COMBINATORICS, GEOMETRY AND PROBABILITY

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A tribute to Paul Erdős

Edited by

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Preface

On Friday, 26 March 1993, Paul Erdős celebrated his 80th birthday. To honour him on this occasion, a conference was held in Trinity College, Cambridge, under the auspices of the Department of Pure Mathematics and Mathematical Statistics of the University of Cambridge. Many of the world's best combinatorialists came to pay tribute to Erdős, the universally acknowledged leader of their field.

The conference was generously supported both by the London Mathematical Society and by the Heilbronn Fund of Trinity College. As at former Cambridge Conferences in honour of Paul Erdős, the day-to-day running of this conference was in the able hands of Gabriella Bollobás, with the untiring assistance of Tristan Denley, Ted Dobson, Tom Gamblin, Chris Jagger, Imre Leader, Alex Scott and Alan Stacey. The conference would not have taken place without their dedicated work.

On the eve of Erdős' birthday, a sumptuous feast was held in his honour in the Hall of Trinity College. The words wherein he was toasted are reproduced in the following pages. This volume of research papers was presented to Paul Erdős by its authors as their own toast, gladly offered with their gratitude, respect and warmest wishes.

Sadly, before this book reached its printed form, Paul Erdős died. Whereas it was conceived in joy it appears now tinged with sorrow. We feel his loss tremendously. But it is not appropriate that grief should overshadow this volume. Erdős lived to do mathematics and he died doing mathematics. So this work remains a tribute to the Erdős we fondly remember — the living Erdős — the mathematician.

B.B.
A.G.T.

Farewell to Paul Erdős

(26/3/1913 – 20/9/1996)

(Paul Erdős died in Warsaw on 20th September 1996. A memorial service was held for him on 18th October 1996 in the Kerepesi Cemetery in Budapest, the traditional resting place of eminent Hungarians. A great number of his friends gathered to mark his passing. Among them were colleagues and former students representing mathematics from many countries and four continents. The orations were given by Ákos Császár, Paul Révész, Gyula Katona, Ron Graham, András Hajnal, George Szekeres, and by Béla Bollobás, whose tribute is reproduced below.)

Paul Erdős was one of the most brilliant and probably the most remarkable of mathematicians of this century. Not only was his output prodigious, with fundamental papers in many branches of mathematics, including number theory, geometry, probability theory, approximation theory, set theory and combinatorics, and not only did he have many more coauthors than anybody else in the history of mathematics, but he was also a personal friend of more mathematicians than anybody else. The vast body of problems he has left behind will influence mathematics for many years to come.

Many of us are lucky to have known him and to have benefited from his incisive mind, fertile imagination and desire to help. But hardly any one of us knew him in his prime, from the mid-thirties to the early sixties. He was hardly twenty when he took the mathematical world by storm, so that the great Issai Schur of Berlin dubbed him *der Zauberer von Budapest.*

Throughout his life, he lived modestly, despising material possessions and coveting no honours, and was always somewhat outside the mathematical establishment. Nevertheless, he was showered with honours. Among others, he was an Honorary Member of the London Mathematical Society and an Honorary Fellow of the Royal Society. These illustrious institutions have sent wreaths to express their grief at his loss. But I am here mainly to represent Paul's many friends, colleagues and, above all, his students.

Thinking of him, David's psalm springs to mind: *"surely goodness and mercy shall follow me all the days of my life."* For decades, he was the window to the West for the Hungarian mathematicians, and has helped more mathematicians all over the world than anybody else. He was especially kind to young people. I was just over fourteen when he called me to him and so changed the course of my life. There is no doubt that I became a combinatorialist only because of him, and I owe him a tremendous debt of gratitude for all his kindness and inspiration. Many people owe their careers to him.

As David in his psalm, he could also have said: *"though I walk in the valley of the shadow of death, I will fear no evil."* Sadly, he was always in the shadow of death. When he was born, his two sisters died; when he was a year-and-a-half his father was taken prisoner of war and spent six years in Siberia; when his father died of a heart attack, he could not come to Hungary to comfort his mother; most of his relatives perished in the

Holocaust; in the fifties even America abandoned him and he was saved only by Israel; finally, the loss of his mother was a terrible blow to him, from which he never really recovered. But whatever happened, he always had a passionate desire to be *free*: he could not tolerate constraint of any kind, he was never willing to compromise.

Perhaps there were only two happy periods in his adult life: from 1934 to 1939 when he was in Manchester and Princeton, and from 1964 to 1971, when he travelled around the world with his beloved mother. I was lucky enough to have known him in this second happy period.

The death of Paul Erdős marks the end of an era. No conference will be the same without the p.g.o.m., the *poor great old man*, as he called himself, no mathematical discussion will be as much fun as it was with him. Our beloved *Pali Bácsi* has left us all orphans.

This exceptional man did think about what will happen after him. Endre Ady, the famous Hungarian poet, wrote: *"Let him be cursed who takes my place!"* Paul's wish was rather different, reflecting his character: *"Let him be blessed who takes my place!"*

Now, when we have to say our final goodbye to Paul Erdős, we all know that there is no chance of that. His death is a tremendous loss to us all, and this sense of loss will stay with us for ever. But we should console ourselves that he has had a marvellous life, in which he has produced an exceptional amount of outstanding mathematics, and we are privileged to have known him.

Kerepesi Cemetery, Budapest, 18/10/1996

Béla Bollobás

Toast to Paul Erdős

(The following is the toast of the Banquet for the 80th Birthday of Paul Erdős, held in Trinity College, Cambridge, on 25 March 1993, the eve of the birthday. The banquet was attended by many of Erdős' other friends, including Lady Jeffreys, Mrs Davenport and Peter Rado, in addition to the conference participants. Trinity College was represented by Sir Andrew Huxley, OM, former president of the Royal Society and former Master of the College, who presided at the feast. Cambridge mathematics was represented by the present and former Sadlerian Professors, John Coates, FRS, and J.W.S. Cassels, FRS.)

Professor Erdős, Sir Andrew, Ladies and Gentlemen,

Mathematics is rich in unusual characters, as everyone here at this dinner will know. Nevertheless, most of us would agree that there is none whose achievement and lifestyle are more extraordinary than those of the man we are celebrating tonight, on the eve of his birthday, following a Hungarian custom. For over 60 years, his fertile mind has maintained a staggering output in many branches of mathematics: he has made notable contributions and broken fresh ground in set theory, number theory, probability theory, classical analysis, geometry, approximation theory and combinatorics. Most of us are particularly aware of his contributions to the last of these subjects: he has done more than anyone else to establish combinatorics; many branches of the subject find their origin in his ideas; the stimulus of his striking theorems and inspiring problems is one that we have all felt, and for which we owe him an incalculable debt of gratitude. It is also true that, as well as being so remarkably gifted intellectually, he has the most admirable and attractive personal qualities. He is generous to a fault, gentle, unassuming, always eager to fight for the downtrodden. Many a young student has been delighted to discover that this famous man is so easily approachable and so interested in their work. He has always made it his business to nurture young talent, possibly his greatest find being Pósa.

What anybody, who has ever heard of this unique man, knows is that he is unceasingly on the move. It is hardly an exaggeration that he has not slept in the same bed for more than a week in over 50 years. As a constant globe-trotter, he is the living link between mathematicians across the world, carrying with him news of theorems, conjectures and problems.

Paul Erdős was a precocious child: at the age of three he was good at arithmetic to the point of discovering for himself negative numbers. Much of Paul's education was done in private; altogether he spent less than four years in schools. At the age of 17, he proceeded to university, where he soon became the focus of a wonderfully talented group of mathematicians.

At the age of 21, he completed his degree, and as was the custom, he looked to spend a year abroad. In the world of 1934, the country that most attracted him was Britain. As an undergraduate, he had corresponded with Louis Mordell, the great American number

theorist, who by that time had left St John's College, Cambridge to work in Manchester. Mordell offered Erdős a Fellowship in his department, and the offer was gladly accepted. On 1 October 1934, Erdős arrived in London, from where he took the train to Cambridge. At the station he was met by two outstanding young mathematicians who for many years to come were to be his closest friends, Harold Davenport and Richard Rado. Sadly, Harold Davenport and Richard Rado are no longer with us, but it is indeed a pleasure to see Anne Davenport and Peter Rado at this banquet tonight. In fact, it is due to Erdős's friendship with Davenport that my own connection with Trinity came about.

At that time Erdős stayed in Cambridge only for a couple of days, but long enough to meet Hardy and Littlewood, the leading English mathematicians. He then travelled on to Manchester, to Mordell, who became his mentor and friend. In the 1930s Mordell gathered a remarkable group of mathematicians to Manchester: in addition to Erdős, and later Davenport, the group included Mahler, Heilbronn, du Val and Chao Ko. It is extremely fitting that this conference has been supported by Heilbronn's generous bequest to the mathematicians of this college. On looking down on us, Heilbronn must be smiling that we are celebrating his great friend tonight.

Another prominent member of the Manchester group was the eminent fluid dynamicist Miss Swirles, who befriended Paul soon after his arrival. It is a great pleasure that Miss Swirles, by now Lady Jeffreys, can share in this happy celebration tonight.

Paul stayed in Manchester for four years, first as the Bishop Harvey Goodwin Fellow, and then as a Royal Society Fellow. During that time he made frequent visits to Cambridge and other centres of mathematics. In 1938 Paul left England for the States to take up a Fellowship at Princeton. It was to be ten more years before Paul returned to Hungary, and he would never again stay there for more than a few months at a time.

After a year or two at the Institute, the travelling began in earnest, and the now familiar pattern was soon set. In a short space of time, he visited Philadelphia, Purdue, Stanford, Syracuse and Johns Hopkins, and many other universities for even shorter periods.

Since then Paul has been travelling from university to university, from country to country, bringing news, inventing problems, writing joint papers, stimulating the minds of mathematicians everywhere, and generally being the Erdős we know and love so well. By now he has over 300 coauthors, and it has often been said that if a train journey is long enough, he will write a joint paper with the conductor. His 1300 research papers place him in a league of his own among research mathematicians.

It has been said that the world wants geniuses but it wants them to behave just like other people. Paul found this out when one apocryphal, but not too far-fetched, night in Chicago he was out walking by himself. Suddenly a police car appeared and the officers began to question Paul. "So what are you doing out here, all by yourself?" "I am thinking" came the reply. "What do you mean you are thinking? What are you thinking about?" "I am proving a theorem." "You'd better come with us back to the station, Sir."

Back at the station, the officer in charge said "Now, what's all this about your theorem? Tell me about it." "It doesn't matter anymore" grumbled Paul testily, "I've found a counterexample."

In fact, this incident is atypical for, as we know, Paul is remarkably successful in proving theorems. A striking example is quoted by Mark Kac.

"As a mathematician Erdős is what in other fields is called a 'natural'. If a problem can be stated in terms he can understand, though it may belong to a field with which he is not familiar, he is as likely as, or even more likely than, the experts to find a solution. An example of this is his solution of a problem in dimension theory, a part of topology of which in 1939 he knew absolutely nothing. The late Witold Hurewicz and a younger colleague, Henry Wallman, were writing a book on dimension theory which later became an acknowledged classic. They were interested in the unsolved problem of the dimension of the set of rational points in Hilbert space. What all this means is unimportant except that the problem seemed very difficult and that the 'natural' conjectures were that the answer is either zero or infinity. Erdős overheard several mathematicians discussing the problem in the common room of the old Fine Hall at Princeton. "What is the problem?" asked Erdős. Somewhat impatiently he was told what the problem was. "What is dimension?" he asked, betraying complete ignorance of the subject matter. To pacify him, he was given the definition of dimension. In a little more than an hour he came with the answer, which, to everyone's immense surprise, turned out to be '1'!"

In addition to being successful in his own personal research, one of Paul's greatest gifts to mathematics has been his ability to stimulate the creativity of others through his fascinating and penetrating conjectures. His offer of monetary rewards for solutions is legendary. The winner of the largest reward to date is Szemerédi, for finding long arithmetic progressions in sets of positive density. It is a pleasure to see him here tonight. The biggest sum on offer is $10 000, for proving that the gap between two consecutive primes is rather large infinitely often. Although Schönhage, Rankin, Maier and Tenenbaum have proved exciting results in this direction, they haven't yet managed to claim the prize. Paul is also offering $3000 for finding long arithmetic progressions in sequences of natural numbers whose reciprocals diverge, and so, in particular, among the primes. A group of Swedish computers has just discovered an arithmetic progression of 22 primes but I doubt that any payment will be forthcoming from Paul.

Paul worked with most of the leading Hungarian mathematicians, especially the number theorist Paul Turán and the probabilist Alfréd Rényi, who were his great friends. Turán's wife, Vera Sós, has also been a close friend and collaborator for many years, and it is fitting that she too should be celebrating tonight.

My own friendship with Paul is also of many years standing. We met when I was 14, and I was tremendously impressed by his willingness to talk to me about his fascinating problems. To me he seemed to be from a different planet, a flamboyant man with an air of the exotic, with his expensive foreign suits and ready cash, brought from the unattainable free Western world. Now I know better; I think it was Paul who inspired the saying: "The man who leaves footprints on the sands of time never wears expensive shoes."

In those days, I also got to know Paul's mother, Annus néni, a charming lady who adored Paul, and was, in turn, adored by her son. She kept his reprints in immaculate order, and sent copies to those who requested them. A year or two later they got to know my family, and were frequent visitors to our house whenever Paul was in Hungary.

In 1964, at the age of 84, Annus néni began to travel with Paul. Their first trip was to Israel; soon Western Europe followed, including England a year later. In 1968, when she was 88, Annus néni accompanied Paul to Hawaii and Australia. When asked whether she liked to travel, she used to reply: "You know I don't travel because I like it, but to be with my son." It was moving too see their affectionate care for each other, catching up

with those lost years, when they couldn't see each other. Annus néni greatly enjoyed her role as Queen Mother of mathematics, meeting and entertaining all the people coming to see Paul; her cocoa cake with coffee cream was especially delicious.

Erdős's own tastes in food are well known to be frugal, and he doesn't care for wine, which he calls poison. It has been suggested that the College should on this occasion produce a meal of bread and water. Unfortunately when I checked with the Kitchens, they could not find the recipe, so we had to use the second choice menu.

Paul Erdős has always kept up his close links with Trinity and Cambridge. Some years ago he was a Visiting Fellow Commoner of Trinity College, and in 1991 Cambridge awarded him an Honorary Doctorate – the first citizen of Hungary to receive this honour. At the ceremony it was charming to see the great actor Sir Alec Guinness taking it upon himself to shepherd Paul through the long ritual.

Since his youth, Paul Erdős has had catholic interests: in particular, he has maintained an enthusiasm for history and medicine. It is always fascinating to engage him in discussion of his favourite historical events. Nevertheless, Paul is the quintessential mathematician: he breathes, eats, drinks, and sleeps mathematics, if he sleeps at all. It could have been Erdős, whom Littlewood had in mind when he wrote:

> "There is much to be said for being a mathematician. To begin with, he has to be completely honest in his work, not from any superior morality, but because he cannot get away with a fake. It has been cruelly said of arts dons, especially in Oxford, that they believe there is a polemical answer to everything; nothing is really true, and in controversy the object is to prove your opponent a fool. We escape all this. Further, the arts man is always on duty as a great mind; if he drops a brick, as we say in England, it reverberates down the years. After an honest day's work a mathematician goes off duty. Mathematics is very hard work, and dons tend to be above average in health and vigour. Below a certain threshold a man cracks up; but above it, hard mental work makes for health and vigour (also – on much historical evidence throughout the ages – for longevity)."

If hard mental work be the secret of longevity then Paul Erdős will live forever and continue to enrich us all with the brightness of his intellect and the warmth of his heart. In the meantime, we honour him on his 80th birthday.

Ladies and Gentlemen, please rise and toast Paul Erdős.

B.B.

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