Engineering Analytic Principles and Predictive Computational Skills for K-12 Students:

Statistics on High School Age-Possible Engineering Economics Topics to Engineering and Technology Educators and Curriculum Developers

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Introduction

In the most recent decade, middle and high schools across the United States have tried to incorporate engineering design into traditional technology curriculum, with various degrees of success; however, "the fragmented focus and lack of a clear curriculum framework" had been "detrimental to the potential of the field and have hindered efforts aimed at achieving the stated goals of technological literacy for all students" (Smith and Wicklein, 2007, pp. 2-3). A report issued on September 8, 2009, by the Committee on K-12 Engineering Education established by the National Academy of Engineering and the National Research Council, titled *Engineering in K-12 Education: Understanding the Status and Improving the Prospects* (2009), confirmed the existence of similar problems, such as the "absence of a clear description of which engineering knowledge, skills, and habits of mind are most important, how they relate to and build on one another, and how and when (i.e., at what age) they should be introduced to students" (pp. 7-8; p. 151). K-12 engineering curriculum in the United States remains skeletal so far; its main focus is on generic design process using a "trial-and-error" approach; and the coverage of analytic and predictive knowledge contents is generally in an "ad hoc" fashion and not sequentially structured. In response to the above problems, many scholars have voiced their points of view. Hacker (2011) pointed out that "trial-and-error problem solving takes substantial classroom time, and often does not allow teachers and students to focus on the most important learning goals." Lewis (2007, pp. 846-848) discussed the need to: (a). establish a "codified body of knowledge that can be ordered and articulated across the grades" instead of short term efforts focused on a particular topic or unit, and (b). make engineering education a coherent system with the creation of content standards for the subject area, in line with science and technology education.

High School Age-possible Engineering Topics (Engineering Economics)

Research Questions and Practical Conceptual Framework

The above evaluation of the current status of K-12 engineering education in the United States could lead to these questions: (1). "How could we determine what engineering analytic principles and predictive skills from what subject should be taught to students at what Grade in the K-12 curriculum, in a rational and scientific way?" (2). "How could we make sure that what students learned from high school engineering curriculum could be transferred to university programs?" Based on the way engineering curriculum has been historically developed, I have constructed a practical conceptual framework to answer the above two questions. If we read any typical information sheet for university level undergraduate engineering program, we will see that the courses are organized in a sequence based on the fulfillment of pre-requisites in mathematics, physics, chemistry, technology and previous engineering courses; and these pre-requisites are usually listed in course descriptions. Therefore, we could hypothesize that the same principles used historically in the development of curricular structure in university undergraduate engineering programs could apply to the selection of K-12 age-possible engineering analytic principles and predictive skills for any particular Grade, and for any particular subject of engineering. In addition, based on the fact that university undergraduate engineering textbooks, especially those used in foundation courses (such as statics, dynamics, strength of materials, engineering economics, etc.), all contain portions that are based on pre-calculus mathematics and scientific principles which are usually covered in K-12 mathematics and science courses, we could also hypothesize that these pre-calculus portions of engineering topics could possibly be taught at various Grade levels, provided that the pre-requisite pre-calculus mathematics and science principles have been covered in previous Grade levels (or in some cases, taught as special topics); and the coverage of such pre-requisites are usually mandated by the performance standards in mathematics and science established by any particular state. This conceptual framework has been used as a practical tool for the initial determination of 9th grade age-possible statics and fluid mechanics topics. The step-by-step procedure or the "ideal" procedure (Locke, 2009a, pp. 26-27) includes the following (*Figure 1*): (1) selection of data source (selection of popular university undergraduate engineering textbooks and other instructional and learning materials); (2) analysis of data source (careful reading of every paragraph in the body text as well as relevant computational formulas to find and record the pre-requisite mathematics skills and scientific principles needed for each topic; (3) comparison (between the recorded mathematics and science pre-requisites, and my interpretation of the mandates of the Performance Standards for Mathematics and Sciences of the Department of Education of a selected state, in this case, the State of Georgia, to determine the Grade level for the age-possible inclusion of the topics). I selected the State of Georgia's Standards as a reference for the research because (1) the University of Georgia, my alma mater, gave me the opportunity to study the subject of K-12 engineering education and (2) many professors at the College of Education and the College of Agricultural and Environmental Sciences (Department of Biological and Agricultural Engineering) offered me valuable advice and criticism. Due to the fact that the variations among the K-12 mathematics and science performance standards of the 50 states are not substantial, the outcomes of the research should apply to other states with some reasonable adaptations.

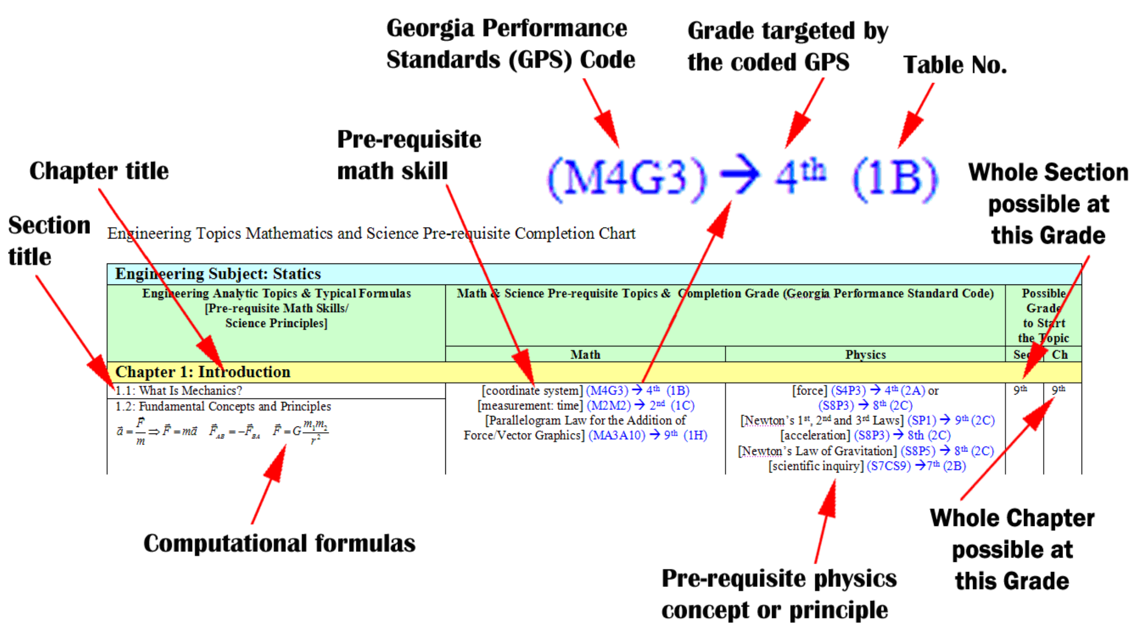

Figure 1. The original research data table used to initially determine high school 9th Grade age-possible statics topics.

After completing all lower-division undergraduate mechanical engineering courses plus two upper-division ones, and conducting a careful and fairly thorough examination of many other college-level engineering textbooks, I have made the conclusion that all engineering textbooks include the following major elements:

(1) **Descriptive and informational:** Paragraphs, data tables, charts, graphs, illustrations and photos that explain natural phenomena, scientific principles, properties of materials, behaviors of structures and systems, in "plain English," without going into the details of analytic and predictive computations using formulas based on mathematics skills.

(2) **Analytic and predictive:** Mathematics-based formulas, including those used in pre-requisite physics and chemistry concepts, principles and analysis, and those used in engineering analysis and design, and step-by-step procedures, including sample problems with solutions, for analyzing problems, predicting outcomes, or designing systems or products; and these mathematics skills could be at either pre-calculus level, i.e., arithmetic, trigonometry, geometry, algebra, or at calculus level, i.e., integration and differentiation.

In terms of the relative amount of each of the above major elements in the overall composition of the content of the textbooks, all sets of college-level engineering textbooks used in any particular course or subject could be classified into three major categories; i.e., (1) Mixture of Pre-calculus and Calculus, (2) Heavily Pre-calculus, and (3) Heavily Descriptive and Informational. It takes different amounts of time and efforts to examine different sets of textbooks under different categories in order to tentatively determine and select K12 age-possible engineering content knowledge and skills, including descriptive and informational materials, analytic and predictive computational formulas and step-by-step problem solving procedures; and the procedure of this examination include (a) interpretation of the mandates of the Performance Standards for Mathematics and Sciences of the Department of Education of a selected state, in this case, the State of Georgia, to create a coded list of items of mathematics, physics and chemistry concepts and skills, such as *M4G3→4th Grade (1B)* shown in *Figure 1*, from the original online government document, to be used for comparison with the mathematics, physics and chemistry concepts and skills found from the relevant textbooks; (b) paragraph-by-paragraph or page-by-page examination of the selected textbooks for the extraction and documentation of the mathematics, physics and chemistry concepts and skills needed to understand the content and to solve homework problems; and (c) comparison between the interpreted, itemized and coded lists of Performance Standards and the items extracted from the textbooks, to tentatively determine and select sections and chapters in the textbooks that could be K12 age-possible. In the United States, we have a very decentralized management structure for the publication and adaptation of textbooks; and this is especially true for textbooks used in the institutions of higher education where professors usually select textbooks out of their own choices free from government intervention; for any college courses or subject, we can find several excellent and popular textbooks, all of them cover a majority of similar topics plus a small number of different ones; therefore, to be holistic and comprehensive, at least two of the most popular textbooks will be used, one as the "primary source of data" and the rest as "secondary source of data" and "additional sources of data." The nature of composition of the above-mentioned three major categories of textbooks and the average amount of time it takes for their examination are as follows:

1. **Mixture of Pre-calculus and Calculus:** Textbooks under this category include, for the undergraduate mechanical engineering major, those used in the courses of statics, dynamics, strength of materials, electric machines, mechanical design, aerodynamics, fluid mechanics, electrical circuits, heat transfer, thermodynamics, and others. For these textbooks, calculus and pre-calculus skills are used intermittently throughout substantial portions of most of the chapters. These textbooks are usually voluminous and the numbers of pages range from 600 to 900. Therefore, a thorough investigation of all paragraphs, formulas, and even sample problems in the textbooks, and a very detailed record of all pertinent information in tabular forms is needed to determine and to select K-12 age-possible engineering topics for different grade levels. My research projects on the subjects of statics and fluid mechanics have been completed this way. This procedure is very thorough and time-consuming and for one subject, it takes between 3 to 5 weeks for one textbook (the "primary source of data"), and additional 1 to 2 weeks for another textbook (the "secondary source of data" used to pick up additional K12 age-possible topics); these amounts of time cover careful reading of all chapters, sections, and even appendices and glossaries throughout the entire textbooks, analysis and recording of mathematics, physics and chemistry concepts and skills involved, typing of titles of chapters, sections, formulas, names of pre-requisite items, write-ups of conclusions, as well as a section-by-section review. Typing of titles of chapters, sections, and formulas could take up to one third of the above amounts of time needed for the research. It is the exact or "ideal" procedure advocated in my published Vision Paper.
2. **Heavily Pre-calculus:** Textbooks under this category include those used in the courses of engineering economics, probability and statistics, and others. For these textbooks, the mathematics skills involved in the majority or even the overwhelming majority of chapters and sections are at pre-calculus level; the calculus skills involved in a few sections or chapters are the very beginning ones such as [first integral] and [first derivative]; and the principles and skills related to physics and chemistry are also the very basic ones; therefore, a less time-consuming approach is used to determine and select K12 age-possible engineering topics, by carefully examine each page in the textbooks to record (1) the pre-calculus level mathematics skills as well as physics and chemistry concepts, principles and skills found in all pages; (2) the calculus-level mathematics skills found in some pages, the page numbers where these calculus skills are found, the numbers and names as well as the pages ranges of the sections involving the calculus skills; and (3) result of comparison between the pre-calculus skills as well as physics and chemistry concepts and skills found throughout the textbooks, and the mandates of the Performance Standards for Mathematics and Sciences of the Department of Education of a selected state, in this case, the State of Georgia, to determine the earliest Grade level for the age-possible inclusion of the topics. My research projects on the subjects of engineering economics, probability and statistics, and engineering materials have been completed this way. This procedure is fairly thorough but much less time-consuming because no record of mathematics-based formulas or typing of the names of chapters and sections of the textbooks that involve only pre-calculus mathematics skills is needed, and for one subject, it takes between 5 to 7 days for one textbook (the "primary source of data") and additional 2 to 4 days for another textbook (the "secondary source of data"). These amounts of time cover careful reading of all chapters, sections, and even appendices and glossaries throughout the entire textbooks, analysis and recording of

mathematics, physics and chemistry concepts and skills involved as pre-requisites, typing of page numbers and titles of chapters and sections involving calculus stills as well as numbers of the individual pages involved, write-ups of conclusions, as well as a section-by-section review. It is a convenient and "ad hoc" revision of the "ideal" procedure advocated in my published Vision Paper.

3. **Heavily Descriptive and Informational:** Textbooks under this category include those used in the courses of introduction to science, engineering and technology, ethics and professionalism in engineering, and others. These textbooks involve little or no mathematics skills; their primary goal is to expose students to broad knowledge about engineering, science, technology, as well as their relationship with "other stuff" such as society, ecology, legal system, philosophy, and others. Similar method as the one used for the "Heavily Pre-calculus" textbooks is used here but the amounts of time spent is substantially reduced because, for the "Heavily Descriptive and Informational" textbook, mathematics, physics and chemistry pre-requisites are rarely involved. For one subject, it takes between 1 to 3 days for one textbook (the "primary source of data") and additional 1 to 2 days for another textbook (the "secondary source of data"). These amounts of time cover careful reading of all chapters, sections, and even appendices and glossaries throughout the entire textbooks, analysis and recording of a few mathematics, physics and chemistry concepts and skills involved as pre-requisites, write-ups of conclusions, as well as a section-by-section review. It is a convenient, "ad hoc" and more drastic revision of the "ideal" procedure advocated in my published Vision Paper.

For the particular subject of engineering economics, the knowledge content covered in the reading of the textbooks selected in this research, classroom lecture, homework assignments and quizzes or examinations are, for all practical purposes, using predictive and computational formulas based on pre-calculus mathematics concepts and skills, with only one section with 4 pages in the selected Textbook 2 involving a few beginning calculus skills such as [first integral] and [first derivative], and the involvement of concepts and skills in physics and chemistry is minimal and not applicable. Therefore, for all practical purposes, all pages of the textbooks used as reference sources have been carefully and thoroughly examined to record the pre-calculus-level mathematics skills, physics and chemistry concepts and skills, as well as calculus level ones with the numbers and names of relevant chapters or sections. An overall analysis of the data so collected has then been conducted to reach a practical conclusion about the selection of K12 age-possible topics from the selected Textbooks 1 and 2.

Sources of Data

Table 1 lists (1) the college-level Textbooks 1 and 2 used for the extraction of analytic and predictive principles and computational formulas related to the subject of engineering economics, and (2) the instructor's or student's solution manuals used to double-check for the mathematics computational skills needed for the study of various topics of engineering economics contained in the selected Textbooks 1 and 2.

Table 1. Data Source (Engineering Economics Textbooks)

	Textbook 1	Textbook 2
Title	Engineering Economic Analysis, 10th Edition	Engineering Economy, 13th Edition
Authors	Donald G. Newnan, Jerome P. Lavelle, and Ted G. Eschenbach	William G. Sullivan, Elin M. Wicks, and James T. Luxhoj
Publisher	Oxford University Press	Prentice Hall (Pearson)
Year	2009	2006
ISBN	978-0-19-539463-4	0-13-148649-7
Number of Pages	605	664

Initial Determination of High School Age-Possible Engineering Economics Topics

The outcome of this research is very encouraging. Tables 2A and 2B indicate that: (1). **for Textbook 1**, 100% of all sections, and 100 % of the volume in the selected Textbook 1 is based on pre-calculus mathematics skills; and (2). **for Textbook 2**, 99.3% of all sections, and 99.4 % of the volume is based on pre-calculus mathematics skills; and (3) no prior mastery of physics and chemistry concepts or skills is needed for reading and homework assignments.

Table 2A. Statistic on Textbook 1 (Engineering Economic Analysis, 10th Edition, by Donald G. Newnan, Jerome P. Lavelle, and Ted G. Eschenbach)

<table>
<tr><th colspan="3">Pre-Calculus Level Concepts and Skills Found in All Chapters/Sections</th><th colspan="2">Page Information</th></tr>
<tr><th>Mathematics</th><th>Physics</th><th>Chemistry</th><th>Page Numbers</th><th>Number of Pages</th></tr>
<tr><td>[four operations], [power], [root], [inequality], [log], [natural log], [limit], [infinity], [chart], [flow chart], [graph], [percentage], and [summation]</td><td>N/A</td><td>N/A</td><td>1-605</td><td>605</td></tr>
<tr><th colspan="3">Calculus Level Mathematics</th><td colspan="2" rowspan="2"></td></tr>
<tr><th>Concepts and Skills</th><th colspan="2">Chapters/Sections</th></tr>
<tr><td>N/A</td><td colspan="2">N/A</td><td>N/A</td><td>0</td></tr>
<tr><td colspan="5">Chapters with Pre-Calculus Level Mathematics Concepts and Skills ONLY
Volume = Total Number of Pages – Number of Pages with Calculus Skills = 605 - 0 = 605 pages
Number of Chapters = Total Number of Chapters – Number of Chapters with Calculus Skills = 17 – 0 = 17 chapters</td></tr>
<tr><th colspan="5">Statistical Summary</th></tr>
<tr><td colspan="2">Total Number of Pages Covered by Text
(Excluding “Index”): 605</td><td colspan="3">Total Numbers of Chapters:
17</td></tr>
<tr><td colspan="2">Percentage of Pre-Calculus Sections
$\%_{\text{Pre-Calculus}} = \left(\frac{\text{Number of Pre-Calculus Chapters}}{\text{Total Number of Chapters}}\right)(100\%)$
$= \left(\frac{17}{17}\right)(100\%) = 100.0\%$</td><td colspan="3">Percentage of Sections with Calculus Skills
$\%_{\text{Calculus}} = \left(\frac{\text{Number of Sectionss with Calculus Skills}}{\text{Total Number of Sections}}\right)(100\%)$
$= \left(\frac{0}{17}\right)(100\%) = 0\%$</td></tr>
<tr><td colspan="2">Total Numbers of Chapters with Pre-Calculus Skills Only:
21 out of 21</td><td colspan="3">Total Number of Pages with Pre-Calculus Skills Only:
605 out of 605</td></tr>
<tr><td colspan="5">Percentage of Pre-Calculus Volume:
$\%_{\text{Pre-Calculus}} = \left(\frac{\text{Number of Pre-Calculus Pages}}{\text{Total Number of Pages}}\right)(100\%) = \left(\frac{605}{605}\right)(100\%) = 100.0\%$</td></tr>
<tr><td colspan="5">Conclusion on the Textbook:
(1) This book is one of the most popular textbooks on the subject and has been used at East Los Angeles College and many other places.
(2) For all practical purposes, no pre-requisite skills are needed in physics or chemistry.
(3) The mathematics concepts and skills required for the study of the topics are minimal and they are all at pre-calculus level.
(4) All topics in this textbook could be high school age-possible.
(5) Nevertheless, this course does require students to have a higher level cognitive maturity, and the difficult part is to use appropriate pedagogy to get abstract ideas into the brain of high school students.</td></tr>
</table>

Table 2B. Statistic on Textbook 2 (Engineering Economy, 13th Edition, by William G. Sullivan, Elin M. Wicks, and James T. Luxhoj)

Pre-Calculus Level Concepts and Skills Found in All Chapters/Sections			Page Information	
Mathematics	**Physics**	**Chemistry**	**Page Numbers**	**Number of Pages**
[four operations], [power], [root], [inequality], [log], [natural log], [limit], [infinity], [chart], [flow chart], [graph], [percentage], and [summation]	N/A	N/A		
Calculus Level Mathematics				
Concepts and Skills	**Chapters/Sections**			
[first integral], [first derivative]	Section 12.2.The Distribution of Random Variables		500-503	4

Chapters with Pre-Calculus Level Mathematics Concepts and Skills ONLY

Volume = Total Number of Pages – Number of Pages with Calculus Skills = 664 - 4 = 660 pages

Number of Sections = Total Number of Sections – Number of Sections with Calculus Skills = 139 – 1 = 138 sections

Statistical Summary

Total Number of Pages Covered by Text (Excluding "Index"): 664

Total Numbers of Chapters and Sections: 14, 139

Percentage of Pre-Calculus Sections

$$\%_{\text{Pre-Calculus}} = \left(\frac{\text{Number of Pre-Calculus Chapters}}{\text{Total Number of Chapters}}\right)(100\%) = \left(\frac{138}{139}\right)(100\%) = 99.3\%$$

Percentage of Sections with Calculus Skills

$$\%_{\text{Calculus}} = \left(\frac{\text{Number of Sections with Calculus Skills}}{\text{Total Number of Sections}}\right)(100\%) = \left(\frac{1}{139}\right)(100\%) = 0.7\%$$

Total Number of Chapters with Pre-calculus Mathematics Skills: 14 out of 14

Total Number of Sections with both Pre-calculus and Calculus Mathematics Skills: 1 out of 139

Total Number of Pages with Pre-Calculus Skills Only: 660 out of 664

Percentage of Pre-Calculus Only Volume:

$$\%_{\text{Pre-Calculus}} = \left(\frac{\text{Number of Pre-Calculus Pages}}{\text{Total Number of Pages}}\right)(100\%) = \left(\frac{660}{664}\right)(100\%) = 99.4\%$$

Conclusion on the Textbook:

(1) This book has been used at East Los Angeles College and many other places, and is one of the most popular ones on the subject.
(2) For all practical purposes, no pre-requisite skills are needed in physics or chemistry.
(3) The mathematics concepts and skills required for the study of the topics are minimal and most of them are at pre-calculus level.
(4) Only one section covering 4 pages involves 8 formulas using [first integral] and the implied [first derivative] calculus skill, and these skills could be treated as a special mathematics topic, or these Sections could be eliminated altogether.
(5) The overwhelming majority of all topics in this textbook could be high school age-possible.
(6) Nevertheless, this course does require students to have a higher level cognitive maturity, and the difficult part is to use appropriate pedagogy to get abstract ideas into the brain of high school students.

Conclusions and Recommendations

This report has presented (1) information about two popular college-level engineering economics textbooks selected for the initial determination and selection of high school age-possible topics (Table 1), and (2) the outcome of the research on the inclusion of mathematics, physics and chemistry concepts and skills needed for reading and homework assignments (Tables 2A and 2B). The following are recommended: (1) **Pilot study**: High schools could conduct pilot pedagogic experiments to determine the actual age-feasibility and age-appropriateness of all engineering economics-related analytic knowledge content identified in Tables 2A and 2B, using the selected Textbooks 1 and 2; and K-12 mathematics and science teachers could use the same Tables 2A and 2B as references to incorporate engineering economics topics into respective curriculum; and (2) **Curriculum development**: Existing K-12 engineering and technology curriculum developers could use the Tables 2A and 2B as references for the development of new K-12 engineering instructional materials or for the incorporation of engineering economics-related knowledge and skills into their previously developed instructional materials.

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About the Author:

Edward Locke is a product designer, CADD specialist, digital graphic artist, and independent scholar on K12 STEAM issues. He taught engineering graphics and CADD technology with product design projects to students from diverse ethnic backgrounds (Latino, Vietnamese-, African-, Caucasian-Americans, and others) at Santa Ana College, California (2000-2007) as an adjunct instructor, practiced product design and graphic design (1994-2014), pursued graduate studies at California State University Los Angeles (2004-2007) and then at the University of Georgia as a National Center for Engineering and Technology Education Fellow (2007-2009). He graduated in 2009 with an Education Specialist degree from the College of Education, Department of Workforce Education, Leadership and Social Foundations at The University of Georgia, Athens. He is currently working on issues of K12 engineering and technology curriculum, in collaboration with professors of the Engineering Department, at East Los Angeles College; and he could be reached at edwardnlocke@yahoo.com. Edward Locke's professional works, college-level textbooks and instructional materials, as well as research writings and curriculum development documents are featured in his four websites: (1) Scholar STEAM K12 Plus (K12 engineering and technology curriculum at http://scholarsteamk12plus.weebly.com/), (2) SuniSea Products (consumer product design, engineering graphics and CADD technology at http://suniseaproducts.weebly.com/), (3) SuniSea Design (graphic design and visual communication at http://suniseadesign.weebly.com/), and (4) SuniSea Creation (traditional and digital arts at http://suniseacreation.weebly.com/).

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