SIAM J. DISC. MATH.
Vol. 2, No. 1, pp. 68-72, February 1989

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ON THE SIZE OF SYSTEMS OF SETS EVERY t OF WHICH HAVE AN SDR, WITH AN APPLICATION TO THE WORST-CASE RATIO OF HEURISTICS FOR PACKING PROBLEMS*

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Abstract. Let $E_1, \cdots, E_m$ be subsets of a set V of size n, such that each element of V is in at most k of the E_i and such that each collection of t sets from $E_1, \cdots, E_m$ has a system of distinct representatives (SDR). It is shown that $m/n \leqq (k(k-1)^r - k)/(2(k-1)^r - k)$ if $t = 2r - 1$, and $m/n \leqq (k(k-1)^r - 2)/(2(k-1)^r - 2)$ if $t = 2r$. Moreover it is shown that these upper bounds are the best possible. From these results the "worst-case ratio" of certain heuristics for the problem of finding a maximum collection of pairwise disjoint sets among a given collection of sets of size k is derived.

Key words. packing, system of distinct representatives, worst-case ratio, heuristics

AMS(MOS) subject classifications. 05C65, 05A05, 90C27

1. Introduction. We prove the following theorem, where m, n, k, and t are positive integers, with $k \geqq 3$.

THEOREM 1. *Let $E_1, \cdots, E_m$ be subsets of the set V of size n, such that we have the following*:

(1) (i) *Each element of V is contained in at most k of the sets $E_1, \cdots, E_m$*;
(ii) *Any collection of at most t sets among $E_1, \cdots, E_m$ has a system of distinct representatives.*

Then, we have the following:

$$(2)\quad \text{(i)}\ \frac{m}{n} \leqq \frac{k(k-1)^r - k}{2(k-1)^r - k} \quad \text{if } t = 2r-1;$$
$$\text{(ii)}\ \frac{m}{n} \leqq \frac{k(k-1)^r - 2}{2(k-1)^r - 2} \quad \text{if } t = 2r.$$

Note that by the König–Hall Theorem, condition (1)(ii) can be replaced by the following:

(3) For any $s \leqq t$, any s of the sets among $E_1, \cdots, E_m$ cover at least s elements of V.

We give a proof of Theorem 1 in § 2. We also show that the bounds given in (2) are best possible in the following sense.

THEOREM 2. *For any fixed k, t (with $k \geqq 3$), there exist m, n and $E_1, \cdots, E_m \subseteq V$ (with $|V| = n$) satisfying* (1) *and having equality in the appropriate line of* (2).

The proof of Theorem 2 is based on a construction using regular graphs of large girth (see § 3).

Finally, in § 4 we apply these results to derive the worst-case ratio of certain heuristic algorithms for the problem of finding a largest family of pairwise disjoint sets among a given family of sets of size k (this problem is NP-complete for any $k \geqq 3$).

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* Received by the editors April 1, 1988; accepted for publication July 13, 1988. Part of this research was performed while the authors were visiting the Rutgers Center for Operations Research, Rutgers University, New Brunswick, New Jersey 08903.

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2. Proof of Theorem 1. To show Theorem 1, we first give a lemma. Let $E_1, \cdots, E_m$ be a collection of finite nonempty sets, which we order so that $|E_1|, \cdots, |E_h| \geqq 2$ and $|E_{h+1}| = \cdots = |E_m| = 1$, for some $h \leqq m$. We define a new collection as follows. Let

$$W := E_{h+1} \cup \cdots \cup E_m. \tag{4}$$

Let for each $i = 1, \cdots, h$, X_i be a set of size $|E_i| - 2$, disjoint from $E_1 \cup \cdots \cup E_m$ and so that if $i \neq j$ then $X_i \cap X_j = \varnothing$. Let $X_1 \cup \cdots \cup X_h =: \{y_1, \cdots, y_q\}$. Then the *derived* collection of sets is formed by the following sets:

$$(E_1 \backslash W) \cup X_1, \cdots, (E_h \backslash W) \cup X_h, \{y_1\}, \cdots, \{y_q\}. \tag{5}$$

Furthermore, we define a collection $E_1, \cdots, E_m$ to have the t-SDR-*property* if any t sets among $E_1, \cdots, E_m$ have a system of distinct representatives.

LEMMA. *For $t \geqq 3$, if $E_1, \cdots, E_m$ has the t-SDR-property, then the derived collection (5) has the $(t-2)$-SDR-property.*

Proof. Suppose (5) does not have the $(t-2)$-SDR-property. Then there exists a collection Π of p sets among (5) covering at most $p - 1$ elements, for some $p \leqq t - 2$. Assume we have chosen p minimal. This immediately implies the following:

(6) (i) $|\cup \Pi| = p - 1$;
(ii) Each element in $\cup \Pi$ is covered by at least two sets in Π.

From (6)(ii) we directly have for any $i = 1, \cdots, h$ and $x \in X_i$:

$$\{x\} \in \Pi \Leftrightarrow (E_i \backslash W) \cup X_i \in \Pi. \tag{7}$$

Without loss of generality, all sets $(E_1 \backslash W) \cup X_1, \cdots, (E_h \backslash W) \cup X_h$ belong to Π (as we can delete all sets E_j from $E_1, \cdots, E_h$ for which $(E_j \backslash W) \cup X_j \notin \Pi$), and without loss of generality, $(E_1 \cup \cdots \cup E_h) \cap W = E_{h+1} \cup \cdots \cup E_m$.

Note the following:

$$q = |X_1 \cup \cdots \cup X_h| = \sum_{i=1}^{h} (|E_i| - 2), \qquad p = h + q, \tag{8}$$
$$\left| \bigcup_{i=1}^{h} (E_i \backslash W) \right| = |\cup \Pi| - q = (p-1) - q = h - 1.$$

So,

$$\left| \bigcup_{i=1}^{m} E_i \right| = \left| \bigcup_{i=1}^{h} (E_i \cap W) \right| + \left| \bigcup_{i=1}^{h} (E_i \backslash W) \right| = (m-h) + (h-1) = m - 1. \tag{9}$$

Moreover, by (6)(ii), $\sum_{i=1}^{h} |E_i \backslash W| \geqq 2 \cdot |\bigcup_{i=1}^{h} (E_i \backslash W)|$, and hence

$$\begin{aligned} m &= h + \left| \bigcup_{i=1}^{h} (E_i \cap W) \right| \leqq h + \sum_{i=1}^{h} |E_i \cap W| = h + \sum_{i=1}^{h} |E_i| - \sum_{i=1}^{h} |E_i \backslash W| \\ &\leqq h + \sum_{i=1}^{h} |E_i| - 2 \cdot \left| \bigcup_{i=1}^{h} (E_i \backslash W) \right| = h + 2h + \sum_{i=1}^{h} (|E_i| - 2) - 2(h-1) \\ &= h + 2h + q - 2(h-1) = h + q + 2 = p + 2 \leqq t. \end{aligned} \tag{10}$$

Inequalities (9) and (10) contradict the fact that $E_1, \cdots, E_m$ has the t-SDR-property. □

Proof of Theorem 1. We prove Theorem 1 by induction on t.

Case 1. $t = 1$. Then we have that each of $E_1, \cdots, E_m$ is nonempty, and hence $m \leqq \sum_{i=1}^{m} |E_i| \leqq kn$, by (1)(i).

Case 2. $t = 2$. Then we have that each of $E_1, \cdots, E_m$ is nonempty, and that no two of the singletons among $E_1, \cdots, E_m$ are the same. Without loss of generality, let $E_{h+1}, \cdots, E_m$ be the singletons among $E_1, \cdots, E_m$. Then $m - h \leqq n$, and

$$(11) \qquad m+h=2h+(m-h) \leqq \sum_{i=1}^{h} |E_i| + \sum_{i=h+1}^{m} |E_i| = \sum_{i=1}^{m} |E_i| \leqq kn$$

(by (1)(i)). Hence $2m = (m - h) + (m + h) \leqq (k + 1)n$, and (2) follows.

Case 3. $t \geqq 3$. Then consider the derived collection $E'_1, \cdots, E'_{m'}$ on $V' := \bigcup_{i=1}^{m'} E'_i$ as in (5). Note that $m' = h + q$ and $n' := |V'| = n - |W| + q$. Denote the right-hand side term in (2) by $\varphi(k, t)$.

As by the lemma above, $E'_1, \cdots, E'_{m'}$ has the $(t-2)$-SDR-property, and as trivially each element of V' is in at most k of the sets $E'_1, \cdots, E'_{m'}$ we have by induction that $m' \leqq \varphi(k, t-2)n'$. That is,

$$(12) \qquad h+q \leqq \varphi(k,t-2)(n-|W|+q).$$

Writing the terms in different order, we have

$$(13) \qquad \varphi(k,t-2)|W|+h-(\varphi(k,t-2)-1)q \leqq \varphi(k,t-2)n.$$

Moreover, as $E_1, \cdots, E_m$ cover any element at most k times:

$$(14) \qquad |W|+2h+q=|W|+2h+\sum_{i=1}^{h} (|E_i|-2) = |W| + \sum_{i=1}^{h} |E_i| = \sum_{i=1}^{m} |E_i| \leqq kn.$$

Hence,

$$(15) \qquad \begin{aligned} m &= h+|W| \\ &= \frac{1}{2\varphi(k,t-2)-1}(\varphi(k,t-2)|W|+h-(\varphi(k,t-2)-1)q) \\ &\quad + \frac{\varphi(k,t-2)-1}{2\varphi(k,t-2)-1}(|W|+2h+q) \\ &\leqq \frac{1}{2\varphi(k,t-2)-1}\varphi(k,t-2)n + \frac{\varphi(k,t-2)-1}{2\varphi(k,t-2)-1}kn \\ &= \frac{(k+1)\varphi(k,t-2)-k}{2\varphi(k,t-2)-1}n = \varphi(k,t)n. \end{aligned}$$

The last equality follows directly by substituting the corresponding right-hand side of (2). $\square$

3. Proof of Theorem 2. To prove Theorem 2 we use a result of Erdös and Sachs [1]:

(16) For every k and γ there exists a k-regular graph of girth γ.

As a consequence of (16) we have the following:

(17) For every k, s, and γ there exists a bipartite graph of girth at least γ, with color classes U and W, say, such that each vertex in U has degree k, and each vertex in W has degree s.

(To see that (17) follows from (16), let H be a $2ks$-regular graph of girth γ. Consider any Eulerian orientation of the edges of H (i.e., one for which all indegrees and outdegrees equal ks). Split each vertex v into $k + s$ vertices $v_1, \cdots, v_k, w_1, \cdots, w_s$ and divide the arcs entering v equally over $v_1, \cdots, v_k$ and divide the arcs leaving v equally over $w_1, \cdots, w_s$. Forgetting the orientations, we obtain a bipartite graph with the required properties.)

Now choose k, t. Let $r := \lfloor \frac{1}{2}t \rfloor$. Consider the tree T, with vertices $1, 2, \cdots, 1 + (k-1) + (k-1)^2 + \cdots + (k-1)^{r-1}$, so that for $i < j$, vertices i and j are connected by an edge, if and only if $(k-1)i \leqq j \leqq (k-1)i + (k-2)$. So each vertex has degree k, except for vertex 1, which has degree $k - 1$, and for the vertices $1 + (k-1) + \cdots + (k-1)^{r-2} + 1, \cdots, 1 + (k-1) + \cdots + (k-1)^{r-1}$, which have degree one.

First let t be even. Let G be a $(k-1)^r$-regular graph of girth $t + 1$ (cf. (16)). Let G have p vertices: $v_1, \cdots, v_p$. Consider p copies $T_1, \cdots, T_p$ of T (denoting the copy of vertex i in T_j by i_j). For each $j = 1, \cdots, p$, partition the set of $(k-1)^r$ edges of G incident to v_j (arbitrarily) into $(k-1)^{r-1}$ classes of size $k - 1$, and connect them to the $(k-1)^{r-1}$ vertices i_j in T_j of degree one. So the final graph $H = (W, F)$ has all degrees equal to k, except for the vertices $1_1, \cdots, 1_p$, which have degree $k - 1$. Let $E_1, \cdots, E_m$ be the collection $F \cup \{\{1_1\}, \cdots, \{1_p\}\}$. This collection clearly satisfies (1)(i), and direct counting shows equality in (2)(ii). To see that the collection satisfies (1)(ii), let $E_1, \cdots, E_s$ form a subcollection with $|E_1 \cup \cdots \cup E_s| < s$ and s as small as possible. Suppose $s \leqq t$. As $E_1, \cdots, E_s$ must form a connected hypergraph, it contains at most one singleton (since any path between 1_i and 1_j in H contains at least $t - 1$ edges). So assume $E_2, \cdots, E_s$ are edges of H. Then they do not contain any circuit (as each T_i is a tree and as G has girth $t + 1 > s$). So $|E_2 \cup \cdots \cup E_s| \geqq s$, a contradiction.

Next let t be odd. Let G be a bipartite graph, of girth at least $t + 1$, so that in one color class U each vertex has degree $(k-1)^r$ and in the other color class W each vertex has degree k. Let $U =: \{u_1, \cdots, u_p\}$. Consider again p copies $T_1, \cdots, T_p$ of T, as above. For $j = 1, \cdots, p$ partition the set of $(k-1)^r$ edges of G incident to u_j (arbitrarily) into $(k-1)^{r-1}$ classes of size $k - 1$, and connect them to the $(k-1)^{r-1}$ vertices i_j in T_j of degree one. Again, the final graph $H = (W, F)$ has all degrees equal to k, except for the vertices $1_1, \cdots, 1_p$ that have degree $k - 1$. Let $E_1, \cdots, E_m$ be the collection $F \cup \{\{1_1\}, \cdots, \{1_p\}\}$. Similarly, as above, we show that this collection satisfies (1) and has equality in (2)(i).

4. Application to the worst-case ratio of heuristics. The problem of finding a largest collection of pairwise disjoint sets among a given collection $X_1, \cdots, X_q$ of k-sets is NP-complete, for any $k \geqq 3$. Call any collection of pairwise disjoint sets a *packing*.

For any fixed s, we can apply the following heuristic algorithm H_s. Start with the empty packing. If we have found a packing $Y_1, \cdots, Y_n$ from $X_1, \cdots, X_q$, we could select $p \leqq s$ sets among $Y_1, \cdots, Y_n$, and replace them by $p + 1$ sets from $X_1, \cdots, X_q$, so that the arising collection is a packing with $n + 1$ sets. Repeating this, the algorithm terminates with a collection $Y_1, \cdots, Y_n$ so that

(18) For each $p \leqq s$, the union of any $p + 1$ pairwise disjoint sets among $X_1, \cdots, X_q$ intersects at least $p + 1$ sets among $Y_1, \cdots, Y_n$.

This defines heuristic H_s, which is, for any fixed s, a polynomial-time algorithm—however it clearly need not lead to a largest packing. We might ask how far the packing found with H_s is from the largest packing.

To this end, consider a largest packing $Z_1, \cdots, Z_m$ from $X_1, \cdots, X_q$. We claim that m/n satisfies the bounds given in (2), taking $t := s + 1$, and that these bounds are best possible. That is, the "worst-case ratio" of the heuristic is given in (2).

Indeed, let

(19) $V:=\{Y_1, \cdots, Y_n\}$ and $E_i:=\{Y_j \mid Y_j \cap Z_i \neq 0\}$ for $i=1, \cdots, m$.

Then by (18), $E_1, \cdots, E_m$ satisfy (1), and hence we obtain the bounds given in (2).

In turn, it is not difficult to see that for any collection $E_1, \cdots, E_m$ of sets of size at most k, containing any point at most k times, we can assume they are of form (19) for certain packings $Y_1, \cdots, Y_n$ and $Z_1, \cdots, Z_m$ of k-sets. Thus starting with $E_1, \cdots, E_m$ as described in § 3 above, making these $Y_1, \cdots, Y_n, Z_1, \cdots, Z_m$, and taking $\{X_1, \cdots, X_q\} := \{Y_1, \cdots, Y_n, Z_1, \cdots, Z_m\}$, we obtain a system of sets attaining the worst-case ratio. (That is because we may assume that H_s selects the sets $Y_1, \cdots, Y_n$ in the first n iterations.)

Note that we may assume even that the sets $Y_1, \cdots, Y_n, Z_1, \cdots, Z_m$ form the collection of all cliques of size k in a graph. Hence, we cannot obtain a better worst-case ratio by restricting the collections of sets to collections of k-cliques.

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