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Power law distribution of student’s achievement in stem: indication of ability or failure

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Abstract

Analyses of results on recent state matura examination in Croatia suggest power law distribution in physics similar to corresponding examination on Advancing physics in G. Britain. Same distribution has been observed in some other STEM subjects (e.g. informatics and mathematics) in Croatian matura examination. Interpreting results through the lens of Gauss distribution (traditionally prevailing in educational community) lead to wrong conclusions. Grounded on heuristic argument that nature of school knowledge differ, we justify choice of power law distribution as more appropriate for analyzing STEM subjects, not questioning suitability of Gauss distribution for analyzing achievement in humanities and arts.

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1. Introduction

State matura examination in Croatia begun in 2010. Students successfully passed the 4nd class of gymnasium or vocational schools (in average at age of 19) are eligible to undergo matura examination. The purpose of matura is evaluation of student’s school achievements. In spite of, according critics (Bezinović, 2010), numerous drawbacks (inclination to facts testing, does not

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evaluate application of knowledge in everyday life, does not examine critical thinking, does not assess ability for hypotheses making, reduces teaching on preparation for exams instead of developing student’s high cognitive competences and creativity), matura, from its inclusion, also serves as university entrance exam. It was questioned matura exam as appropriate instrument of university success prediction. Some universities departments (arts, medicine, law, physical) add some domain specific entrance examination. It is expected that matura in future be shaped more as certification of high student’s school achievements.

In the shadow of controversies concerning the purpose of matura state examination, which attract public attention, we accept challenge (Bezinović, 2010) of discussion on metric characteristics of exam tests. While Bezinović (2010) blames absence of predefined (expected) metric characteristics in exam preparation, we claim that authors of matura exam implicitly expected Gauss distribution of results. It is obvious if one see post tests analyses, made by same educational agency responsible for matura exam realization. Our position is that Gauss distribution is appropriate for analyzing achievement in humanities and arts, but leads to wrong conclusions applied on exam data concerning STEM subjects (especially physics and informatics). We propose power law distribution (Newman, 2006) as superb to Gauss in analyzing results in physics and informatics. Similar distribution of data on A-level physics examination (Advancing physics) in G. Britain is described (A-level results, 2012). Finally, we pose heuristic argument that difference in empirical data for STEM versus humanities school subjects on matura examination may stem from somewhat different nature of corresponding school knowledge.

2. High school curriculum and knowledge assessment

High school curriculum in Croatia is composed of mainly two parts: STEM (mathematics, informatics, physics, chemistry, biology and technology in some vocational schools) and humanities (mother languages, classic and foreign languages, history, arts, philosophy and religious) subjects. Some social (sociology, economy, geography) subjects, physical training and promoting citizenship and health form rest of curriculum but with minor impact on student’s school success. Obligatory subjects on matura examination are mother language (Croatian at the most), mathematics and one foreign language (English at the most). Students can choose elective subjects too.

Exam questions are based on the learning outcomes. Besides multiple choice questions, some tasks are open ended or in essay form to access high cognitive competences and creativity.

3. Results of 2012 Croatia matura exam in physics, informatics and languages

3.1. Croatian and English language as typical instances of humanities subjects

Results of examination on Croatian language (in gymnasium and vocational schools) are shown in Fig.1.
Similar results, shown in Fig. 2, are obtained for foreign language (at the most English).
3.2. Physics and informatics as representatives of STEM subjects

Results of examination on physics (in gymnasium and vocational schools) are shown in Fig.3.

![Fig.3. Distribution of percent success on physics](image1)

Results of examination on informatics (in gymnasium and vocational schools) are shown in Fig.4.

![Fig.4. Distribution of percent success on informatics](image2)
On each graph on horizontal axe is shown percentage of successfully solved tasks, while on vertical axe is shown percentage of students who had corresponding success. E.g. closer examination of upper figure reveals that 15 % of students (i.e. 420) successfully solved 30 % tasks (multiple choice questions and open ended tasks) which qualified them for mark two because examination agency considered success of 25 % as lower limit to pass exam on informatics.

4. Analyses of results

4.1. Results on humanities exams are well approximated with Gauss distribution

Results of exams on four school subjects (Ispiti državne mature 2011/2012, 2012) shown on previous graphs has been analysed by state examination agency responsible for matura exam realisation. We agree with treating data on languages exams as belonging to Gauss distribution. It is obvious from the graphs (Fig.1 and Fig.2) that exam data for languages are very well approximated with bell-shaped Gauss distribution. Majority of students (60 %) is grouped in middle bin with mark good (3). The rest of them are distributed in class with mark enough (2) or with mark very good (4) or excellent (5). A certain degree of skewness to the right show an over dominance of reproduction type questions which is characteristic of school subjects inclined to transfer of cultural heritage. Also, the mean on Croatian language for gymnasium population is greater (76 %) than for vocational schools (62 %), what is expected when knowing higher primary school grades of students entering gymnasium.

4.2. Results on STEM (physics and informatics) are to be approximate with power law distribution

Key point of our work is that we disagree with treating exam data on physics and informatics as appropriate to be described by Gauss distribution. Visual inspection of graphs (Fig.3. and Fig.4.) is enough to reject attempt of psychometric experts to push empirical data under the bell of theoretically imposed Gauss distribution (green curve on figures). Quantitative analyses is not necessary to accept need for another distribution, better approximating data. We propose power law distribution. Quantitative proving of appropriateness of that distribution and advantages over possible choice of some exponential distribution will not be undertaken in this work (Clauset, 2009). For the first approximation it will suffice visual inspection.
Here we have to emphasize that values on the graph are not crude data from physics exam in Croatia 2012. We made one important correction. Mark one (1) is missing on upper graph. Really, about 20% students on that exam did not pass exam because they earned less than lower limit of 22% successfully solved questions. We claim that these students had not been allowed to approach the matura exam. They have positive finished 4th class as result of constantly lowering of threshold in Croatian school system. Result on matura exam clearly indicates that they had not acquired competences in course of four year learning of physics. Same conclusion is concerning informatics result too.

5. Comparison with results of advancing physics exam in G. Britain
It is very suggestive to compare results of Croatian matura exam on physics with similar state examination on Advancing physics curriculum in Great Britain. That curriculum has similar coverage of themes, use of mathematics and cognitive load expectation (problem solving) but is realised more compactly, in two year. To be consistent with marking schemas as used in Croatia and other continental Europe we transformed British marking schema so that level of success A’ is mapped to mark excellent (5), level A to mark very well (4), level B to mark good (3), levels C,D and E are mapped to single mark enough (2). Several percents of students which had not passed exam are neglected, being inside statistical error. It is obvious good fitting of data to power law distribution whose mathematical expression has form:

\[ y = x^\alpha \]

\[ a \text{ is parameter } \approx -2,5 \]

Empirical data partially depart from theoretical distribution in range of level A, where has more than expected students. We guess that reason is very competitive British high school system and more than expected fraction of, STEM inclined students, capable to study science and engineering faculties.

6. Does different nature of school subject’s knowledge cause different exam data?

What's matter interpreting results of all school subjects as susceptible to Gauss distribution? First obvious impression is success in humanities and failure in STEM subjects. School authority in Croatia, parents and media proclaimed that schools made good jobs in humanities subjects while teacher of STEM subjects did not. We disagree with this interpretation insisting that results of STEM subjects are not to be expected to behave according to law of Gauss distribution, but, instead, to power law distribution.

Power law distribution is appropriate when describing phenomena in which huge events happen to occur extremely rare, smaller events occur often but very small events occur quite often. Examples of such events are numerous:

- distribution of earthquakes (huge earthquakes are extremely rare, small are very often)
- number of injuries in wars (very rare there are a lot of injuries in war, usually there are only several),
- number of cities with certain population (there is little cities with population like New York, but a lot of cities with small population),
• number of islands with area larger than certain (little islands with great area, almost infinity islands with very small area)
• etc

Applied on school knowledge based on mathematical reasoning (STEM subjects), heuristics is next:

• not too much students are ready to face unknown situation and solve problems using mathematical reasoning, majority of them are conform dealing with only familiar tasks. If so, rare students can earn excellent mark on exam, and the most of them are satisfied with just passing exam. Fast changing nature of informatics and sciences, process of constant construction and deconstruction of meaning fare from equilibrium is not acceptable to majority, satisfied only with using new technology. But for development and solving complex problems our civilization is faced, involvement of talented students which outperformed on exams is crucial. Science has nature of constant development and improvement, so keen to talented minority ready for experimenting. Schools and teachers providing power law distribution of student’s success on STEM subjects work good job.

What about majority passing good on humanities exams?

• they are of outmost importance, because only well educated majority of citizenship can be guaranty of preserving values and cultural heritage of our civilisation. Creativity is key word in education (Robinson, 2006), but one can not expected that the biggest part of recent cultural artefacts will resist the judgement of future. The Bible, Mozart or Picasso have to be transfered to next generation. One do not expect better music than composed by Mozart, maybe only different.

To conclude, school education is balance between preserving and change, we need all values, but have to be aware of them when measure educational outcomes.

7. References


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