

Ireland's Participation in the 56th International Mathematical Olympiad

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This document contains a report on Ireland's participation in the 56th International Mathematical Olympiad (IMO). Any reported facts are accurate to the best of my knowledge, while any opinions expressed are entirely my own.

The 56th International Mathematical Olympiad (IMO) took place in Chiang Mai, Thailand, from 4–16 July 2015. A total of 577 students (52 of whom were girls) participated from 104 countries. This record number of participating countries was achieved only once before in IMO history, at the 50th IMO in Germany in 2009 (the number of participating students was higher this year than in 2009).

The Irish delegation consisted of six students (see Table 1). Accompanying the students to the competition in Chiang Mai were the Team Leader, Mark Flanagan (UCD) and the Deputy Leader, Gordon Lessells (UL).

1. TEAM SELECTION AND PREPARATION

The team detailed in Table 1 consisted of those six students (in order) who scored highest in the Irish Mathematical Olympiad (IrMO),

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Name	School	Year
Luke Gardiner	Gonzaga College, Dublin 6	6 th
Paul Clarke	St. Paul's College, Dublin 5	6 th
Oisín Flynn-Connolly	Home-schooled, Co Cavan	5 th
Anna Mustata	Bishopstown Community School	3 rd
Ioana Grigoras	Mount Mercy College, Cork	5 th
Robert Sparkes	Wesley College, Dublin 16	5 th

TABLE 1. The Irish contestants at the 56th IMO

which was held for the 28th time on Saturday, 25th April, 2015. The IrMO contest consists of two 3-hour papers on one day with five problems on each paper. The students who participated in the IrMO sat the exam simultaneously in one of five *Mathematics Enrichment Centres* (UCC, UCD, NUIG, UL and MU). This year, a total of 107 students took part in the IrMO. The top performer is awarded the *Fergus Gaines cup*; congratulations to Luke Gardiner, who achieved this honour in IrMO 2015.

The students who participate in the IrMO usually attend extra-curricular Mathematics Enrichment classes, which are offered at the five Mathematics Enrichment Centres listed in the previous paragraph. These classes run each year from January until April and are offered by volunteer academic mathematicians from these universities or nearby third-level institutions. More information on the organisation of these classes, as well as links to the individual maths enrichment centres, can be found at the Irish Maths Enrichment/IrMO website <http://www.irmo.ie/>.

Each year in November, the Irish Mathematical Olympiad starts with *IrMO Round 1*, a contest that is held in schools during a regular class period. In 2014, more than 12,000 students, mostly in their senior cycle, from about 260 second level schools participated in Round 1. Teachers were encouraged to hand out invitations to their best performing students to attend the mathematics enrichment classes in their nearest maths enrichment centre.

Some of the top performing students in the IrMO are not in their final year of school, and therefore have a chance to compete for a place on the Irish IMO team again the next year. It is important that such ‘returning’ students are kept mathematically engaged and challenged. To this end, an Irish Maths Olympiad “Squad” was formed, building on a very successful experience in 2013. The 19 students who were among the top performers in IrMO 2014 and who were also eligible to participate in IMO 2015 were invited to participate in two training camps (one in June and one at the end of August) as well as a centrally organised “remote training” programme.

The remote training programme, which was initiated in 2013, works as follows. At the beginning of each month from September to December inclusive, two sets of three problems are emailed to the participating students. They return their (complete or incomplete) solutions, by email or by post, to the proposer of the problems

before the end of the month. The problem proposer then provides feedback on their work, as well as full solutions. The rationale is that the problem-solving abilities of talented students is enhanced most when they work on problems *themselves*, and the provision of worked solutions is also most effective after the students have worked hard on the problems in question. The eight trainers involved in the remote training in 2014 were Mark Flanagan, Eugene Gath, Norbert Hoffmann, Gordon Lessells, Maria Losada, John Murray, Anca Mustața and Andrei Mustața.

Each of the five maths enrichment centres listed above hosts a local contest for the students, which takes place in February or March (this contest is specific to that centre). In addition, this year a number of students from Ireland was invited to participate in the British Mathematical Olympiad Round 1 (28 November 2014) and Round 2 (29 January 2015). This is a great opportunity for talented students as they get to experience challenging problem solving in a real olympiad-style environment. I would like to thank UKMT, and in particular Geoff Smith, for giving our students this opportunity.

Three training camps were organised at various locations for the Irish Maths Olympiad Squad; during these mathematically intense 3–5 day events, students have the opportunity to socialise with their enthusiastic peers and to increase motivation for their work throughout the year. A kick-start camp for the remote training was organised in UCC for the wider squad from 20–23 August 2014. A training camp for the top performing students in IrMO 2015 was held at Mary Immaculate College, Limerick, from 3–5 June 2015, featuring an IMO-style exam in which $3\frac{1}{2}$ hours were given to solve 3 problems. A training camp for the six members of the Irish IMO team was held at the University of Limerick from 23 to 25 June 2015. The camps were organised by Anca Mustața, Bernd Kreussler and Gordon Lessells. The sessions with the students at these camps were directed by Mark Burke, Mark Flanagan, Eugene Gath, Finbarr Holland, Bernd Kreussler, Jim Leahy, Gordon Lessells, Anca Mustața, Andrei Mustața, and special guest Maria Losada (the IMO Team Leader of Colombia).

A final joint training camp was held immediately before the IMO in collaboration with the team from Trinidad and Tobago. This camp, which builds on the success of a similar collaboration last year, was held at the Holiday Garden Hotel in Chiang Mai. The

sessions were conducted by the two Deputy Leaders Gordon Lessells and Jagdesh Ramnanan. As per last year, the students enjoyed this opportunity to train with a team having a comparable level of problem-solving ability.

2. THE DAYS IN CHIANG MAI

The team (including Leader and Deputy Leader) arrived around 10:30pm on Tuesday, the 3rd of July. We were pleasantly surprised to find that an IMO delegation was there to help us. They had been deployed to help us to secure a visa-on-arrival which was needed for one of our team members, Ioana Grigoras. However, as our connecting flight was delayed and arrived later than expected, there was no connecting flight to be had to Chiang Mai and we had to stay the night in Bangkok. Fortunately, the airline put us up in a rather fabulous 5-star hotel which was located very near to Bangkok International Airport (plus a welcome meal before going to sleep!).

The next morning we awoke refreshed after so many hours travelling, and took an early flight to Chiang Mai. There we were met by an official welcome party who garlanded us with flowers. We all proceeded to the Holiday Garden Hotel, at which the team would carry out their intensive pre-IMO training camp in collaboration with the Trinidad and Tobago team. A meeting room in the hotel proved inexpensive to book and served this purpose adequately. Led by the Irish Deputy Leader Gordon Lessells and the TTO Deputy Leader Jagdesh Ramnanan, this consisted of a lot of intensive problem-solving sessions. It also allowed our students to acclimatise to the hot weather and the time difference. On the day after our arrival, I left Gordon and the students at the training camp and travelled to the Jury site.

The Jury of the IMO, which is composed of the Team Leaders of the participating countries and a Chairperson who is appointed by the organisers, is the prime decision making body for all IMO matters. Its most important task is choosing the six contest problems out of a shortlist of 30 problems provided by the IMO Problem Selection Committee, also appointed by the host country. This year's Chairperson of the Jury was Associate Professor Dr. Soontorn Orintara. He proved to be a very efficient and effective Chairman of the Jury.

The Jury meetings involved much intense discussion and debate around choosing the 6 problems for the IMO paper. Some points were noteworthy this year:

- One of the first pieces of business for the Jury was to vote on the adoption of a problem selection protocol, used already in IMO 2013 and IMO 2014, which would ensure that one problem from each of the four areas (algebra, combinatorics, geometry and number theory) would be included in problems 1, 2, 4 and 5. This protocol has the principal advantage of ensuring a balance between the four areas among the less difficult problems in the contest (of course, in principle problems 3 and 6 are possible for any student to solve, but in practice these problems are often extremely difficult). However, the protocol also has the disadvantage that many problems are eliminated before a holistic view of the paper is taken.
- One item which attracted quite some attention this year was the absence of candidate ‘easy’ problems on the shortlist, i.e., candidate Problems 1 and 4. This is not a new phenomenon but has been observed in the last few IMOs. For example, the algebra problem on the shortlist which ranked as the easiest (as judged by the Problem Selection Committee) was eventually classed by the Jury as having a ‘medium’ level of difficulty, and not an ‘easy’ one. The easiest problem in the number theory category was N1, but this was excluded due to its similarity to a Chinese Olympiad problem from 2010. Certainly, a range of options for ‘easy’ level problems is important for the Jury to be able to choose a good IMO paper.
- This year, quite a lot of time was available for devising and debating the marking schemes for the problems, which in my opinion was a very good addition. As a result, the marking schemes were fair and well thought out, with consideration given to the many diverse ways in which students might make progress on a particular problem. Another positive aspect of the marking schemes was that care was taken that students would not lose a mark on a problem due to some very minor arithmetic slip, or the non-inclusion of some very minor calculation which could have been done mentally. In the past, such deductions have caused frustration to some students,

as a very minor error can cause the denial of a medal or an Honourable Mention at the IMO.

- An unexpected complication arose this year, in that some Deputy Leaders were accidentally given access to the Second Day contest paper on the morning of the First Day of the contest. The Jury dealt with this irregularity as follows: on the evening of the First Day of the contest, they selected in a short time a replacement Second Day contest paper from a number of alternatives (the Problem Selection Committee had efficiently prepared these alternatives based on the Jury's preferences as expressed during their previous days of deliberations). Thus the Jury and Problem Selection Committee dealt with this irregular situation in a highly efficient and professional manner, and the IMO 2015 contest papers were both of a high standard.

The opening ceremony of IMO 2015, which took place on the 9th of July, was presided over by Her Royal Highness Princess Galyani Vadhana Krom Luang Naradhiwas Rajanagarindra. Certainly, it was a mark of the official recognition given to the status of the IMO contest that a member of the host nation's royal family was in attendance for this ceremony.

The two exams took place on the 10th and 11th of July, starting at 9 o'clock each morning. On each day, $4\frac{1}{2}$ hours were available to solve three problems. During the first 30 minutes, the students were allowed to ask questions if they had difficulties in understanding the formulation of a contest problem.

Usually at the IMO, soon after the students have finished the contest, the Leaders join the students and Deputy Leader at the IMO site. This year was different, however, in that the Leaders remained at the Jury site for the entire IMO duration; instead, the Deputies were moved to the Jury site, arriving in the evening of July 11. Fortunately, the excellent organisation and staffing of the IMO 2015 contest site ensured that sufficient supervision was given to the students at all times.

Upon the arrival of the Deputies, Gordon and I went into the detailed study of our student's scripts. Our team had some nice solutions to some difficult problems. The team performed best on Problem 4, which was a Geometry problem. Paul and Anna gave excellent solutions both of which were worth full marks, and Ioana

gained significant partial credit on this problem by successfully reducing the problem to an easier one. Oisín managed to completely solve Problem 1, which was a great achievement not least because the problem had two distinct parts, meaning that two fundamental insights were needed to completely solve the problem. I noticed that as expected, Problems 2 and 5, which had a rather technical nature and thus favoured the better trained and more experienced students, were somewhat more difficult for our students than in previous years. It was obvious that a higher level of training and preparation could have been useful for our students in dealing with these problems.

On one of the coordination days, the students were entertained with an excursion to a traditional Chiang Mai umbrella production center, the popular Sankampaeng hot springs, as well as a visit to the spectacular temple “Wat Doi Suthep”. This provided some welcome relaxation after the intensive concentration of the contest days.

The final Jury meeting, at which the medal cut-offs were decided, took place on Tuesday 14th July. The closing ceremony was held on the following day, followed by a Farewell Banquet that evening. Gordon and I accompanied the team back to Ireland on Thursday 16th July.

3. THE PROBLEMS

The two exams took place on the 10th and 11th of July, starting at 9 o'clock each morning. On each day, $4\frac{1}{2}$ hours were available to solve three problems. Since the second day of the contest was a Saturday, candidates who were unable to sit the paper on this day for religious reasons were permitted to enter quarantine during that day, and to sit Paper 2 after sunset.

First Day. Problem 1.

We say that a finite set \mathcal{S} of points in the plane is *balanced* if, for any two different points A and B in \mathcal{S} , there is a point C in \mathcal{S} such that $AC = BC$. We say that \mathcal{S} is *centre-free* if for any three different points A , B and C in \mathcal{S} , there is no point P in \mathcal{S} such that $PA = PB = PC$.

- (a) Show that for all integers $n \geq 3$, there exists a balanced set consisting of n points.
- (b) Determine all integers $n \geq 3$ for which there exists a balanced centre-free set consisting of n points.

*(The Netherlands)***Problem 2.**

Determine all triples (a, b, c) of positive integers such that each of the numbers

$$ab - c, \quad bc - a, \quad ca - b$$

is a power of 2.

(A power of 2 is an integer of the form 2^n , where n is a non-negative integer.)

*(Serbia)***Problem 3.**

Let ABC be an acute triangle with $AB > AC$. Let Γ be its circumcircle, H its orthocentre, and F the foot of the altitude from A . Let M be the midpoint of BC . Let Q be the point on Γ such that $\angle HQA = 90^\circ$, and let K be the point on Γ such that $\angle HKQ = 90^\circ$. Assume that the points A, B, C, K and Q are all different, and lie on Γ in this order.

Prove that the circumcircles of triangles KQH and FKM are tangent to each other.

*(Ukraine)***Second Day. Problem 4.**

Triangle ABC has circumcircle Ω and circumcentre O . A circle Γ with centre A intersects the segment BC at points D and E , such that B, D, E and C are all different and lie on line BC in this order. Let F and G be the points of intersection of Γ and Ω , such that A, F, B, C and G lie on Ω in this order. Let K be the second point of intersection of the circumcircle of triangle BDF and the segment AB . Let L be the second point of intersection of the circumcircle of triangle CGE and the segment CA .

Suppose that the lines FK and GL are different and intersect at the point X . Prove that X lies on the line AO .

*(Greece)***Problem 5.**

Let \mathbb{R} be the set of real numbers. Determine all functions $f: \mathbb{R} \rightarrow \mathbb{R}$ satisfying the equation

$$f(x + f(x + y)) + f(xy) = x + f(x + y) + yf(x)$$

for all real numbers x and y .

(Albania)

Problem 6.

The sequence a_1, a_2, \dots of integers satisfies the following conditions:

- (i) $1 \leq a_j \leq 2015$ for all $j \geq 1$;
- (ii) $k + a_k \neq \ell + a_\ell$ for all $1 \leq k < \ell$.

Prove that there exist two positive integers b and N such that

$$\left| \sum_{j=m+1}^n (a_j - b) \right| \leq 1007^2$$

for all integers m and n satisfying $n > m \geq N$.

(Australia)

4. THE RESULTS

Table 2 shows the scores achieved by all contestants on the 6 problems. The Jury tries to choose the problems such that Problems 1 and 4 are the most accessible, while Problems 2 and 5 are more challenging. Problems 3 and 6 are usually the most difficult problems, whose existence on the paper is justified in posing a sizeable challenge even to the top students in the IMO competition. It may be seen from Table 2 that this gradient of difficulty was generally maintained this year also.

The medal cut-offs were as follows: 26 points needed for a Gold medal (39 students), 19 for Silver (100 students) and 14 for Bronze (143 students). A further 126 students were awarded an Honourable Mention (an Honourable Mention is awarded to any student who did not win a medal, but achieved 7 points out of 7 on at least one problem). Overall, only 30.9 % of the possible points were scored by the contestants, compared to the figure of 38.2 % last year. The low level of the medal cutoffs, together with the low number of points scored by the contestants, is a testament to the extreme difficulty of this year's IMO. It is noteworthy that the average scores for problems 1 and 4 were significantly lower than last year.

	P1	P2	P3	P4	P5	P6
0	75	240	479	24	301	514
1	23	32	43	103	60	7
2	14	25	1	28	83	7
3	22	17	2	16	10	11
4	15	14	3	5	8	0
5	18	39	0	3	3	5
6	23	71	4	3	11	1
7	370	122	28	378	84	15
average	5.348	2.971	0.505	5.189	1.709	0.296

TABLE 2. The number of contestants achieving each possible number of points on Problems 1–6.

Table 3 shows the results of the Irish contestants. In light of the extreme difficulty of this year’s IMO, the three Honourable Mentions awarded to the Irish contestants represents a very good achievement. Indeed, 2015 represents the fourth year in a row with at least two Honourable Mentions for the Irish team.

Name	P1	P2	P3	P4	P5	P6	total	ranking
Paul Clarke	3	1	0	7	1	0	12	307
Oisín Flynn-Connolly	7	0	0	0	2	0	9	365
Anna Mustaşa	0	0	0	7	1	0	8	394
Ioana Grigoras	1	0	0	3	0	0	4	465
Luke Gardiner	1	1	0	1	0	0	3	480
Robert Sparkes	0	0	0	1	0	0	1	532

TABLE 3. The results of the Irish contestants

The figures in Table 4 have the following meaning. The first figure after the problem number indicates the percentage of all points scored out of the maximum possible. The second number is the same for the Irish team and the last column indicates the Irish average score as a percentage of the overall average.

The Irish students’ performance on Problem 4 (geometry), as given in Table 4, shows that Irish students are becoming internationally competitive in this subject area. Note that a similar relative performance was seen in a geometry Problem 4 last year (73.9%), which suggests that our students’ improvement in this subject area is somewhat sustained in the last few years.

Problem	topic	all countries	Ireland	relative
1	combinatorics	61.5	28.6	46.4
2	number theory	19.4	4.8	24.5
3	geometry	9.3	0.0	0.0
4	geometry	68.5	45.2	66.1
5	algebra	21.6	9.5	44.1
6	algebra	5.1	0.0	0.0
all		30.9	14.7	47.5

TABLE 4. Relative results of the Irish team for each problem

It is noteworthy that two of the Irish contestants this year won awards in Mathematical Olympiads other than IMO. Luke Gardiner was chosen also for the team representing jointly the UK and Republic of Ireland at the Balkan Maths Olympiad, and won a Bronze medal at this competition. Anna Mustața represented Ireland at the European Girls' Mathematical Olympiad (EGMO) in Minsk, Belarus, in April 2015, and Anna Mustața won a Silver medal at this competition. Congratulations to Luke and to Anna on these great achievements.

It is also notable that a student on the Trinidad and Tobago team, Prasanna Ramakrisnan, achieved a silver medal. This is the second ever silver medal for Trinidad and Tobago. Congratulations to Prasanna on this great achievement.

Although the IMO is a competition for individuals only, it is interesting to compare the total scores of the participating countries. This year's top teams were USA (185 points), China (181 points) and the Republic of Korea (161 points). Ireland, with 37 points in total, shared the 77th place with Albania.

This year, only one student achieved a "perfect score" (42 points). This was Alex Song of Canada, who now moves into the leading position in the IMO Hall of Fame, having achieved 5 Gold medals and one Bronze medal in 6 participations at the IMO.

The detailed results can be found on the official IMO website, which is located at <http://www.imo-official.org>.

5. OUTLOOK

The next countries to host the IMO will be

2016	Hong Kong	6–16 July
2017	Brazil	
2018	Romania	
2019	United Kingdom	

6. CONCLUSIONS

This year’s Irish IMO team performed to a level consistent with that achieved on average over the last few years. The number of points scored was lower than last year, but this fact must be set against the fact that this year’s IMO was at an extremely difficult level.

Since Ireland’s first participation in 1988, the Irish teams have won 8 medals and 34 Honourable Mentions. 13 of these 34 Honourable Mentions were achieved in the last three years. This is evidence that while there are fluctuations in performance year on year, a generally sustained team-level improvement can be detected within the last few years. The extra effort being invested in training activities in the last few years correlates well with this improvement.

However, there are still some key challenges which in my opinion, will be key to improving Ireland’s IMO performance in the longer term:

- (1) Students who achieve excellent results at the IMO are invariably students who immerse themselves in problem-solving activities. While our current training activities are very beneficial to students in that they provide a “way in” to this kind of activity, students must reach a level of independence where they can work on their own. This can involve working on problems with relatively little guidance required from trainers, as well as finding their own problems as well as their own training materials. Challenges for trainers in this context include (a) how to help students to develop this level of independence, and (b) how to keep such students motivated and enthusiastic while having a less intensive level of contact with the students. In my opinion, the remote training is an excellent step in this direction as it demands a higher level of independence of the students, while maintaining a structured form of support from trainers.
- (2) In looking at the general performance of students at the IMO, and in particular on an international scale, it may be seen

that students who get involved in problem-solving activities at an earlier age have a much enhanced probability to succeed at a high level. This point is not independent of Point 1 above, since students who grasp problem-solving at an earlier age will naturally reach independence at an earlier stage, and then have more years to hone their problem-solving abilities in an independent manner. Some important work has begun in the last few years which aims to address this gap in early problem-solving opportunities. For example, the maths enrichment centre at UCC now runs Junior Maths Enrichment Classes for students in second and third year; this initiative is a by-product of the “Maths Circles” initiative which was set up for Junior Cycle students in second level schools in the Cork area in 2013. It would be extremely good if such early-stage regional activities became more widespread, and if teachers can be motivated to support problem-solving activities at a local level. It is worthwhile to note that engagement in such problem-solving activities greatly enhances the general mathematical education of school-level students. It is worth mentioning two mathematics contests in this context. The first is the PRISM (Problem Solving for Post-Primary Schools) competition, which is a multiple-choice contest designed to involve of the majority of pupils in mathematical problem solving; it has a paper for Junior Cycle students and one for Senior Cycle students. This contest is organised since 2006 by mathematicians from NUI Galway, and takes place in October every year during Maths Week. It normally attracts about 2 500 participants. The second is the Kangaroo Mathematics contest, an international mathematics contest which introduces school students aged 7-19 years to Mathematics challenges in a fun and enjoyable way, thus inspiring their further interest and advancement in Mathematics. The Kangaroo contest is undertaken by students in over 60 countries, and over 6 million students took part in 2015. This contest was organised in Ireland this year by Michael Cotter and Mark Flanagan, and attracted about 600 participants. This number is extremely low compared to that of other countries around the world, and strongly indicates that to be successful

in Ireland, the Kangaroo contest crucially requires the support and involvement of enthusiastic Irish maths teachers.

- (3) While our students are well equipped to solve problems at the level of the Irish Maths Olympiad, they have less experience is attempting problems at IMO level. This can be disheartening for students who, at the IMO contest, find themselves unable to comfortably deal with the difficulty level as well as aspects of time management within the exam. Students from other countries have more experience in sitting exams of the difficulty level and duration of the IMO; this is an experience we need to build into our training programmes. However, this must be done carefully, as placing students into an IMO-style examination prematurely could destroy their confidence. This point has a relationship with Point 2 above, as it is envisaged that this difficulty will be easier to address when students have a longer time to reach the point on the training trajectory where they are ready to engage with IMO-level problems.
- (4) The delivery of these new initiatives, as well as the running of training camps and the sending of a full team of six students, together with Leader and Deputy Leader, to the IMO contest requires sustained funding, and to increase the level of provision of training requires increased funding. Efforts to secure funding for these activities should be increased.

7. ACKNOWLEDGEMENTS

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leader to the IMO. In particular, the pre-IMO training camp in Chiang Mai was only possible because of Eoghan's generous sponsorship.

The foundation for the success of the contestants is the work with the students done in the enrichment programmes at the five universities. This work is carried out for free by volunteers in their spare time. Thanks go to this year's trainers at the five Irish centres:

- At UCC:
Kieran Cooney, Gleb Dzus, David Goulding, Finbarr Holland, Desmond MacHale, Ben McKay, Joseph Manning, Anca Mustața, Andrei Mustața, Keegan O'Mahoney and Jonathan Peters.
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- At NUIG:
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- At UL:
Mark Burke, Ronan Flatley, Eugene Gath, Norbert Hoffmann, Bernd Kreussler, Jim Leahy and Gordon Lessells.
- At MU:
Stefan Bechtluft-Sachs, Stephen Buckley, Peter Clifford, David Malone, Ollie Mason, John Murray, Anthony G. O'Farrell, Lars Pforte, Adam Ralph and David Redmond.

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