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In this paper, we introduce two special classes of digraphs. A limited outdegree grid (LOG) directed graph is a digraph derived from an $n \times n$ grid graph by removing some edges and replacing some edges with arcs such that no vertex has outdegree greater than 1. A greatest increase grid (GIG) directed graph is a LOG digraph whose vertices can be labeled with distinct labels such that each arc represents the direction of greatest increase in the underlying grid graph. We enumerate both GIG and LOG digraphs for the 3×3 case.

1. Introduction

Some search algorithms, such as hill climbing [Russell and Norvig 2010], use local information to seek a global maximum of a function of two variables, $f(x, y)$. At every point in an $n \times n$ lattice, the algorithm determines the direction of greatest increase in f, and moves to the adjacent lattice point in that direction. We can think of this algorithm as discrete gradient ascent. In what follows, we make the simplifying assumptions that the function values are the integers $1, 2, \ldots, n^2$ and directions are restricted to horizontal and vertical on a square grid. For example, consider the function values 1 through 9 on the 3×3 lattice shown in Figure 1(a). The direction of greatest increase from each lattice point is shown in Figure 1(b) as an arrow to the appropriate adjacent point. Note that there are no arrows originating at local maxima on this lattice.

MSC2010: 05C20, 05C30.

Keywords: graph, directed graph, greatest increase grid graph, limited outdegree grid graph, discrete gradient ascent, enumeration.

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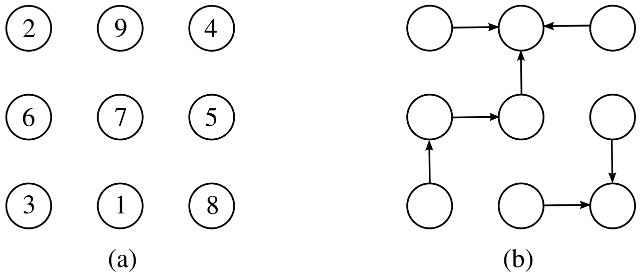

Figure 1. (a) A sample function $f(x, y)$ mapping a 3×3 grid onto $1, 2, \ldots, 9$. (b) The direction of greatest increase in $f(x, y)$ from each grid point.

The lattice points and arrows in Figure 1 are easily described in the language of graph theory [Tutte 2001]. In particular, Figure 1(b) is derived from a grid graph by replacing some edges with a single arc, and eliminating other edges entirely, so there is at most one arc originating at each vertex. We call these limited outdegree grid (LOG) digraphs. If the vertices in a LOG digraph can be labeled with the integers $1, 2, \ldots, n^2$ such that each arc is in the direction of greatest increase from that vertex, we call the graph a greatest increase grid (GIG) digraph. The directed graph in Figure 1(b) is clearly a GIG digraph since it was derived from a labeling of the vertices of a lattice. Other LOG digraphs, such as that shown in Figure 2, are not GIG digraphs. Additionally, GIG digraphs can also be viewed as a type of proximity graph [Bose et al. 2012].

Graph labeling problems, that is, questions that ask if integers can be assigned to the vertices or edges (or both) of a graph subject to given conditions, have been studied for over 50 years. Gallian [2015] has compiled a dynamic survey of the known results of graph labeling problems, and many graph labeling problems are accessible to undergraduate students, such as that in [Poet et al. 2005].

In this paper, we describe two approaches to enumerating the 3×3 GIG digraphs, and a method for enumerating 3×3 LOG digraphs. Finally, we suggest two procedures for deciding if a given LOG digraph is a GIG digraph.

2. Enumerating LOG and GIG digraphs

In counting the number of distinct LOG and GIG digraphs, there are two complicating factors. First, a LOG digraph can be isomorphic to as many as 7 others: those obtained by 90-, 180-, and 270-degree clockwise rotations, and those obtained by reflecting each of these through a horizontal line. These motions are described by the dihedral group on the square. However, a LOG digraph with reflexive or rotational symmetry will have fewer than 8 LOG digraphs in its isomorphism class. Figure 2 illustrates the 8 LOG digraphs in one isomorphism class.

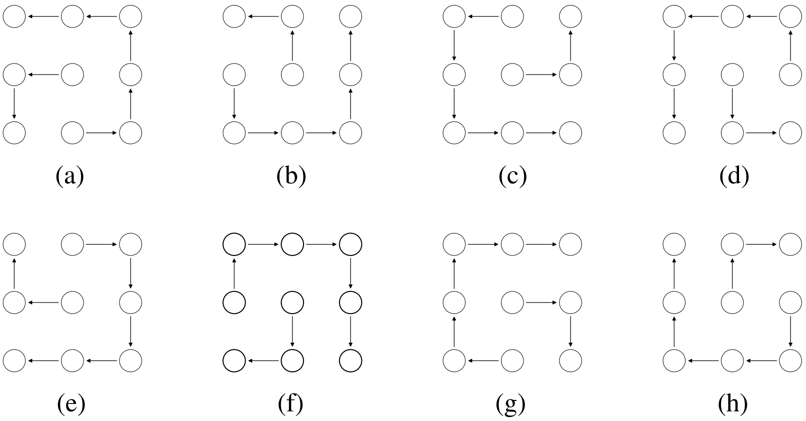

Figure 2. (a) A LOG digraph that is not also a GIG digraph, and its (b) 90-degree, (c) 180-degree, and (d) 270-degree rotations. The LOG digraphs in (e)–(h) are obtained by reflecting those in (a)–(d) through a horizontal line.

The second complicating factor is that a particular GIG digraph can be labeled in more than one way, and the number of ways is dependent upon the underlying LOG digraph. For example, Figure 3 shows three labelings of one particular GIG digraph. The variability described in these two observations prohibits us from being able to find the number of nonisomorphic LOG or GIG digraphs by computing the total number of directed graphs with a certain property and dividing by an easily computable constant. Our research group of undergraduates was split across two campuses, Missouri Western State University and Davidson College. Students from the two campuses took different approaches to enumerating GIG digraphs.

2.1. ***Counting approach 1:*** *construct one candidate LOG digraph from each isomorphism class, and test each one to see if it can be labeled.* On the Missouri Western campus, we approached the problem by considering the list of nonisomorphic candidate LOG digraphs, and then asking if each of these could be labeled.

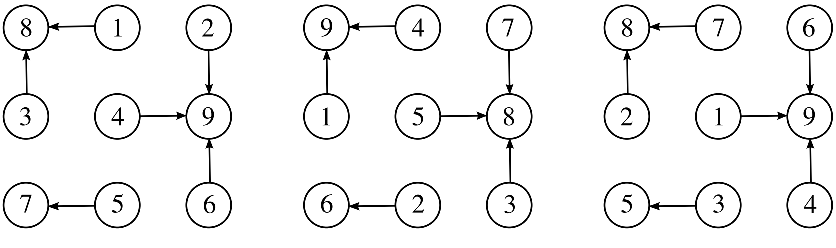

Figure 3. Three possible labelings of the same GIG digraph.

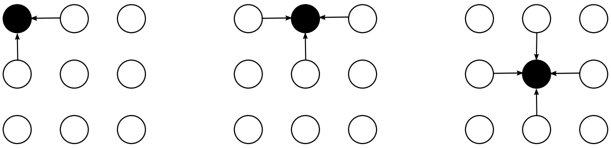

Figure 4. Three possible locations (black vertex) of a complete sink corresponding to the label 9, upper left corner, upper middle, and center.

First, we observe that every GIG digraph must contain at least one vertex that is a complete sink, that is, a vertex with indegree equal to the number of adjacent vertices in the underlying grid graph, corresponding to the label 9. Furthermore, because we want to consider only one candidate LOG digraph in each isomorphism class, we need only consider the label 9 in one of three positions: the upper left corner, the upper middle, and the center. Any valid candidate LOG digraph can be put into correspondence with (at least) one of these three by an appropriate rotation. Hence, the candidate LOG digraphs can be put into three piles (A, B, and C) according to the location of the complete sink, labeled as 9, shown in Figure 4.

These three piles can further be subdivided according to the location of the label 8. For example, if the label 9 is in the upper left, then there are five locations (see Figure 5) that could be labeled with 8 since we want to account for a reflection about the main diagonal. We refer to these configurations as A1, . . . , A5. If the label 9 is in the upper middle, then the label 8 can go in one of the five positions shown in Figure 6 as B1, . . . , B5, taking into account the possible reflection through

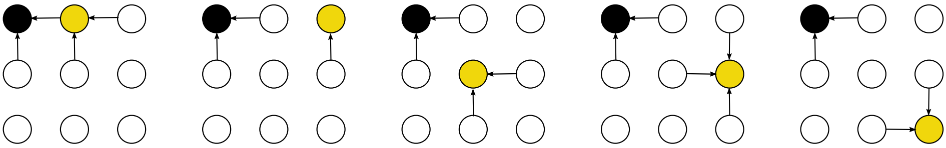

Figure 5. The five possible configurations, A1, . . . , A5, for placing the label 8 (gold vertex), given that the label 9 (black vertex) is in the top left corner.

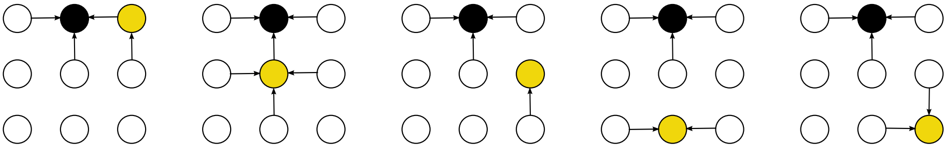

Figure 6. The five possible configurations, B1, . . . , B5, for placing the label 8 (gold vertex), given that the label 9 (black vertex) is in the upper middle.

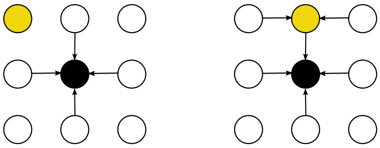

Figure 7. The two possible configurations, C1 and C2, for placing the label 8 (gold vertex) in the upper left and upper center, given that the label 9 (black vertex) is in the center.

the center vertical line. Finally, if the label 9 is in the center, there are only two places (up to rotation) we need to consider for the label 8: the upper left (C1) and the upper middle (C2) as shown in Figure 7. Observe that the digraphs A4 and B5 are isomorphic by a flip through the diagonal that runs from lower left to upper right so we eliminate B5, leaving 11 subsets of candidate LOG digraphs.

With each of these "skeletons" in place, it is relatively straightforward to consider all completions to a GIG digraph by exhaustion. As an example, for subset C1 in Figure 7, we need only consider what arcs might originate from the other three corner vertices. In each case, there are three possibilities: there could be a vertical arc, a horizontal arc, or neither. This leads to a family of 27 candidate LOG digraphs. However, by again taking symmetry into account, this number can further be reduced to the 11 candidates in Figure 8.

Similar arguments can be made to construct the other subsets. While each of our eleven subsets (A1, . . . , A5, B1, . . . , B4, C1, C2) was complete with regard to its

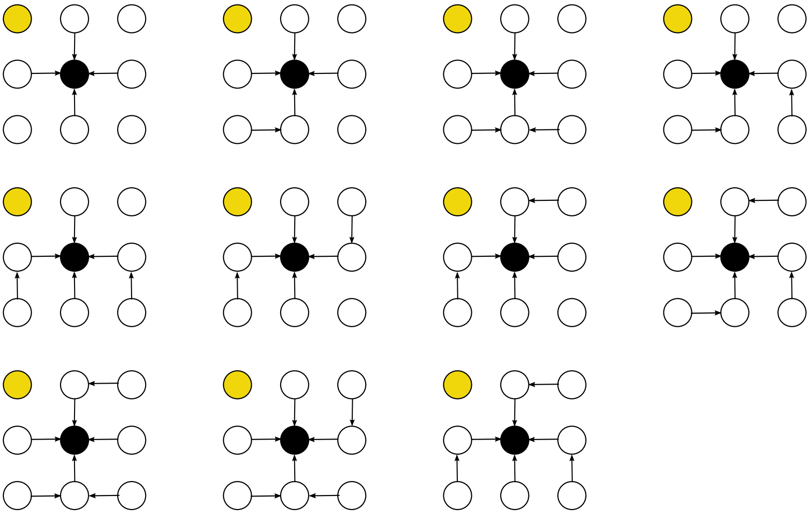

Figure 8. The 11 candidate configurations resulting from enumerating possible completions of configuration C1 in Figure 7.

construction, we knew there was the potential for overlap between sets. Through extensive cross-checking, we were able to eliminate these redundancies. Finally, for each of these potential GIG graphs, we either supplied a labeling of the vertices or provided a justification for why such a labeling was not possible. Our final product was a complete list of the 246 nonisomorphic GIG digraphs.

2.2. *Counting approach 2:* *construct all LOG and GIG digraphs, and identify and discard isomorphic copies.* On the Davidson campus, we produced digraphs on a 3×3 grid using the open-source mathematical software Sage [Stein et al. 2012], and filtered the results for the desired subsets of LOG and GIG digraphs. In this approach, we first needed a convenient data structure for storing and manipulating the graphs. Because a 3×3 grid graph has 12 edges (6 horizontal and 6 vertical), we can represent a 3×3 LOG digraph with a 12×1 arc indicator vector $\vec{a}$. Specifically, we let $a_i = -1$ if arc i points down or to the left, $a_i = 1$ if arc i points up or to the right, and $a_i = 0$ if no arc is present at the ith location. The locations are ordered as shown in Figure 9(a), numbering arcs clockwise around the perimeter of the grid, and then clockwise around the interior of the grid. For example, the LOG digraph in Figure 9(b) is represented by

$$\vec{a} = [1, -1, 0, -1, 1, 0, 1, 0, 1, 0, 0, 1].$$

Using the arc indicator representation, we began by producing all $3^{12} = 531,441$ possible arc indicator vectors, and discarding those that did not correspond to LOG digraphs. Specifically, we removed those vectors that produce an outdegree greater than 1 from any vertex. However, many of the remaining 36,250 LOG digraphs were isomorphic to each other. The isomorphism class of a given LOG digraph is easily obtained through multiplication by rotation and reflection matrices. For example, the equation below illustrates a 90-degree clockwise rotation of the LOG digraph in Figure 9(b):

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ -1 \\ 0 \\ -1 \\ 1 \\ 0 \\ 1 \\ 0 \\ 1 \\ 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ -1 \\ 1 \\ 0 \\ -1 \\ -1 \\ 0 \\ -1 \\ 1 \\ 0 \\ 0 \end{bmatrix} \tag{1}$$

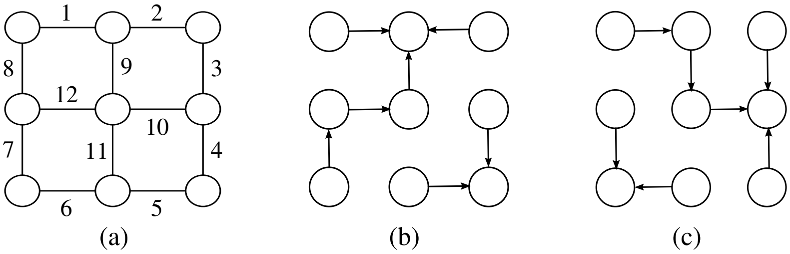

Figure 9. (a) The order in which the arc indicator vector represents arcs in a LOG digraph. (b) The LOG digraph from Figure 1(b). (c) The result of applying a 90-degree clockwise rotation to the LOG digraph in (b).

Note that although the ordering of arcs in the indicator vector was arbitrary, we chose the order illustrated in Figure 9(a) because this ordering produces nice patterns in the rotation and reflection matrices. Discarding isomorphic copies from the list of 36,250 distinct LOG digraphs produced 4,616 isomorphism classes of LOG digraphs. Note that this set includes not only the candidate LOG digraphs from the first approach, but also many LOG digraphs that do not contain a complete sink.

We produced the set of all GIG digraphs, and a unique representative of each isomorphism class, in a similar brute force manner. First, we considered all permutation of the integers 1 through 9, and removed those that were the reverse of another permutation in the set. This reduction was an easy way to filter out those labelings whose GIG digraphs were isomorphic under a 180-degree clockwise rotation. We produced all possible GIG digraphs by mapping these $9!/2$ permutations to the 3×3 grid, and drawing an arc in the direction of greatest increase from each vertex. We obtained 1,853 distinct labeled GIG digraphs with varying numbers of labelings corresponding to each one. Discarding isomorphic copies from the list of 1,853 GIG digraphs produced 246 isomorphism classes of GIG digraphs, the same number obtained through the first approach described in Section 2.1. One advantage of this brute-force computational approach to enumerating LOG and GIG digraphs is that we could easily collect various statistics about the graphs as they were produced. For example, the number of LOG and GIG digraphs with each possible number of arcs is summarized in Table 1.

number of arcs	0	1	2	3	4	5	6	7	8	9
GIG digraphs	0	0	0	0	6	23	86	98	33	0
LOG digraphs	1	4	36	174	570	1,128	1,378	949	335	41

Table 1. The number of GIG and LOG digraphs with each possible number of arcs.

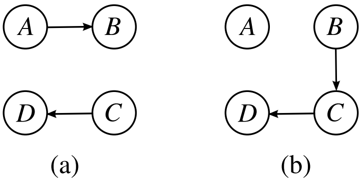

Figure 10. (a) Forbidden subgraph with arcs in opposite directions. (b) Forbidden subgraph with vertex of outdegree 0 and path of length 2.

2.3. ***Determining whether a LOG digraph is a GIG digraph.*** As stated earlier, there are 4,616 nonisomorphic LOG digraphs and 246 of these are GIG digraphs. What follows is a classification of the 4,370 LOG digraphs that are not labelable as GIG digraphs. To show the nonexistence of a labeling for these LOG digraphs, we filter our results with four filters and handle the remaining nine exceptions with ad hoc arguments.

First, observe that for a LOG digraph to be a GIG digraph, it must contain (at least) one vertex that is a complete sink. That is, a 3×3 GIG digraph will contain one of the following: a corner vertex of indegree 2, a side vertex of indegree 3, or a central vertex of indegree 4. The necessity of such a vertex is clear when one considers that the label 9 must appear as a label on a GIG digraph and will be the direction of greatest increase from each of its adjacent vertices. Of the 4,370 unlabelable LOG digraphs, only 614 have a complete sink.

Second, in a GIG digraph, there cannot exist two adjacent vertices (in the underlying grid graph) with outdegree 0. Any vertex of outdegree 0 has the greatest label in its neighborhood, and two adjacent vertices are each in the neighborhood of the other implying that $A < B$ and $B < A$.

Third, a GIG digraph cannot contain a 2×2 subgrid with two arcs on opposite sides of that subgrid pointing in opposite directions. In such a grid, if the vertices are labeled clockwise as A, B, C, and D with arcs AB and CD (as shown in Figure 10(a)), we observe that B and D are each in the neighborhood of A and the arc AB implies that $B > D$. The vertices B and D are also each in the neighborhood of C and the arc CD implies that $D > B$, a contradiction. Thus, such a subgraph cannot occur in a GIG digraph.

These two forbidden conditions are easy to spot in LOG digraphs. Of the 614 unlabelable LOG digraphs with at least one complete sink, all but 74 are eliminated by these two criteria. As our fourth and final filter, we next consider another 2×2 forbidden subgraph.

Suppose a GIG digraph contains a 2×2 subgrid with a vertex of outdegree 0, which we label A, and a path of length 2 on the other three vertices which we label to yield arcs BC and CD, as shown in Figure 10(b). Note that we can assume

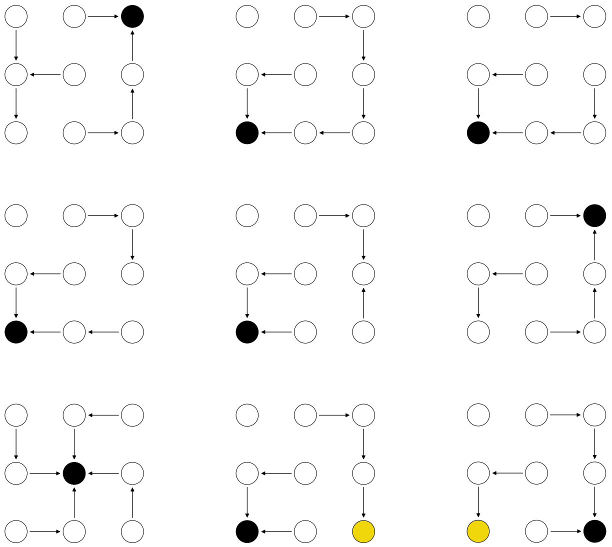

Figure 11. The nine unlabelable LOG digraphs that contain a complete sink, but do not contain one of the two forbidden induced subgraphs.

that D is not of outdegree 0 or the GIG digraph would have adjacent vertices with outdegree 0, which is forbidden. Since A has outdegree 0 and D is adjacent to A in the grid graph, $A > D$. Since A and C are both adjacent to B and the GIG digraph contains arc BC, we have $C > A$. Along any directed path in a GIG digraph, the labels must increase. Hence $D > C$. This gives a contradiction: $A < D$ and $D > A$.

Of the 74 remaining unlabelable GIG digraphs, 65 contain the forbidden subgraph in Figure 10(b), leaving only the 9 graphs in Figure 11. Of these 9 exceptional graphs, the first 7 can be eliminated from consideration as possible GIG digraphs by observing that in addition to a GIG digraph having a complete sink (so that the label 9 can be placed), it must also have either a second complete sink or a near complete sink, so that the label 8 can be placed. A near complete sink is a vertex that is (i) distance 2 from the complete sink in the underlying grid graph and (ii) all vertices adjacent to this vertex in the underlying grid graph and not adjacent to the complete sink terminate at this vertex.

Finally we consider the last two of our exceptional graphs, each of which have one complete sink and one near complete sink, these must be labeled with 9 and 8, respectively. It is easy to see that the label 7 cannot be placed on any of the remaining vertices without creating a contradiction. The vertex of label 7 must be the terminal vertex of an arc for every adjacent vertex that is not also adjacent to the complete sink or the near complete sink, but this does not hold for any of the 7 remaining vertices.

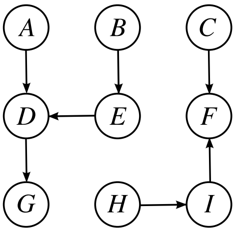

Figure 12. A LOG digraph that is not a GIG digraph.

We have, therefore, shown the nonexistence of a labeling scheme for 4,370 nonisomorphic LOG digraphs and have demonstrated a labeling (not shown here) for each of the 246 nonisomorphic GIG digraphs.

The second approach for determining if a LOG digraph is a GIG digraph relies on the properties of a GIG digraph, specifically the strict inequalities that each arc (or lack thereof) confers on the labels of the vertices. For example, consider the LOG digraph on vertices A–I shown in Figure 12. Suppose this is a GIG digraph. Then arc ED implies $D > F$, arc IF implies $F > I$, arc HI implies $I > G$, and arc DG implies $G > D$. Hence $D > D$, a contradiction. Therefore, this LOG digraph cannot be labeled as a GIG digraph. Note that we could have used other criteria to draw this conclusion, as this LOG digraph does not contain a complete sink. The inequality consistency checking method works for every 3×3 LOG digraph, as we confirmed with a SAGE program.

Many questions about LOG and GIG digraphs remain open. An obvious question is how the numbers of each type of graph, and the numbers of isomorphism classes, grow with increasing grid size. However, applying the techniques described here make extensions of this problem, even to a 4×4 grid, a monumental (and tedious) task, even for a computer. In future research, we hope to investigate new techniques to generalize our results, with the ultimate goal of enumerating $m \times n$ LOG and GIG digraphs. Another potential direction would be to search for efficient characterizations of forbidden subgraphs as the size of the $n \times n$ grid increases. We hope to prove such sets of forbidden subgraphs are both necessary and sufficient by some nonexhaustive method.

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