The International Olympiad in Informatics Syllabus (Background information)

February 25, 2008

1 Authors

The original proposal of the IOI Syllabus was co-authored by Tom Verhoeff[1], Gyula Horváth[2], Krzysztof Diks[3], and Gordon Cormack[4].

The current maintainer of the Syllabus is Michal Forišek[5].

The Syllabus evolves thanks to input from the IOI community. The following people helped to evolve the Syllabus by sending in their feedback: Paul Ashton (NZL), Thomas Barnet-Lamb (GBR), Giorgio Casadei (ITA), Brian Dean (USA), Richard Forster (GBR), Sergejs Kozlovics (LVA), Martins Opmanis (LVA) Pavel Pankov (KGZ), Margot Phillipps (NZL), Peter Taylor (AUS), Velin K. Tzanov (BGR), and Troy Vasiga (CAN).

2 Other International Science Olympiads

This section contains an overview of how other Science Olympiads handle the Syllabus issue.

The international olympiads in physics (IPhO [14]), chemistry (IChO [9]), and biology (IBO [8]) have officially defined syllabi, somehow connected to their regulations. On the other hand, the International Mathematical Olympiad (IMO [12]) does not have an official syllabus, and this has been a deliberate decision. It appears that the younger international olympiads in

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astronomy (IAO [7]), geography (IGeO [10]), and linguistics (ILO [11]) do not have an official syllabus.

2.1 International Mathematical Olympiad (IMO)

The "General Regulations for an IMO" state in C1:

> "The problems should, if possible, cover various fields of pre-university mathematics and be of different degrees of difficulty."

In current IMO practice, only four general topics occur: Geometry, Number Theory, Algebra, Combinatorics. (This is not an official policy.) Note that these topics are often not covered extensively (if at all) by mathematics curricula for secondary education in many countries.

2.2 International Physics Olympiad (IPhO)

The IPhO Statutes state in §5:

> "The theoretical problems should involve at least four areas of physics taught at secondary school level, (see Syllabus). Secondary school students should be able to solve the competition problems with standard high school mathematics and without extensive numerical calculation."

And the IPhO Regulations to §5 state:

> "The examination topics should require creative thinking and knowledge contained within the Syllabus. Factual knowledge from outside the Syllabus may be introduced provided it is explained using concepts within the Syllabus."

The IPhO Syllabus seems to cover all physics generally taught in secondary education. The *Theoretical Part* is divided into 11 subfields: Mechanics, Mechanics of Rigid Bodies, Hydromechanics, Thermodynamics and Molecular Physics, Oscillations and Waves, Electric Charge and Electric Field, Current and Magnetic Field, Electromagnetic Waves, Quantum Physics, Relativity, Matter. The *Practical Part* elaborates on measurement, instruments, errors, approximation and curve fitting, graphing, and safety in laboratory work.

2.3 International Chemistry Olympiad (IChO)

The IChO Syllabus classifies topics on three levels:

Level 1 These topics are included in the overwhelming majority of secondary school chemistry programs and need not to be mentioned in the preparatory problems.

Level 2 These topics are included in a substantial number of secondary school programs and maybe used without exemplification in the preparatory problems.

Level 3 These topics are not included in the majority of secondary school programs and can only be used in the competition if examples are given in the preparatory problems.

The IChO Regulations state in §10 item (3):

> "The organizer cannot give theoretical problems of level 3 (Appendix C) from more than 3 fields and a minimum of 6 tasks should be presented in the set of preparatory problems from each field. Subjects assigned to level 3 can be classified as level 2 if sufficient background is included in the formulation of the problem (e.g. formulas, graphs, structures, equations)."

Also the IChO Syllabus seems to cover all chemistry generally taught in secondary education. The general part of the (new) syllabus is divided into 12 subfields (10 pages in total): The atom, Chemical bonding, Chemical calculations, Periodic trends, Inorganic chemistry, Physical chemistry, Chemical kinetics, Spectroscopy, Organic chemistry, Polymers, Biochemistry, Analytical chemistry. A major part of the syllabus is devoted to safety and the handling and disposal of chemicals. The *Syllabus for the experimental part of the IChO competition* covers: Synthesis of inorganic and organic compounds, Identification of inorganic and organic compounds (general principles), Determination of some inorganic and organic compounds (general principles), Special measurements and procedures, Evaluation of results.

2.4 International Biology Olympiad (IBO)

The IBO Rules state in §4.1, concerning the selection of topics for the competition:

> "All disciplines of biology are acceptable for the IBO."

In Appendix I, it is stated that "the Theoretical test [...] should cover the following 7 topics in the indicated proportions": Cell biology (20%), Plant anatomy and physiology (15%), Animal anatomy and physiology (25%), Ethology (5%), Genetics and Evolution (20%), Ecology (10%), Biosystematics (5%). Each of these topic areas is described in more detail (8 pages in total). The section on *Basic Skills for the Practical Part of the IBO* covers such things as science process skills, basic biological skills, biological methods, physical and chemical methods, microbiological methods, statistical methods, and handling of equipment.

3 Purpose and Motivation for an IOI Syllabus

One of the main objectives of the IOI is "to bring the discipline of informatics to the attention of young people" (Statute S1.7 from the IOI Regulations). The olympiads in mathematics, physics, chemistry, biology, and geography are in the fortunate position that these sciences are regular exam topics in secondary education in most countries. Informatics, however, is not in this position. And even if it is, the topics of algorithmics and programming often receive minimal attention.

Algorithmics and programming were chosen as the main topics for the IOI competition; these were the only areas for which a sufficient number of self-taught contestants could be found. The wide availability of personal computers with easily accessible programming tools has helped create this situation. These areas are, in addition, fundamental to computing science.

Over the years, the difficulty level of IOI competition tasks has increased considerably. Among the best contestants, performance has certainly improved to warrant some increase in difficulty. But this improvement is not so much manifested by the 'average' contestant. In part, this disparity may be attributed to the lack of systematic education in computing science.

An IOI Syllabus would benefit:

- candidate IOI contestants,
- coaches of IOI contestants,
- teachers of computing science in secondary education,
- developers of curricula in computing science for secondary education,
- authors of computing science textbooks for secondary education,
- creators of competition tasks for the IOI and similar competitions,
- organizers of computing competitions,

- interested outsiders.

We must also point out possible dangers in having an official IOI Syllabus. Such a syllabus could easily obtain the status of a dogmatic standard. Any attempt to step outside the scope of the syllabus could be blindly suppressed, thereby stifling innovation. The process of deciding about the appropriateness of candidate competition tasks could be paralyzed by time-consuming discussions about the syllabus. Coaches and contestants could be misled to believe that knowing what is in the syllabus will guarantee some success in the competition.

In view of these dangers, the syllabus must contain information concerning its proper use, must be flexible, and must include a mechanism for its ongoing revision.

Finally, there are a number of challenges in composing an IOI Syllabus, such as obtaining sufficient consensus on form and content, ensuring clarity and precision (a single interpretation), and ensuring sufficient completeness. We hope that this article will help address these challenges.

4 Roles of Mathematics in Computing Science

It is important to understand the various roles that mathematics plays in computing science. These roles are often confused, especially in secondary education. One can distinguish the following roles of mathematics in computing science:

1. *As a problem domain.* For example, design an algorithm to compute the greatest common divisor of positive integers A and B.

2. *As a language to express formalized models*, both in the problem analysis and the solution domain. For example, a street network can be modeled as a directed graph.

3. *As a language to reason about models.* For example, if a graph has no cycles, then one can draw the conclusion that it has fewer edges than vertices.

4. *As a language to reason about computations, algorithms and data structures, and their implementation*; in particular, to reason about functional correctness, termination, and efficiency. For example, the binary search algorithm applied to an array of N elements, terminates in $\mathcal{O}(\log N)$ steps.

Note that the second and third roles (concerning the formulation of and reasoning about models) are present in most branches of science. The type of mathematical models depends to some extent on the science in question. For instance, group theory (to study symmetry), differential equations, numerical analysis, probability theory and statistics are more relevant in the natural sciences. Logic and discrete models involving combinatorial structures are more relevant in computing science.

The first and last role (as problem domain and for reasoning about computations) are more specific to computing science. Mathematical knowledge concerning the first role (as problem domain) could be avoided by allowing only competition tasks that involve non-mathematical problem domains. However, such a restriction would be unrealistic:

- There are few non-mathematical domains that all IOI contestants can be expected to know well enough. Such knowledge is often difficult to present succinctly and clearly as part of the problem statement in an attempt to compensate for deficiencies.
- Mathematics as a problem domain has the advantage that it allows very compact and precise problem statements. Furthermore, a rich problem domain is available through elementary mathematics, which should be well within reach of students from secondary education.
- Mathematics in the second role (to express models) is indispensable for the development of algorithmic solutions, even when dealing with algorithmic problems from a non-mathematical domain. There is a significant overlap between mathematics in the first and second role.

Mathematical knowledge in the first and second role mostly concerns concepts, terminology, and notations. Verhoeff [18] presents a classification of elementary concepts, terminology, and notations with respect to their usability in IOI competition tasks. This classification could be used in an IOI Syllabus. It should, however, be augmented with some relevant methods and techniques to combine and apply these elementary notions.

Mathematical knowledge in both the third and fourth roles both concerns *reasoning*, viz. about models and about computations. This skill demands some familiarity with mathematical logic. Contestants need the ability

- to express conjectures and theorems (even if only informally), and
- to construct and understand logical deductions, applying theorems.

They are also expected to know certain (elementary) mathematical theorems.

Note that the mathematics in the fourth role (reasoning about computations) is most specific to computing science, and is often not encountered in other branches of science. Unfortunately, it tends to be underexposed in secondary education.

Any IOI Syllabus must clarify what mathematical knowledge is important in what roles. However, it should always be kept in mind that the IOI is an informatics competition and not a math contest.

5 General Principles behind the Syllabus

Our first principle is that we intend to capture the current accepted IOI practice in the syllabus. There may be reasons for changing the IOI and they may become even clearer by writing a syllabus, but it is not our goal to reform the IOI through the syllabus.

Because it does not seem to be documented anywhere, we feel that a brief explanation is in order as to why the IOI competition focuses on algorithmic problem solving and programming. This narrow focus is similar to the IMO, and contrasts sharply with the IBO, which strives for comprehensive coverage of the discipline.

The IOI competition is not meant to be an ordinary exam that tests whether the participants have learned their lessons. It is aimed at discovering and challenging talented pupils. For this, it was decided that depth rather than breadth, and innovative problems rather than standard exercises are of primary importance. To minimize the advantage of having special prior knowledge, the topics should be elementary and fundamental.

The reasons for requiring programmed implementations of algorithms are[6]:

- There is no standardized abstract algorithm notation suitable for use in the IOI. Programming languages have a well-defined syntax and semantics[7], and can stand in to express algorithms.
- Pupils interested in computing typically know a popular programming language. It is easy to learn the basics of programming.

[6] Also see §7.2 of [1]: "Where does programming fit in the introductory curriculum"

[7] We refer to a semantics in terms of an abstract machine, rather than via a specific compiler.

- Implementing an algorithm as a computer program requires you to fill in all the gaps. You cannot afford to be vague anywhere.
- Programs can be executed and thereby facilitate automated evaluation to some extent.
- Producing a working program is a satisfactory experience. This is common to all engineering disciplines.
- Programming is one of the fundamental topics of computing science.

Nevertheless, the overwhelming details of modern computing platforms (programming languages, programming tools, operating systems, system and processor architecture) should not become an obstacle to success.

Currently, imperative programming languages are used in the IOI, but the authors wish to point out that functional languages would also be suitable for this purpose.

5.1 The Broader Context of Algorithms

It is tempting simply to list various algorithms and data structures, and underlying design techniques that are relevant to the IOI competition. Rather than collecting a large number of topics for an IOI Syllabus, we find it more valuable to state some general principles to guide the inclusion and exclusion of specific topics.

The decision about the relevance of a particular algorithm should be based not only on how complicated the algorithm is when written in pseudocode. It is important to distinguish

- how complicated an algorithm is (in a static sense) and
- how advanced the reasoning behind the algorithm's design is, concerning correctness and/or efficiency[8].

Here are some typical examples:

- The pseudocode for the *Knuth-Morris-Pratt string search algorithm* is not complicated, but the reasoning behind its correctness is.
- The *linear median selection algorithm* by Blum et al. is not complicated, but the proof of its worst-case linear time efficiency is.

[8] In current IOI practice, algorithms are only assessed for functional correctness and time/space efficiency, and not for other qualities.

- Hoare's *Quicksort* is not a complicated algorithm, but the analysis of its average-case running time involves advanced mathematics.

Whether or not a specific algorithm is to be considered prerequisite IOI knowledge should also be based on the (mathematical) techniques relevant for the underlying reasoning.

It is also important to distinguish

- how seemingly straightforward an algorithm is and
- how demanding it can be to implement it as an actual correct and efficient computer program.

Again, an example may help:

- *Kruskal's algorithm* for computing a minimum spanning tree is simple when expressed in terms of an abstract data type that maintains a partition of the nodes, but an efficient implementation of this data type is much more involved.
- *Algorithms for determining whether two line segments intersect* involve a careful case distinction, which can easily lead to hard-to-spot implementation errors.

It seems inappropriate to ask contestants to develop algorithms that require advanced reasoning techniques to understand their correctness and/or efficiency, even if the algorithms themselves are not complicated.

It may also not be a good idea to ask contestants to develop algorithms whose implementation is intrinsically troublesome, even if the abstract algorithm is not so complicated. Keep in mind that the IOI is not just an implementation contest.

Thus, the required reasoning techniques and implementation techniques play a fundamental role in selecting topics for the IOI Syllabus.

5.2 Main Topic Areas for an IOI Syllabus

To organize the relevant topics we have consulted the ACM curriculum models for college [1] and K–12 [2]. The latter refers to, and is in part derived from, the former, but the K–12 curriculum is too restrictive for our purposes. We have chosen to use the Computing Curricula (CC2001) topics of [1] as a basis for our syllabus proposal. Because CC2001 is aimed at university-level education, it offers the required depth. It also contains many topics that will not occur in the IOI competition. However, we think that it is good to be able to point out explicitly what further topics exist in computing and are not relevant for the IOI.

Taking a top-down view, we arrive at the following main areas:

- Mathematics, in particular, Discrete Structures (DS), but with small additions from number theory and geometry;
- Computing Science, in particular, Programming Fundamentals (PF), and Algorithms and Complexity (AL);
- Software Engineering, in particular, its application "in the small";
- Computer Literacy, in particular, use of a computer for program development and other competition-related purposes (e.g. submitting files via a web browser, printing).

Some basic science and engineering skills and methods will be included under Computing Science and under Software Engineering respectively.

6 Conclusion

Contestants are well served when given clear, correct, and timely guidelines as to what they may expect in a competition. They are poorly served when unanticipated expectations are placed on them. While no syllabus should be construed to supplant reason or discretion, we advance the current proposal as a framework through which to make the expectations on IOI contestants more clear.

The proposed syllabus provides a mechanism for contestants, educators, and contest designers to achieve a better common understanding of the skills and knowledge assumed of contestants. Space does not permit a detailed rationale for every choice; the authors have relied on their experience with international competitions, an examination of past tasks, and an analysis of benefits and drawbacks arising from the inclusion or exclusion of certain concepts and techniques. No doubt some of these choices are controversial — we hope that the structure we have presented will help to guide and focus the ensuing debate.

It is desirable to cite text books and other training materials that contestants and educators might use in preparation for the IOI. None of which we are aware fits the syllabus perfectly; current materials would have to be used selectively so as to be consistent with the syllabus. A book covering a substantial fraction of the syllabus topics is [3].

Our immediate aim is that the IOI adopt a syllabus based on our proposal. In the medium term, we seek to identify specific resource materials supporting each of the included topics. In the long term, we believe it is appropriate to develop and distribute IOI-specific educational and training materials.

The authors wish to acknowledge the inspiration of the IOI Workshop [16].

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