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Preface
Paul Catlin 1948–1995

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On April 20, 1995, Paul Allen Catlin passed away in Detroit, Michigan, at the age of 46, and the community of Graph Theory lost one of its best friends.

Paul Catlin was born on June 25, 1948 in Bridgeport, Connecticut. His life-long love for mathematics was visible from the start. His younger brother, David Catlin, remembers Paul riding around on his tricycle counting for the sheer pleasure of knowing and using numbers [DC]. Paul's fourth grade teacher, Mrs. Frew, recognized his talent and helped him learn trigonometry that year [JC]. At the age of 14, Paul designed an adding machine and built it from relays; only later did he learn that computers actually work on the principles he incorporated into his machine [JC,DC].

Paul attended the Grand Valley (Michigan) Summer Institute of Mathematics when he was 16. The next year he went to Arnold Ross's NSF summer institute in number theory at the Ohio State University. This experience not only led directly to the contents of six of his first seven papers, but also interested him enough in Ohio State that he returned there many years later for graduate work. But even before returning to Ohio State, while still an undergraduate student at Carnegie-Mellon University, he wrote his first research paper (number [C1] in the publications list) and began his other number theory papers.

Paul received his BA at Carnegie-Mellon University in 1970, and then returned to the Ohio State University, where he earned his MS in 1973 and Ph.D. in 1976. In about 1970 he first became interested in Graph Theory, but that interest did not prevent his working on his number theory problems during his first years at Ohio State. Indeed, Dijen Ray-Chaudhuri recalls him working late nights during his first year there, doing his research [DR]. This work resulted in the papers numbered [C2–C4,C6,C7] in his publications list.

However, Paul's time was not spent only on study and research. He was rightly proud of his ability as a pool player. He was a reasonably good shot, and by using English on the cue ball, he could usually complete each shot with the cue ball in the location he wanted for his next shot. Once he kept a record of successive shots

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made. He sank 118 balls in a row [DC]. He even achieved second place in a state competition; it was a double elimination contest, and he beat the first-place person once [DC].

By the time Paul began working with Neil Robertson toward his masters and Ph.D. degrees, he had gained the consuming interest in graph theory that controlled the remainder of his creative life. Neil remembers Paul coming to him early on and saying ‘I don’t like Graph Theory’, following that extraordinary statement with the explanation that he felt graph theorists too often wrote papers developing known ideas instead of exploring new ideas. He took exception to sequences of papers in which conditions are modified to obtain new results. The sequence of developments from Dirac’s Hamiltonian theorem was an example [NR].

We do not doubt that he would have agreed that such sequences of developments are needed in mathematics. Seldom does the originator of an idea see all of the possible uses of that idea, and the more powerful the idea, the less likely it is that the first paper will say all that can usefully be said.

But Paul did not want to be one of the masses who carry on this necessary work; he wanted his papers to display the new ideas that could be exploited. He showed in his masters’ thesis and Ph.D. dissertation that he could do that sort of work. He tackled the extremely hard area of edge-disjoint packings of graphs into complete graphs and made progress that rivaled joint work that Bollobás and Eldridge were doing at the time. These results became the papers numbered [C5,C8,C11,C13,C17] in the publications list.

During his time at Ohio State, Paul not only showed himself to be a strong mathematician, but he demonstrated his independence in a dramatic way. Neil Robertson recalls that, once Paul completed one of the field exams (the first of a set of four qualifying tests required of all Ph.D. candidates at Ohio State University), he disappeared for four or five months. Then one day, he walked into Neil’s office, plunked a bundle of paper on Neil’s desk that turned out to be about two thirds of his thesis, and left to complete the other three field exams [NR].

When he graduated in 1976, Paul had several job offers, including positions at Wayne State University, Wright State University, and Dartmouth. He selected Wayne State University because he liked the ongoing Ph.D. program there and because he liked the big city environment [DC].

At Wayne State University, he turned to research on chromatic numbers and strengthening Brook’s Theorem in the manner he had assured Neil was the best way. His papers resulting from this study include numbers [C9,C10,C14–C16,C18–C21,C27]. One of the most frequently quoted results from this series in his counterexample to Hajos’ coloring conjecture [C14]. Another high point in the sequence is his paper, written jointly with Bela Bollobás and Paul Erdős, which showed that Hadwiger’s conjecture is true for almost every graph [C18].

Paul was promoted to associate professor with tenure in 1981. Like many of us, he relaxed for a couple of years. But unlike most of us, he came back from this contemplative period with a full array of mature research and teaching interests.

He served as chairman of the Recruitment Committee for Teaching Assistants in 1983–1984. He remained in that committee, renamed the Recruitment Committee for Teaching Assistants and Fellows, from then until 1993, chairing the committee again from 1991 to 1993. Early in his career in this capacity, he made successful recruiting trips about the state for minority students. Later he worked at attracting first-rate foreign students, with success that is shown in the list of his own graduate students. These were Hong-Jian Lai (M.S. in 1985 and Ph.D. in 1988), Zhi-Hong Chen (Ph.D. in 1991), X.Y. Su (Ph.D. in 1994), Ciping Chen (nearing completion of his Ph.D.), and M. Bayen (Ph.D. dissertation in progress). In addition, he had as masters students Wen-Jun Wu (M.S. in 1985), He Li (M.S. in 1986), and Jewel Smith (M.S. in 1983).

Paul not only recruited these and other students, but he also learned some Chinese and worked to teach the foreign students the finer points of American customs and English. Further, he took his students to meetings and shared rooms with them to help hold down their expenses.

Paul's research took a new direction in the mid 1980s. This change was signaled by his paper 'Spanning Trails' [C22]. Here he proved that, with modest conditions, if graph G has n vertices, and if every edge xy satisfies $\deg(x) + \deg(y) \geqslant n$, and if u and v are any two vertices of G, then G includes a spanning trail from u to v. If $u = v$ then this spanning trail describes a spanning Eulerian subgraph for G, and G is called supereulerian. Paul continued exploring the characterization of supereulerian graphs. He very quickly developed the concept of a collapsible subgraph, which is a subgraph that can be treated as a single vertex for the purpose of finding spanning Eulerian subgraphs. (The exact definition of a collapsible subgraph is given later.) The concept of a collapsible subgraph proved to be one of the most important and useful tools in the literature of Eulerian subgraphs and Hamiltonian line graphs. Using this tool, he generated an impressive sequence of important papers, numbers [C23–C26,C28,C29,C32–C35,C38,C39,C42,C45,C47–C51] in the publications list. The key paper in this sequence is number [C47].

It quickly became clear to Paul that his work was intimately related to arboricity and double cycle covers. The latter realization led to the sequence of papers [C31,C36,C37,C44] on double cycle covers.

At the Southeast Conference on Graph Theory at Boca Raton, Florida in 1987, Paul Erdős asked Arthur Hobbs if he knew of a short proof of the result that a graph with n vertices in which every edge is in a triangle must have at least $3/2(n-1)$ edges. Hobbs mentioned the question to Paul Catlin, who immediately thought of a simple contraction proof. It was not long before Catlin and Hobbs, joined by Hong-Jian Lai and later by Jerry Grossman, extended this simple result into a fundamental paper (number [C41] in the publications list) relating fractional arboricity and strength in graphs and matroids. He and many others extended these results further, leading to papers numbered [C30,C40,C43,C46] and others which did not involve Catlin.

During his later years, Paul had two consuming hobbies. First, he loved politics and would talk for hours about current events and their implications for the future. Second, he enjoyed investing in the stock market. He carefully read *The Wall Street Journal* every day at lunch time. He liked to do his own investing. Asked once about mutual funds, he replied, 'Mutual funds like to buy high and sell low'. This comment was typical of his wry sense of humor.

Paul left a legacy of papers worthy of future mining, of students eager and well-prepared to explore the vast world of graph theory, of colleagues vibrant with enthusiasm for the work he began, and of friends who mourn his passing. We remember his sense of humor and his intense interest in politics. We admire the aid he gave each of his students, not only with mathematics but with English and culture.

The remainder of this article describes some of Paul Catlin's research results.

1. Subgraph packings

For simple graphs G_1 and G_2 with $n = |V(G_1)| = |V(G_2)|$, we say that there is a *packing* of G_1 and G_2 if G_2^c, the complement of G_2, contains G_1 as a subgraph. In 1974 Catlin proved [C0] that if $2\Delta(G_1)\Delta(G_2) < n$, then there is a packing of G_1 and G_2. (Here $\Delta(G)$ denotes the maximum degree of G.) This result was later independently proved by Sauer and Spencer [SaSP].

In 1976, Catlin ([C0,C8]), and independently Bollobás and Eldridge [BoEL], conjectured that there is a packing of G_1 and G_2 if $(\Delta(G_1)+1)(\Delta(G_2)+1) \leqslant n+1$. In [C8], Paul presented two classes of examples to show that this conjecture, if true, would be best possible.

Catlin considered in general this problem: let G and H be graphs on n vertices, what lower bound on $\delta(G)$ (upper bound on $\Delta(G)$), in terms of $\Delta(H)$ and n, ensures that H is isomorphic to a subgraph of G. In [C5], Catlin showed that if $\delta(G) \geqslant n - 1 - \beta(H)/2\Delta(H)$, where $\beta(H)$ is the cardinality of a maximum set of independent vertices of H, then H is isomorphic to a subgraph of G. He also proved a similar result on bipartite graphs [C5]. In [C13], Catlin found some such lower bounds of $\delta(G)$ in terms of n and the number of triangular components of H.

2. Graph colorings

One of Catlin's contribution to Graph Theory is his well-known counterexamples to Hajos' graph-coloring conjectures [C14]. Later, jointly with Bollobás and Erdős, Catlin showed that Hadwiger's coloring conjecture is true for almost every graph [C18]. Catlin also studied extensions of Brooks' coloring theorem. In [C9], Catlin showed that whenever G contains no complete subgraph K_r with $r \geqslant 4$, then Brooks theorem can be improved to $\chi(G) \leqslant \Delta(G) + 1 - [(\Delta(G)+1)/r]$. (This was independently discovered by Borodin and Kostochka [BK].) And in [C10], Catlin improved this further to show that if G has no $K_{r+2} - e$ as a subgraph, for some $r \geqslant 3$, then $\chi(G) \leqslant r/(r+1)\Delta(G) + 3)$. In [C15], Catlin took another angle to extend Brooks theorem. He proved that if Brooks' Theorem implies $\chi(G) \leqslant \Delta(G)$, then one of the color classes may be chosen to be some maximum independent set in a $\Delta(G)$-coloring of G. This is further extended in [C46] that if Brooks' Theorem implies $\chi(G) \leqslant \Delta(G)$, then G has a $\Delta(G)$-coloring with color classes $V_1, V_2, \ldots, V_{\Delta(G)}$ such that for $i = 1, 2, \ldots, \Delta(G)$, V_i is a maximum independent set of G_i, where $G_1 = G$ and where $G_i = G_{i-1} - V_{i-1}$, for $i \geqslant 2$. In [C46], Theorems analogous to Brooks' Theorem for colorings with forests as coloring classes are also obtained. Regarding a coloring is a special case of a graph homomorphism, Catlin investigated homomorphism onto odd cycles, and he characterized edge-minimal graphs having no homomorphism into the 5-cycle [C27].

3. Eulerian subgraphs

For a graph $G, O(G)$ denotes the set of vertices of odd degree in G. A graph G is *even* if $O(G) = \emptyset$, is *Eulerian* if it is both even and connected, and is *supereulerian* if it has a spanning Eulerian subgraph.

Call a graph H *collapsible* it for every even cardinality set $X \subset V(G), G$ has a spanning connected subgraph H_X such that $O(H_X) = X$. In [C26] Catlin proved that if H is a collapsible subgraph of G, then G is supereulerian if and only if G/H, the graph obtained from G by contracting H, is supereulerian.

The main reduction method in [C26] is very powerful. With it, Catlin proved several significant results. We list a few below.

For a simple 2-edge-connected graph G with n vertices, if the minimum degree $\delta(G) \geqslant (n/5) - 1$, then either G is supereulerian, or G can be contracted to a $K_{2,3}$ such that the preimage of every vertex in this $K_{2,3}$ is a complete graph of order $n/5$. This proved a conjecture of Bauer [Ba].

Let G be a simple 2-edge-connected graph of order n. For a matching M_3 consisting of three edges, $\sum(M_3)$ denotes the sum of the degrees of the six vertices incident with M_3. If $\sum(M_3) \geqslant 2n+2$ for all 3-matchings of G, then either G is supereulerian, or there is a connected subgraph H such that $G/H = K_{2,t}$ for some odd t. This sharpened prior results of Brualdi and Shanny [BS], Clark [CLA], Veldmen [VEL], and of Benhocne et al. [BCKV].

Let G be a simple 2-edge-connected of order n. If $n \geqslant 100$ and if for every pair of nonadjacent vertices u and v in G, $d(u) + d(v) > (2n/5) - 2$, then G is supereulerian. This proved a conjecture of Benhocne et al. [BCKV].

Let G be a 2-edge-connected simple graph of order n, and let m and p be natural numbers. If $n > p + 6$, if G contains no K_{m+1}, and if

$$|E(G)| \geqslant \binom{n - p + 1 - k}{2} + (m - 1)\binom{k + 1}{2} + 2p - 4,$$

where $k = \lceil (n - p + 1)/m \rceil$, then either G is supereulerian, or G can be contracted to a nonsupereulerian graph with at most $p - 1$ vertices. With $p = 5$ and $m \geqslant n - 4$, this proved a conjecture of Cai [C39].

One of the tools Catlin used to study Eulerian subgraphs is the function $F(G)$, defined to be the minimum number of edges that must be added to G so that the resulting graph has two edge-disjoint spanning trees. Thus, $F(G) = 0$ if and only if G has 2 edge-disjoint spanning trees. Jaeger showed that if $F(G) = 0$, then G is supereulerian. Catlin succeeded in showing [C26] that if $F(G) \leqslant 1$, then either G is supereulerian or G is contractible to a K_2. Recently, Catlin and others [C48] proved that if G is connected and if $F(G) \leqslant 2$, then either G is supereulerian, or G is contractible to a K_2, or to a $K_{2,t}$ for some odd t. Catlin conjectured [C45] that if G is 2-edge-connected and if $F(G) \leqslant 3$, then either G is supereulerian, or G is contractible to the Petersen graph.

Catlin left several other conjectures in this area. A graph G is *reduced* if it does not have any nontrivial collapsible subgraphs. Catlin conjectured [CL] that if G is reduced, then $\chi(G) \leqslant 3$. Since reduced graphs are K_3-free, Grötzsch's Theorem on 3-coloring K_3-free planar graph implies that this conjecture holds for planar graphs. Catlin also conjectured [C23] that a graph H is collapsible if and only if for any graph G containing H as a subgraph, G/H is supereulerian if and only if G is supereulerian. Several other conjectures related to collapsibility can be found in [C36]. He also asked of the class of supereulerian graphs. "Given a supereulerian graph G, let H be a spanning Eulerian subgraph of G with the maximum number of edges, and let $s(G) = |E(H)|$. What is the best possible lower bound of the ratio $|E(H)|/|E(G)|$ among all supereulerian graphs?" he noted that this ratio is $\frac{1}{3}$ for Hamiltonian cubic graphs. The general problem remains open.

4. Reduction beyond Eulerian subgraphs

The success of the reduction method in dealing with Eulerian subgraphs led Catlin to explore its application in other areas. He called a family $\mathscr{C}$ of graphs *complete* if $\mathscr{C}$ contains all edgeless graphs, and the contraction image of a member in $\mathscr{C}$ remains in $\mathscr{C}$ (closed under contraction) and

$$H \subseteq G, H \in \mathscr{C} \quad \text{and} \quad G/H \in \mathscr{C} \Rightarrow G \in \mathscr{C}.$$

In one of his most recent papers [C47], he indicated that the reduction method is applicable when there is a complete family involved. He showed that the reduction method can be applied to the study of edge-connectivity, integer flows, weak k-link graphs, and matroid principal partitions, among others.

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