $\mathbb{R}^2$ , and the point  $v_4$  must lie either in  $\operatorname{int}(C)$  or in  $\operatorname{ext}(C)$ . Without loss of generality we can suppose  $v_4 \in \operatorname{int}(C)$  (or else we can permute the roles of  $v_1, v_2, v_3, v_4$  and get a different cycle C and a different interior point). Then the edges  $v_1 v_4, v_2 v_4, v_3 v_4$  all lie entirely in  $\operatorname{int}(C)$  (apart from their end points  $v_1, v_2, v_3$ ):



**Theorem 10.2.**  $K_5$  is nonplanar.

**Proof.** ASSUME  $G = K_5$  is planar. Let  $\tilde{G}$  be a planar embedding of  $K_5$ , with points  $v_1, v_2, v_3, v_4, v_5$ . Since  $K_5$  is complete, any two points of  $\tilde{G}$  are joined by a line. The cycle  $C = v_1 v_2 v_3 v_1$  is a simple closed curve in  $\mathbb{R}^2$ , and the point  $v_4$  must lie either in  $\operatorname{int}(C)$  or in  $\operatorname{ext}(C)$ . Without loss of generality we can suppose  $v_4 \in \operatorname{int}(C)$  (or else we can permute the roles of  $v_1, v_2, v_3, v_4$  and get a different cycle C and a different interior point). Then the edges  $v_1 v_4, v_2 v_4, v_3 v_4$  all lie entirely in  $\operatorname{int}(C)$  (apart from their end points  $v_1, v_2, v_3$ ):



# Theorem 10.2 (continued)

Theorem 10.2. K<sub>5</sub> is nonplanar.

**Proof (continued).** Consider the cycles  $C_1 = v_2v_3v_4v_2$ ,  $C_2 = v_3v_1v_4v_3$ , and  $C_3 = v_1v_2v_4v_1$ . We have  $v_i \in ext(C_i)$  for i = 1, 2, 3 (as seen in Figure 10.3 above). Now  $v_iv_5 \in E(\tilde{G})$  for i = 1, 2, 3, so by the Jordan Curve Theorem we have  $v_5 \in ext(C_i)$  for i = 1, 2, 3 (for example, if  $v_5 \in int(C_1)$ then the line joining  $v_5$  and  $v_1 \in ext(C_1)$  must intersect cycle  $C_1$ , contradicting the planarity of  $K_5$ ). So  $v_5 \in ext(C)$  as well.

### Theorem 10.2 (continued)

**Theorem 10.2.** K<sub>5</sub> is nonplanar.

**Proof (continued).** Consider the cycles  $C_1 = v_2v_3v_4v_2$ ,  $C_2 = v_3v_1v_4v_3$ , and  $C_3 = v_1v_2v_4v_1$ . We have  $v_i \in ext(C_i)$  for i = 1, 2, 3 (as seen in Figure 10.3 above). Now  $v_iv_5 \in E(\tilde{G})$  for i = 1, 2, 3, so by the Jordan Curve Theorem we have  $v_5 \in ext(C_i)$  for i = 1, 2, 3 (for example, if  $v_5 \in int(C_1)$ then the line joining  $v_5$  and  $v_1 \in ext(C_1)$  must intersect cycle  $C_1$ , contradicting the planarity of  $K_5$ ). So  $v_5 \in ext(C)$  as well. But then the line joining  $v_4$  and  $v_5$  crosses C by the Jordan Curve Theorem, CONTRADICTING the planarity of  $K_5$ . Hence the assumption that  $K_5$  is planar is false and therefore  $K_5$  is nonplanar, as claimed.

### Theorem 10.2 (continued)

**Theorem 10.2.** K<sub>5</sub> is nonplanar.

**Proof (continued).** Consider the cycles  $C_1 = v_2v_3v_4v_2$ ,  $C_2 = v_3v_1v_4v_3$ , and  $C_3 = v_1v_2v_4v_1$ . We have  $v_i \in ext(C_i)$  for i = 1, 2, 3 (as seen in Figure 10.3 above). Now  $v_iv_5 \in E(\tilde{G})$  for i = 1, 2, 3, so by the Jordan Curve Theorem we have  $v_5 \in ext(C_i)$  for i = 1, 2, 3 (for example, if  $v_5 \in int(C_1)$ then the line joining  $v_5$  and  $v_1 \in ext(C_1)$  must intersect cycle  $C_1$ , contradicting the planarity of  $K_5$ ). So  $v_5 \in ext(C)$  as well. But then the line joining  $v_4$  and  $v_5$  crosses C by the Jordan Curve Theorem, CONTRADICTING the planarity of  $K_5$ . Hence the assumption that  $K_5$  is planar is false and therefore  $K_5$  is nonplanar, as claimed.