SMALLEST REGULAR GRAPHS OF GIVEN DEGREE AND DIAMETER

MARTIN KNOR

Slovak University of Technology in Bratislava
Faculty of Civil Engineering, Department of Mathematics
Radlinského 11, 813 68 Bratislava
E-mail: knor@math.sk

Abstract

In this note we present a sharp lower bound on the number of vertices in a regular graph of given degree and diameter.

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1. Introduction

The degree/diameter problem consists in determination of the largest order $N(d, k)$ of a graph with (maximum) degree $d$ and diameter $k$. An upper bound for $N(d, k)$ is the Moore bound $M(d, k) = 1 + d + d(d - 1) + \cdots + d(d - 1)^{k-1}$ and graphs achieving this bound are called Moore graphs. As shown in [1, 3, 5], Moore graphs exist only when $d = 2$ or $k = 1$ or when $k = 2$ and the degree is either 3 or 7 or possibly 57. For all other pairs $(d, k)$ we have $N(d, k) \leq M(d, k) - 2$, see [2, 4]. Recently, there are plenty of papers dealing with the degree/diameter problem, some of them constructing “large” graphs of given degree and diameter, which increases the lower bound for $N(d, k)$ for special pairs $(d, k)$, other decreasing $N(d, k)$ for special classes of graphs. For a nice survey see [7].

In this note we consider the inverse of degree/diameter problem. Since usually the degree/diameter problem is formulated for regular graphs (although some authors require only that $d$ is the maximum degree), we ask what is the minimum
order \(n(d, k)\) of a regular graph of degree \(d\) and diameter \(k\). In this note we answer this question completely.

We start with some notation. Let \(G\) be a graph, \(G = (V(G), E(G))\). For two of its vertices, say \(x\) and \(y\), by \(\text{dist}_G(x, y)\) we denote their distance in \(G\). By \(N_i(x)\) we denote the set of vertices that are at distance \(i\) from \(x\). As usual, \(N_1(x)\) is often abbreviated to \(N(x)\). The longest distance in \(G\) is the diameter \(\text{diam}(G)\).

The complete graph on \(n\) vertices is denoted by \(K_n\) and the discrete graph on \(n\) vertices (the complement of \(K_n\)) is denoted by \(D_n\). If \(G\) is a graph, then by \(G^{(−1)} \) (and \(G^{(−2)}\)) we denote a graph obtained from \(G\) by removing all the edges of one 1-factor (one 2-factor).

If \(G\) and \(H\) are graphs, then \(G + H\) denotes the join of \(G\) and \(H\), that is, a graph obtained from the disjoint union of \(G\) and \(H\) by adding all edges \(xy\), where \(x \in V(G)\) and \(y \in V(H)\). The sequential join of graphs \(G_1, G_2, \ldots, G_r\) is denoted by \(G_1 + G_2 + \cdots + G_r\) and is defined by

\[
G_1 + G_2 + \cdots + G_r = (G_1 + G_2) \cup (G_2 + G_3) \cup \cdots \cup (G_{r−1} + G_r).
\]

Thus, one can obtain \(G_1 + G_2 + \cdots + G_r\) from the disjoint union \(G_1 \cup G_2 \cup \cdots \cup G_r\) by adding all edges \(xy\) where \(x \in V(G_i)\) and \(y \in V(G_{i+1})\) for \(i = 1, 2, \ldots, r−1\).

To simplify the expressions, instead of

\[
\underbrace{\cdots + G + G + \cdots + G}_{k \text{ times}} + \cdots
\]

we write

\[
\cdots + (G)^k + \cdots.
\]

Finally, denote by \(G \div H\) a graph obtained from the disjoint union of \(G\) and \(H\) by adding all edges of one 1-factor, every edge of which joins a vertex of \(G\) with a vertex of \(H\). Obviously, \(G \div H\) is defined only if \(|V(G)| = |V(H)|\).

Analogously as in the case of join, by \(G_1 \div G_2 \div \cdots \div G_r\) we denote the graph \((G_1 \div G_2) \cup (G_2 \div G_3) \cup \cdots \cup (G_{r−1} \div G_r)\). We can form also more complicated expressions using both + and ÷. In such a way, \(K_1 + D_2 \div D_2 \div K_2\) is a cycle of length 7; see Figure 1.

![Figure 1. The graph \(K_1 + D_2 \div D_2 \div K_2\).](image)
2. Results

For small diameters we have the following statement.

**Proposition 1.** Let $d \geq 2$. We have

(i) $n(d, 1) = d + 1$;

(ii) if $d$ is even, then $n(d, 2) = d + 2$;

(iii) if $d$ is odd, then $n(d, 2) = d + 3$;

(iv) $n(d, 3) = 2d + 2$.

**Proof.** The case $k = 1$ is obvious since $K_{d+1}$ is the unique graph of diameter 1 and degree $d$.

Let $k = 2$. Let $G$ be a $d$-regular graph of diameter 2, and let $x, y \in V(G)$ such that dist$_G(x, y) = 2$. Then $\{x\} \cup N(x) = N_0(x) \cup N_1(x)$, which gives $|N_0(x)| + |N_1(x)| = d + 1$. Since $y \in N_2(x)$, we have $|V(G)| = |N_0(x)| + |N_1(x)| + |N_2(x)| \geq d + 2$, which gives $n(d, 2) \geq d + 2$. However, if $d$ is odd then $|V(G)|$ cannot be odd and so $n(d, 2) \geq d + 3$ in this case. If $d$ is even then $K_{d+2}^{(-1)}$ is a $d$-regular graph of diameter 2 on $d + 2$ vertices, which shows $n(d, 2) \leq d + 2$; while if $d$ is odd then $K_{d+3}^{(-1)}$ is a $d$-regular graph of diameter 2 on $d + 3$ vertices, which shows $n(d, 2) \leq d + 3$.

Finally, let $k = 3$. Analogously as above, let $G$ be a $d$-regular graph of diameter 3, and let $x, y \in V(G)$ such that dist$_G(x, y) = 3$. Then $\{x\} \cup N(x) = N_0(x) \cup N_1(x)$, which gives $|N_0(x)| + |N_1(x)| = d + 1$, and $\{y\} \cup N(y) \subseteq N_2(x) \cup N_3(x)$, which gives $|N_2(x)| + |N_3(x)| \geq d + 1$. Thus, $|V(G)| = |N_0(x)| + |N_1(x)| + |N_2(x)| + |N_3(x)| \geq 2d + 2$, and so $n(d, 3) \geq 2d + 2$. On the other hand, denote by $K_n$ a complete bipartite graph on $2n$ vertices in which the two partite sets have $n$ vertices each. Then $K_{d+1, d+1}^{(-1)}$ is a $d$-regular graph of diameter 3 on $2d + 2$ vertices, which shows $n(d, 3) \leq 2d + 2$.

Now we turn our attention to larger diameters. Since there are only two 2-regular graphs of diameter $k$, namely the cycle on $2k$ vertices and the cycle on $2k + 1$ vertices, we have the following trivial observation.

**Proposition 2.** If $k \geq 4$, then $n(2, k) = 2k$.

For larger degrees we have a slightly different bound.

**Theorem 3.** Let $k = 3j + t$, where $k \geq 4$ and $0 \leq t \leq 2$, and let $d \geq 3$. Then $n(d, k) = (d+1)(j+1) + t + \delta$, where $\delta = 1$ if either $d$ is odd and $t = 1$ or $d$ is even and $t = 2$. Otherwise $\delta = 0$. 

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Proof. First we prove a lower bound for $n(d, k)$. Let $G$ be a regular graph of degree $d$ and diameter $k$ and let $x, y \in V(G)$ such that $\text{dist}_G(x, y) = k$. Denote $n_i = |N_i(x)|$. Since $x \in N_0(x)$, we have $\{x\} \cup N(x) \subseteq N_0(x) \cup N_1(x)$. Thus, $n_0 + n_1 \geq d + 1$. Analogously $n_{k-1} + n_k \geq d + 1$ since $y \in N_k(x)$. Further, for every $i$, $1 \leq i \leq j-1$, we have $n_{3i-1} + n_{3i} + n_{3i+1} \geq d + 1$ since for $z_i \in N_{3i}(x)$ it holds $\{z_i\} \cup N(z_i) \subseteq N_{3i-1}(x) \cup N_{3i}(x) \cup N_{3i+1}(x)$. Finally, if $t \geq 1$ then $n_{k-1-t} \geq 1$ where $1 \leq t \leq k$. Summing up all these inequalities we get

$$|V(G)| = \sum_{i=0}^{k} n_i \geq (d + 1)(j + t).$$

If $t = 2$ then we use $n_{k-3} \geq 1$ and $n_{k-2} \geq 1$. But if $d$ is even then $G$ cannot have a bridge, and so $n_{k-3} + n_{k-2} \geq 3$. Thus, we get $|V(G)| = \sum_{i=0}^{k} n_i \geq (d + 1)(j + 1) + t + 1$ in this case.

Similarly, if $t = 1$ and $d$ is odd then $(d + 1)(j + 1) + t$ is an odd number. But a regular graph of odd degree cannot have an odd number of vertices, and so $|V(G)| = \sum_{i=0}^{k} n_i \geq (d + 1)(j + 1) + t + 1$ also in this case.

To prove the upper bound we construct extremal graphs, that is, regular graphs of degree $d$ and diameter $k$ on $n(d, k)$ vertices. First we define an extremal graph $G$ for odd $d$. The case $k = 4$ is treated separately. If $d = 3$ then one extremal graph $G$ is on Figure 2. For $d \geq 5$ we set $G = K_2 + K_{d-1}^{(2)} + D_2 \div D_2 + K_{d-1}$.

![Figure 2. An extremal graph for $d = 3$ and $k = 4$.](image)

Recall that $k = 3j + t$. To cover the remaining diameters, that is, 5, 6, 7, \ldots, in the next we assume $j \geq 1$ if $t = 2$, and $j \geq 2$ if $t = 0$ or $t = 1$:

\[ G = K_2 + K_{d-1}^{(2)} + (K_1 + K_1 + K_{d-1})_{j-1} + K_1 + K_1 + K_{d-1}^{(2)} + K_2, \text{ if } t = 2; \]
\[ G = K_2 + K_{d-1}^{(2)} + (K_1 + K_1 + K_{d-1})_{j-2} + K_1 + K_1 + K_{d-1}^{(2)} + K_2, \text{ if } t = 0; \]
\[ G = K_2 + K_{d-1}^{(2)} + (K_1 + K_1 + K_{d-1})_{j-2} + K_1 + K_1 + K_{d-1}^{(2)} + D_2 \div D_2 + K_{d-1}, \text{ if } t = 1. \]

Now we define an extremal graph $G$ for even $d$. To cover all possible diameters, that is, 4, 5, 6, \ldots, in the next we assume $j \geq 1$ if $t = 1$ or $t = 2$, and $j \geq 2$ if $t = 0$:

\[ G = K_3 + K_{d-2}^{(2)} + (K_1 + K_2 + K_{d-2})_{j-1} + K_1 + D_2 + K_{d-1}, \text{ if } t = 1; \]
\[ G = K_3 + K_{d-2}^{(2)} + (K_1 + K_2 + K_{d-2})_{j-1} + K_1 + K_2 + K_{d-2}^{(2)} + K_3, \text{ if } t = 2; \]
G = K_3 + K_{d-2}^{(-1)} + (K_1 + K_2 + K_{d-2})j-2 + K_1 + K_2 + K_{d-2} \div K_{d-2}^{(-1)} + K_3, if t = 0.

Observe that in all these graphs, whenever we removed a 1-factor out of K_q, then the number of vertices q was even. Obviously, in each case G has diameter k and it is a matter of routine to check that G is a regular graph of degree d. (For example, a vertex in the last copy of K_{d-2}^{(-1)} in the last graph is joined to 1 vertex of K_{d-2}, d-4 vertices of K_{d-2}^{(-1)} and to 3 vertices of K_3, so its degree is 1 + d - 4 + 3 = d.) Also, in each of these cases the number of vertices of G attains the bound of the theorem. To verify this statement it suffices to check the number of vertices for the smallest admissible values of j since in each case in the brackets we have exactly d + 1 vertices.

By Proposition 2, if d = 2 then n(d, k) = dk. However, for higher degrees we get n(d, k) \sim \frac{1}{3}dk. Denote by n_{VT}(d, k) the minimum number of vertices in a vertex-transitive d-regular graph with diameter k. As shown in [6], for k \geq 4 and “large” d we have n_{VT}(d, k) \sim \frac{1}{2}dk, and so n_{VT}(d, k) = 2n(d, k) in this case. On the other hand, since the extremal graphs constructed in the proof of Proposition 1 are vertex-transitive, we have n_{VT}(d, k) = n(d, k) when k \leq 3.

References


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