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The Modern Engineering Curriculum in Materials*

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An overview of the teaching of materials to students of engineering is given. Applications of materials utilization and design in industry are highlighted and emphasis on modern materials design techniques include the use of advanced materials. The Australian situation is featured with examples of the curriculum from one particular institution.

INTRODUCTION

THE CONCEPT of advanced materials parallels the progress in new and advanced technologies of the 1990s. Although rapid advances have been made in the development and application of those materials little attention has been paid to the education of personnel who are required to work in this area. The idea of materials science and materials engineering developed in the early 1950s growing out of metallurgy, physics and chemistry, such that today many tertiary institutes (in the context of this paper, the term *tertiary* implies universities and technical institutes forming the higher education sector) encompass materials education in their engineering curricula. In particular, materials related courses are common in the curricula of many nonmaterials engineering departments. This teaching of materials is particularly true in the engineering faculties where materials are often seen as a fundamental building block of many subjects and which may lead to their integration into the development of specific engineering applications [1,2]. These include materials and components for aerospace which are strong light and heat resistant, materials for information and communication which require integrated circuits and high capacity memory chips, and ceramics for high temperature applications, and composites with high strength-to-weight ratios and comparatively high toughness.

MATERIALS RELEVANCE

A number of major studies have been undertaken to emphasize the importance of materials to the economic and technological aspects of a country. In the U.K. following the publication of the Finniston report on engineering, one of the recommendations put forward was for the inclusion of the teaching of materials in engineering degree courses [3]. Subsequent to this was the report of the Collyear committee [4] for the *involvement of industry in new and improved materials and processes*. Similarly in a study commissioned for the Commission of the European Communities [5], they pin-pointed materials research as one of the *pivotal areas for research*. In the U.S.A. a recent extensive study entitled *Materials Science and Engineering for the 1990's — Maintaining Competitiveness in the Age of Materials* describes in detail the apparent lack of extensive training and education in this area and the remedies necessary to alleviate the situation [6]. It has also been recently reported in the U.S.A. that the number of graduates in both engineering and particularly materials science or engineering has been consistently low [7,8]. A similar situation has been reported for graduates of materials in Australia [9], and is showing few signs of improvement.

In a recent Australian survey of its graduates from engineering disciplines, it was seen that over a five year period the number of first degree students in both the secondary area of metallurgy and materials has averaged only 82, whereas the total engineering enrolments for 1987 was approximately 9000 [9]. It appears that the materials engineering graduate is lost among the other graduates, and those who specialize in advanced materials may become few, a situation that was reported by a U.K. institution [10].

ADVANCED MATERIALS

How do advanced materials fit into an engineering syllabus and how can they be easily defined? The development of advanced materials grew out of the complementary area of traditional materials — which at first were ceramics and metals e.g. clay,

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iron, steel, copper, brass, and as society expanded its horizon included electronic materials, polymers and composites.

How then can we define an advanced material? No simple definition exists, since these materials are closely interwoven with advanced technologies. *Advanced materials* in an engineering or scientific sense may be characterized by one or more of the following [11]:

— improved mechanical, thermal, electronic, optical or chemical properties over current materials and developed by application of scientific study of factors controlling materials properties (e.g. microstructures)
— one or more properties which may be attained by relatively sophisticated processing,
— and significant economic advantages in terms of processing, cost of use, high added value or marketability.

Advanced materials may be new materials with advanced properties and functions, and also conventional materials with significantly improved properties. It has been suggested that materials will be important in leading to advances in technology and industrialization through the ability to tailor their properties to applications [11]. For example, in the aerospace industry high-temperature alloys today have twice the rupture strength and operate at much higher temperatures than alloys from the second world war. Similarly, improvements in temperature, strength, corrosion resistance, lightness (weight) of materials have allowed innovation in processes.

Many countries have recognized the importance of materials developments, as described above, and for example, Japan is mounting a broad-based effort to compete in four important areas of materials applications and technology as suggested by their Ministry for International Trade and Industry (MITI) forecasts: fine (or advanced) ceramics, carbon fibres, engineering polymers, and amorphous metals [12]. They consider these areas as showing the most promising commercial growth (Table 1). The focus is on a selection of advanced materials to be able to fully concentrate significant investment and research and development effort. Similarly, based on a report commissioned by the EEC utilizing economic principles [5], it has been suggested that the difference between 'traditional' and 'new or advanced' materials is defined as the former having less than 3% growth per year, corresponding to the average growth rate of industrialized countries, whilst the latter exceed this rate. This also appears to be the economic definition that was decided upon by the Japanese study [12] and shown in Table 1.

For the specialist materials engineer there is a specific place in industry, which itself may not be ready to accept the advanced technology which materials have brought about, or the materials created by high technology. However, it is the remaining 99% of engineers who are required to implement materials into the design, fabrication and marketing of components, be they microchips for computers, composites for automobiles, ceramics for high temperature use, or new cement for high-rise buildings.

THE MATERIALS SPECIALIST

The teaching of materials has followed two parallel courses, one specifically concerned with materials as an integral and whole part of the curriculum, and the other, where materials is seen as a necessary and sufficient service area of

Table 1. Classification of selected old and new materials based upon projected production statistics for Japan from the MITI [12]

Predicted growth for Japan	1990 forecast* × Yen 10^6	Annual growth 1983–1986 percent
Traditional or Conventional Materials		
Steel	19 000	2
Non-ferrous metals	8 500	3
Ceramics	10 500	3
Chemicals	24 000	3
Textiles	9 500	2
Wood and paper	8 200	2
New Materials		
Fine ceramics	1 500	21
High polymers (engineering plastics)	1 000	13–14
New metals (amorphous metals)	550	18–42
Composite materials (carbon fibres)	150	14–29

* based on total price of components.

engineering education for the non-specialist engineer.

The area of specialist education in engineering materials or materials science deserves particular attention (when compared to other engineering streams) as there are few places in the world and especially Australia, where they may be undertaken at the undergraduate level. For example, in Australia there are seven major tertiary institutes which cater for the materials specialist, and a number of others which have a substantial component of their syllabus concerned with both materials and metallurgy, a selection is listed in Table 2. As well as these specialist materials departments there also exist five major faculties of metallurgy which incorporate a large section of their materials' syllabus into the overall metallurgy curriculum. Other departments of metallurgy do exist but appear to be of a fundamental metallurgical nature. It should also be noted that the departments of aeronautical engineering at the University of New South Wales and Sydney University and the department of aerospace engineering at the Royal Melbourne Institute of Technology devote significant sections of their course to advanced aerospace materials and associated design and analysis techniques. In all specific materials engineering courses, advanced materials knowledge is built on basic material *property — structure* relationships allied with concomitant technology for analysis and design. These studies are undertaken during the first two or three years of the course with little hint of what lies ahead. In the final years of the course in-depth studies of specific material groups are undertaken, examples of which include composite, materials, new metals (superalloys), advanced or engineering ceramics, and high or engineering polymers. These studies prepare specialist personnel in their area of expertise who can integrate both conventional and advanced materials and processes.

It is recognized that materials engineers are influential in technology and manufacturing industry, but may be employed only one or two per company. This is often sufficient for most industries and it is the remaining engineers who must be aware of the role materials have in the technological world. However, attempts are being made to increase the materials content of engineering courses together with increasing the number of students enroled in materials courses.

THE NON-MATERIALS ENGINEER

A novice engineer enters a tertiary institute with little or no concept of how he or she will progress or what engineering speciality they will choose. The overwhelming majority of engineers will not specialize in materials. Although the majority of engineering courses are similar in nature they are different in structure. To illustrate this area, I will focus on the courses at the Institute where I lecture, as I am most familiar with them. During the first year, materials engineering is integrated with appropriate aspects of other subjects. Approximately 8% of the year is devoted to materials-related subjects. Moreover, sections of importance to materials are taught in areas as diverse as physics, chemistry, static system and electronics, as shown in Fig. 1. Taken together, they combine to form a powerful basis for future education.

Although, at this stage materials is not taught as a separate subject. An outline of the areas covered in the first year materials syllabus (Fig. 2), show that a strong grounding is needed in the fundamentals of

Table 2. Outline of selected Australian undergraduate courses in materials

First Qualification	Tertiary Location	Comments
B.E.[1]	Monash University	Materials Engineering
B.Sc.[2]	Monash University	Materials Science
B.E.	University of New South Wales	Materials Engineering
B.E.	University of Wollongong	Materials and Metallurgy
B.App.Sci[3]	University of Technology, Sydney	Materials Science
B.E.	Newcastle University	Chemical & Materials
B.E.	Queensland University	Mining, Metallurgy and Materials
B.Sc.	Curtin University	Materials Science
B.E.	[4]Royal Melbourne Institute of Technology	Metallurgical Engineering
B.App.Sci.	[4]Ballarat College of Advanced Education	Metallurgy
B.E.	South Australian Institute of Technology	Metallurgy
B.E.	[4]Royal Melbourne Institute of Technology	Aerospace Engineering
B.E.	University of New South Wales	Aeronautical Engineering
B.E.	University of Sydney	Aeronautical Engineering

[1] Bachelor of Engineering
[2] Bachelor of Science
[3] Bachelor of Applied Science
[4] Now Vic University of Technology

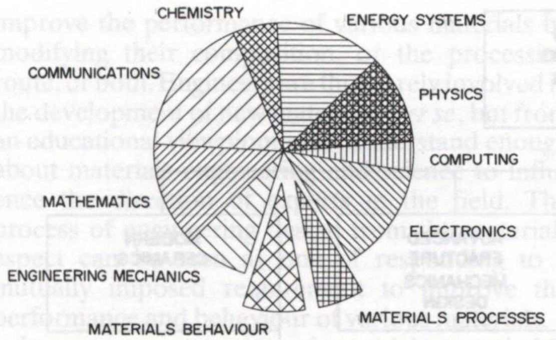

Fig. 1. First year engineering topics.

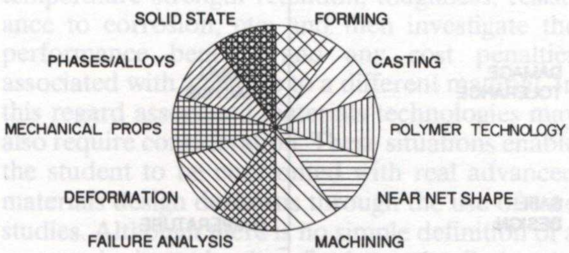

Fig. 2. First year materials syllabus based on materials behaviour and processes.

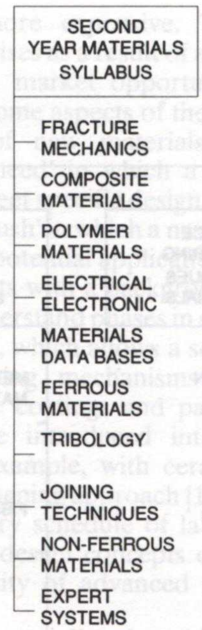

Fig. 3. Second year materials syllabus.

materials behaviour; since advanced materials always require the basics of conventional materials as a building block. Allied to the materials, are concepts of fundamental fabrication techniques, also used as building blocks (for advanced manufacturing process) in later years of the course — this area is not discussed in detail here but may be found in other work [2,9,10]. In the second and third year of the syllabus, an introduction to modern and advanced materials, processes design and analysis is given to the student and pursued by the lecturer (Figs 2 and 3 respectively).

At this stage, materials is divided into two areas — the first, being specific material behaviour, and the second being the properties and design concepts of material. There is also an obvious effect of other subjects impinging on materials behaviour.

Fundamental elasticity and plasticity theory is required for all materials, mathematics and calculus are a need for the fracture mechanics area, as well as the area of rheology and composite materials. The path to advanced materials is becoming less shadowy, and has adopted some mathematical concepts on the way.

The structure of the overall course is such that computer assisted design (CAD) and computer aided manufacture (CAM) begin to infiltrate the application of materials; for example, in the computer integrated manufacture of components produced with cutting tools. Surface engineering of this tool may significantly increase tool life as well as produce a fine surface finish of the component.

These concepts of CAD and CAM are introduced in the first undergraduate year in a purely descriptive manner, and elaborated upon in later years to encompass techniques of manufacture and applications to advanced materials.

At the end of the second year of the course, the student has a general and detailed introduction to the physical and mechanical properties of materials especially in a phenomenological manner, with the mathematical basis verifying these concepts.

It is only after this major ground work has been established that a serious treatment of advanced materials can be attempted. However, by now the time allocated to materials has reduced such that specific areas have to be selected.

In the third year of the course, the educator is finally able to focus attention on areas of materials which are both of importance to industry and require specialized detailed knowledge (Fig. 4). It must be recognized that the first two years of the syllabus formed the basis of this work upon which industry often relies (Fig. 2). At this stage modern tools are introduced into the course in the form of computer assisted materials engineering.

COMPUTER BASED MATERIALS ENGINEERING

During the many years of engineering education, the field of computers has played a significant role. This ranges from the fundamentals of programming, through the areas of CAD/CAM to the field of materials performance analysis, with Finite Element Analysis [13,14] and the expert system approach [15] for materials selection data bases (Table 3).

In all these fields, conventional and advanced materials play a significant role. The field of materials pedagogy cannot be easily separated from these influencing factors. The engineering

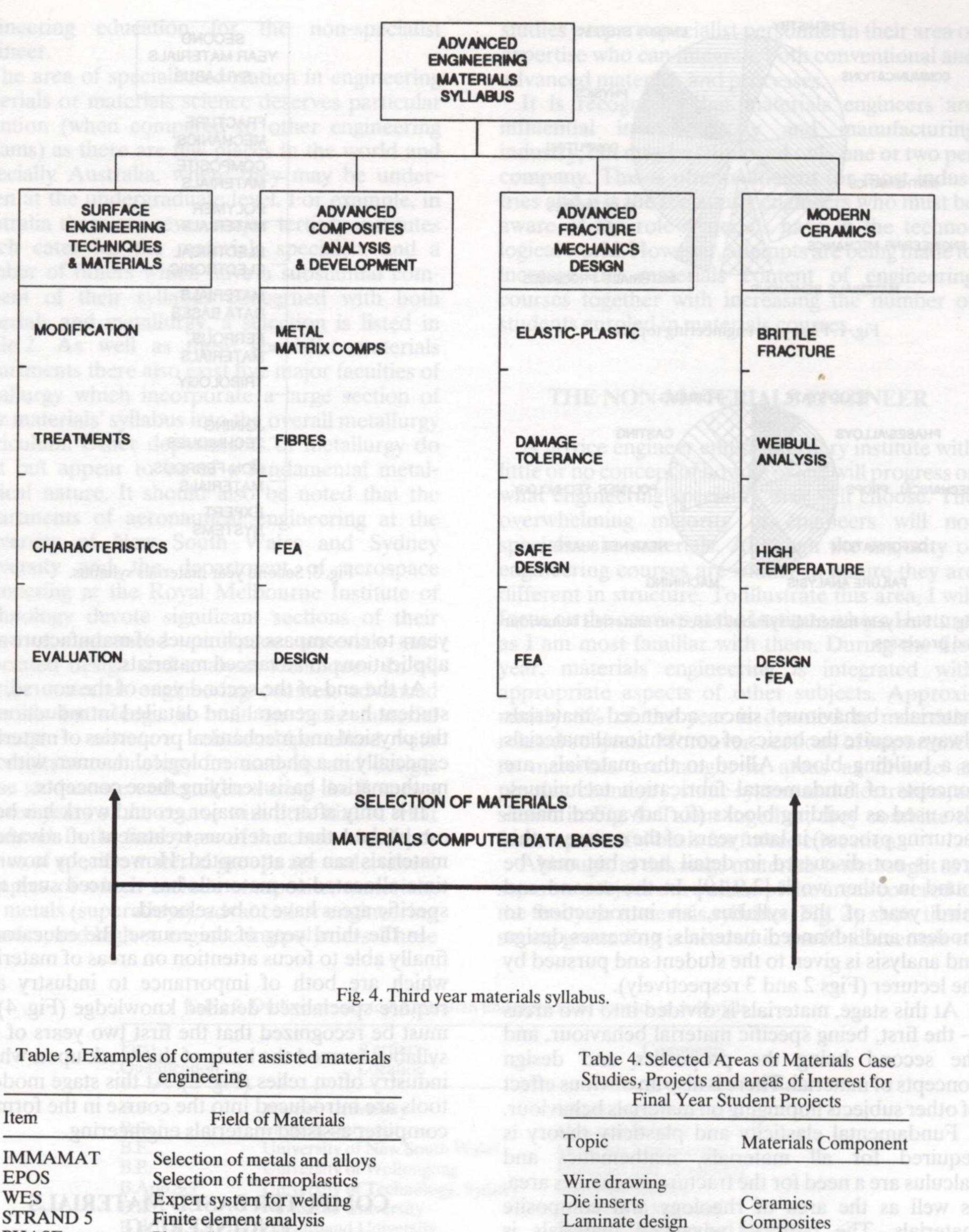

Fig. 4. Third year materials syllabus.

Table 3. Examples of computer assisted materials engineering

Item	Field of Materials
IMMAMAT	Selection of metals and alloys
EPOS	Selection of thermoplastics
WES	Expert system for welding
STRAND 5	Finite element analysis
PHASE	Phase diagram analysis
CADAM	Computer-aided design
MIC-MAC	Composite laminate analysis
GENLAM	Point stress analysis of laminates

student is exposed to all these areas, culminating in a final year thesis. The topics of research may be varied but each one depends to some extent on current and advanced materials. Examples of areas of interest are listed in Table 4. In all cases, often unknown to the student the materials utilized can effect the outcome of the research.

Table 4. Selected Areas of Materials Case Studies, Projects and areas of Interest for Final Year Student Projects

Topic	Materials Component
Wire drawing	
Die inserts	Ceramics
Laminate design	Composites
Failure analysis	Composites
Fracture mechanics	Failure of materials
Expert system	Materials selection
Robot gripper	Friction materials
P/M die	Die materials
Coated taps	Surface engineering
Abrasive finishing	Surface engineering

DESIGNING WITH MATERIALS

In industry, engineers involved in the design process work with materials scientists who wish to improve the performance of various materials by modifying their composition, or the processing route, or both. Engineers are thus rarely involved in the development of new materials, *per se*, but from an educational viewpiont must understand enough about materials engineering and science to influence the direction of experts in the field. The process of engineering design from the materials aspect can be seen as one of responding to a mutually imposed requirement to improve the performance and behaviour of various materials.

In many cases a variety of materials are suitable for a given component and the engineer must first identify the critical properties required, e.g. high temperature strength retention, toughness, resistance to corrosion, etc; and then investigate the performance benefits and any cost penalties associated with a change to a different material. In this regard associated materials technologies may also require consideration. These situations enable the student to be confronted with real advanced materials design decisions through the use of case studies. Although there is no simple definition of a case study, it can be described as a detailed treatment of a real situation, system or process. An example of a typical study is given below.

Example case study

An example of the approach taken to solve one of many case studies is given briefly as follows.

Problem: Design a composite wing for a one-person aeroplane.
Approach: Form a design team to investigate specific tasks.
Materials: Investigate the properties of a range of lightweight/high strength Materials; these include glass fibre/epoxy, graphite/epoxy composites, Kevlar/epoxy composites, wood laminates and aluminium for the outer skin, and polystyrene foam or honeycomb aluminium for the core.
Analysis: Use finite element analysis to determine the loads and deformations arising from using the various combinations of materials.

It must be recognized that processing and fabrication play a significant part in design decision, and this is also evaluated.

The engineer must also have a clear appreciation of the cost implications inherent in any materials change, and the consequential marketing interactions. A particular material might provide a much improved performance under specific conditions, but be very much more expensive in terms of first cost to the customer (e.g. advanced ceramics, superalloys). The question now is whether the market exists for the specific application at the higher price. These considerations may be illustrated by the development of (i) ceramic cutting-tool materials which are superior to other cutting tools only under specific conditions, and surface engineering [16] (Physical Vapour Deposition PVD and Chemical Vapour Deposition CVD) to improve wear resistance (ii) which are two or three times more expensive. Their continued development arises as a result of a number of small though distinct market opportunities. This also demonstrates some aspects of the pressure for the development of new materials. For example, 'technological need' in which a new material is developed to meet specific design demand, and the 'development push' in which a new material is tried in a number of potential applications.

Many students with a background in chemistry and physics understand phases in solid systems and phase diagrams, which allows a selection of alloys and strengthening mechanisms in solids (e.g. titanium nitride coatings and partially stabilized zirconia) to be introduced into the materials syllabus. For example, with ceramics the transformation toughening approach [17], together with a complementary schedule of laboratory experiments, enables design concepts of strength, stiffness and ductility of advanced materials, to be established.

Perhaps one way to link these ideas to the design and manufacturing function is through fracture mechanics [18]. This is taught as a design technique, and is compared and contrasted with continuum approaches to design, such as yield criteria (as mentioned previously). The overall approach to fracture mechanics in brittle, ductile and visco-elastic materials can be used to extend into, for example, ceramics which pose special problems with their extreme brittleness and environmental sensitivity. The very short critical crack lengths in ceramics highlight the current limitations of non-destructive testing (NDT) techniques, and the statistical scatter obtained from a mechanical test on these materials makes the use of continuum approaches very difficult.

The teaching of polymer engineering is from the viewpoint of mechanical properties, particularly where these are linked to the processing route employed, and design studies of particular components. In this way the particular properties of polymers, their response to stress, strain, fracture toughness and temperature limitations may be understood.

In many ways the principles of new alloy development and design techniques with specific materials may be brought together here by emphasizing the fact that metallic alloys are micro-composites, and that composites occur naturally (e.g. wood, bone) as well as being man made [19,20]. The important point for the student to realize is that the materials engineer is now in many ways in a position to 'design-in' the required features of a given material. It is the responsibility of the engineering designer to specify the applied loads, their orientation, and the other service conditions with the required accuracy. The basis of fibre reinforced composite materials (and the newer metal matrix composites) is the requirement to incorporate strong and stiff 'fibres' in the correct quantity at the appropriate orientation. This clearly requires a very close collaboration between the materials developer, the engineering designer, and the materials manufacturer, since the materials as designed is in this case usually the final product. The materials engineer thus requires a knowledge of 'fibre' and matrix' types and the effects of various combinations of these; anisotropic elastic laminate stress-analysis theory; the available processing routes, and the properties of the resulting material, the incorporation of computer analysis techniques often minimizes the need for extensive experimental analysis.

CONCLUSION

The development of an engineering materials program in a broad engineering curriculum has been described. The syllabus follows conventional materials in the early years, with an introduction to advanced or modern materials, processes, analysis and design being given in the later years and concludes with specific application projects in the final year of study. When the engineers finally qualify, they have been exposed to various facets of materials both advanced and conventional, and associated design and analysis techniques. They also have an appreciation that technology and materials are ever changing and require a constant updating of knowledge.

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