Timetable construction—an annotated bibliography

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Papers on timetable construction and related areas are presented which appeared in 1979 or earlier. References to reviews have been added. A sample from the many facets of the timetable problem and some approaches to solving such problems are surveyed.

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Scope of the bibliography

To master the difficulties of timetable problems, timetable constructors continually ask for computer aid. As a result, a vast amount of papers have appeared which we have collected to facilitate future work in this area. Several papers are collections of experiences, sometimes based on a particular computer installation. A significant number of papers (at least those by Aust, Bosler, Csima, Early, Frangos, Junginger, Kreczmar, Leue, Sherman, de Werra, Williams, Wood, Yule, and Zehnder) originated in doctoral dissertations. We have not reported on work of students below this level, unless published in a scientific journal. A listing of internal reports and software projects from the academic environment or by the computer industry has been subjected to the same condition. Related topics and mathematical foundations are included, as far as necessary according to our opinion. If a reference to a review in Computing Reviews (CR), Mathematical Reviews (MR) or Zentralblatt für Mathematik (Zbl. M) has been included in the entry, this may, to a certain extent, be taken as an indicator of some mathematical nature.

The fundamental problem

As yet, a commonly accepted terminology has not evolved, although the timetable problem has already been mentioned in books on graph theory, e.g. Bondy and Murty (1976) and Christofides (1975). We will describe the typical problem, rather informally, introducing some notations along the way.

First, there are '*participants*' in a fairly general sense, i.e. teachers, classes, lecture halls, laboratories, pieces of equipment, and so on. In addition, there exists a set of '*hours*', sometimes called time slots or periods. '*Availabilities*' describe for every participant the subset of hours in which he (it) is free or willing or able to participate in one of the lessons, lectures, conferences or examinations in which he (it) is involved. The latter events are subsumed under the notion of a '*meet*'. Every meet is described by the collection of participants which have to come together and by the number of hours required for it. The classical *bipartite class-teacher timetable problem* is obtained if every meet keeps busy exactly one teacher and one class as participants. However, there may be a demand for a meet which consists of a gymnastics lesson to be held by a male teacher and a female teacher each in different gymnastic halls at the same time. Finally, there may be *preassignments* of some meets to hours.

Given such a situation, a timetable is a schedule assigning to all these meets the precise number of hours required, so that these hours are available for all participants of the meets and such that, as a fundamental requirement, none of the participants is scheduled twice in the same hour.

Special requirements

So far, we have presented only the very fundamental problem. However, there is a diversity of special requirements a timetable must observe depending heavily on the type of school and on administrative peculiarities of the country. We mention some examples from the spectrum of problems. The division of the set of hours into *days* has to be considered, if the scheduling cycle is the *week*. For some participants (namely the classes), it is necessary to avoid free hours scheduled in between other lessons; they may have free hours only at the beginning or the end of a day. Some subjects (e.g. Physics) require consecutive hours not straddled by a break; see the early paper of Appleby, Blake and Newman (1960). There may be limitations on a teacher's daily load, and it may be necessary to provide every teacher with a free day. Subjects taught several times a week should be spread evenly throughout the week. Two-lesson subjects with homework must not be assigned on Saturday and Monday. Teachers may indicate a preference on the length of the interval between their lessons. Of course, not all of these claims are equally important; some are merely aesthetic constraints.

At universities the special requirements are slightly different. While in schools, the size of a class is of minor interest, it becomes very important at universities, because the number of students in a lecture may vary from three to one thousand. Usually, lecture halls may be selected from a set of halls of comparable size. While in the school problem each class should be occupied all of the time, this condition is not required in the university problem. On the other hand, the requirements for the distribution of free hours over the week of either students or lecturers are far less restrictive.

Bookkeeping and heuristics

The first computer programs to attack this problem, that have been reported, are closely related to *timetabling by hand*. Bookkeeping, i.e. maintaining the lists and tables classically used, was executed by a program. Soon, elementary insert and remove techniques had been designed and applied with elaborate heuristic guidance among which arranging the lessons in decreasing order of *complexity* was the most favourite approach.

Lewis (1961) describes such methods. Appleby, Blake and Newman (1960) used some look-ahead by counting arguments. Berghuis, van der Heiden and Bakker (1964) as well as Elizabeth Barraclough (1965) simulated working by hand, with first influences, however, of the Gotlieb approach. They seem to be the first group who applied interchange operations if scheduling a lesson failed at the first attempt. These early heuristic papers were followed by many others which we are unable to mention for lack of space. Several papers contain valuable suggestions on how to cope with special requirements. However, the essence of a heuristic approach is hard to communicate. In a certain sense, an amount of heuristics may be found in every known timetabling system.

Models for the 'exponential' problems

Regarding the fundamental problem initially introduced, we will associate in the following a slightly more formal presentation. Let $\mathbf{P}$, $\mathbf{M}$ and $\mathbf{H}$ denote the sets of participants, meets and hours, respectively. Then, we need a mapping $p:\mathbf{M} \to 2^{\mathbf{P}}$ of $\mathbf{M}$ into the powerset of $\mathbf{P}$ in order to describe the set of participants of every meet. By $r:\mathbf{M} \to \mathbb{N}$, the number of hours required for a meet is determined and the a priori availabilities of the participants are prescribed by $v:\mathbf{P} \to 2^{\mathbf{H}}$.

With $a(M) := \bigcap_{P \in p(M)} v(P)$, we may attach an availability to every meet M by intersecting the availabilities of its participants. What we are looking for is a solution $s:\mathbf{M} \to 2^{\mathbf{H}}$; fulfilling: (i) $s(M) \subseteq a(M)$ (ii) $M \neq M'$, $s(M) \cap s(M') \neq \emptyset \Rightarrow p(M) \cap p(M') = \emptyset$ (iii) $|s(M)| = r(M)$.

The close connection between this problem and the problem of vertex colouring of graphs should be mentioned. Assume $r \equiv 1$ for simplicity. Draw a simple graph on the vertex set $\mathbf{M} \cup \mathbf{H}$. Insert three types of edges by connecting all pairs of different hours, all meets M with hours $h \notin a(M)$, and all pairs of different meets M, M' if $p(M) \cap p(M') \neq \emptyset$. If we manage to colour this graph with $|\mathbf{H}|$ colours, we obtain a timetable.

In the past, thorough mathematical treatment has mainly concentrated on the classical bipartite problem. It is often formalised a little differently by a non-negative integer requirement matrix $R = (R_{tc})$. Its (t, c)-entry is the number of hours teacher t has to meet class c. In addition, a Boolean availability array $A = (A_{tch})$ is given, where A_{tch} indicates whether t and c are both available at hour h; see Gotlieb (1962). Therefore, the problem is sometimes said to be a 3-dimensional assignment problem.

A pictorial description of this problem may be given by a family of graphs, each on a vertex set corresponding to teachers and classes. For every hour h, a graph G_h is drawn with R_{tc} edges joining t and c if t and c are both available at hour h. In this setting, a timetable is a family of appropriate matchings (or an edge colouring). **Fig. 1** shows an example of such a problem with 7 participants, 9 meets, 3 hours, $R_{13} = R_{21} = R_{42} = 0$ and $= 1$ otherwise. A timetable is indicated by dark lines. The problem becomes unsolvable if the availability α is cancelled.

It has always been felt that there exists no polynomial time algorithm to solve the timetable problem, i.e. that it does not belong to the class $\mathscr{P}$. In earlier days, however, the state of complexity considerations was quite imperfect causing the amazing dispute between Broder, Duncan and Griffith. For the k-colourability problem, which is closely related to the timetable problem, Garey, Johnson and Stockmeyer (1974) proved that it is $\mathscr{NP}$-complete, i.e. that a deterministic machine will probably need an exponential amount of time (unless the exciting $\mathscr{P} = \mathscr{NP}$ question should be settled positively). Interpreting the 3-satisfiability problem as a special timetable problem, Even, Itai and Shamir (1975) showed that the timetable problem, also, is $\mathscr{NP}$-complete.

Models for the 'polynomial' problems

Assuming that teachers and classes are always available, we obtain from the bipartite problem the *basic problem*, to which investigations are often restricted. In this case, all the graphs G_h coincide and the following solvability criterion becomes valid. The problem is solvable if and only if the maximal degree of a vertex of G_h is not greater than $|\mathbf{H}|$. Csima (1965) gives a constructive solution; Even, Itai and Shamir (1975) formally proved this problem to be polynomial. It is equivalent to the problem of decomposing the matrix R into a sum of $|\mathbf{H}|$ subpermutation matrices.

Further specialisation leads to the *doubly stochastic problem*, which may be considered a purely theoretical facet of timetabling. In this case, the numbers of teachers and classes are equal and every participant requires the same number of $|\mathbf{H}|$ hours, i.e. R is a doubly stochastic matrix of row and column sum $|\mathbf{H}|$. Such a matrix may be decomposed into a sum of $|\mathbf{H}|$ permutation matrices. The h-th permutation matrix may directly be interpreted as the schedule for the h-th hour. Famous mathematicians have contributed to this theorem concerning matrices with non-negative integers, among them Frobenius (1912, 1917), König (1916), Birkhoff (1946) and Ryser (1957).

We have seen that the more restrictive the conditions, the more powerful the results become. Investigators have, for this reason, tried to fit treatment of special requirements by artificial constructions to these basic problems. Csima's (1965) embedding of the basic problem into the doubly stochastic problem, using pseudo classes, may be considered under this aspect. Meets with exactly one participant, representing a free hour of a class or an idle hour of a teacher, have been added by creating fictitious (virtual) classes or teachers in order to obtain the classical bipartite problem; see Berghuis, van der Heiden and Bakker (1964).

However, this device is not applicable to all the special requirements. Often, an introduction of meets with a number of participants not necessarily equal to two has been recommended, e.g. by Barraclough (1965). The timetable problem will then become a family of hypergraphs. With this construction, however, we arrive again at the exponential problem.

Gotlieb's approach

The first nonheuristic attack is embodied in the famous process of reducing the availability array, presented by Gotlieb at the 1962 Munich IFIP Congress. The idea of Gotlieb's algorithm is to detect some tight assignments (i.e. those contained in every timetable as α in Fig. 1), and some pseudo-availabilities (i.e. assignments not contained in any timetable) by investigating certain subproblems of minor complexity. Concentrating upon a single participant or a single hour, one will obtain a 2-dimensional or planar section which turns out to be an assignment problem or a simple network problem, sometimes revealing tightnesses and pseudo-availabilities or even unsolvability. Such tightness or pseudo-availability will eventually cause further ones, thus establishing an iterative reduction process. If unsolvability is not proved in the course of this reduction, the process will become stationary, if all implications of local situations have been evaluated. The result was called the

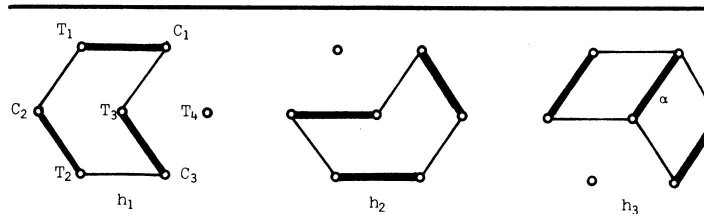

Fig. 1 **Timetable problem with solution**

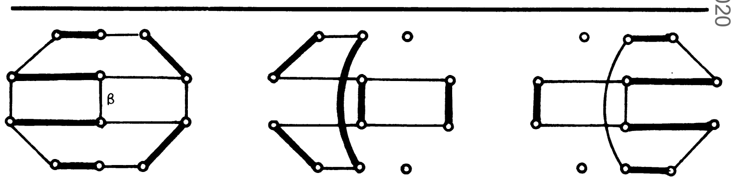

Fig. 2 **Mincut flexibility**

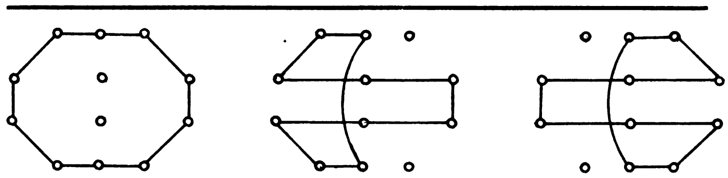
Fig. 3 **Residual problem**

reduced availability array.

Using the hypergraph concept from Schmidt and Ströhlein (1973), which obeys special requirements, the associated subproblems consist of refined networks for which uptodate maxflow-mincut algorithms are needed. The reduction process will be called mincut analysis and a problem will be called mincut flexible if mincut analysis does neither prove unsolvability nor produce further results.

Gotlieb originally thought his reduction process powerful enough to eliminate all pseudo-availabilities. However, this is easily proved false, for example by the problem of Fig. 1 with availability α deleted. Csima and Gotlieb in 1964 refined their conjecture by postulating that an assignment of a pseudo-availability in a mincut flexible problem will result in a residual problem which is not mincut flexible, thus preventing backtracking. However, a computer generated counterexample was published by Lions (1966). A smaller counterexample is due to Dempster (1968). An example we find impressive is shown in **Fig. 2** assuming $r \equiv 1$. The residual problem of **Fig. 3**, obtained after the assignment β, is mincut flexible. Nevertheless, it turns out to be unsolvable.

Subproblems of minor complexity

Since timetabling cannot be done by polynomial algorithms alone and further overall considerations of the problem are necessary, the application of assignment, matching and network algorithms deserves special attention. Exponential criteria for the solution of assignment and matching problems are due to König and P. Hall (1935). Efficient algorithms closely related with the names of Egerváry (1931), M. Hall (1948; 1956) and Kuhn (1955) are often called the Hungarian method and are studied applying alternating chains. Modified techniques stem from Edmonds (1965) and Gabow (1976). Algorithms for the general matching problem are now reported by Even and Kariv (1975) to run in $0(n^{2 \cdot 5})$ time.

The asymptotical growth rate of the maximum flow algorithms has been decreased from $0(n^5)$ to $0(n^3)$. See for example Ford and Fulkerson (1956; 1958) and Edmonds and Karp (1970). Another line of improvements is due to Dinic (1970) and Karzanov (1974) using layered networks; similar techniques had been applied in practice earlier, however.

Mincut analysis in networks is, in addition, based on the evaluation of the lattice of mincuts of a network. The bipartite case was studied by Dulmage and Mendelsohn (1958) while the general case was independently investigated by Escalante (1972; 1973) and Schmidt (1973).

Graph recolouring and recursive exchange operations

A formulation of the timetable problem in terms of graph recolouring is very appealing. There are certain techniques and algorithms which may be reinterpreted as timetable algorithms. Both vertex colouring and edge colouring have been tried. Investigations on the chromatic number of a graph have come from Maghout (1959), Corneil and Graham (1973), Sakaki, Nakashima and Hattori (1976), and many others. Timetabling by graph colouring is reported at least by Early (1968), McDiarmid (1972), Welsh and Powell (1967), especially by several papers of de Werra (1970-1975) and only recently by Scott (1976). Korfhage and Matula, Garey and Johnson and an area editor contributed to the controversy concerning the Salazar and Oakford paper, the origins of which were traced, back to Kirchgässner (1963).

Colouring algorithms often proceed step by step. However, $\mathcal{NP}$-completeness of the problem is an indicator that a process without blind alleys will not exist. Therefore, algorithms designed for realistic problems usually comprise graph recolouring procedures. The counterpart of such procedures in other timetable formulations are 1- or 2-displacement procedures, see Uhlemann, Schöllkopf and Knauer (1969), and recursive exchange operators. The latter have already been tried by Berghuis, van der Heiden and Bakker (1964). Such techniques, based on a generalisation of alternating chains in hypergraphs, known since Edmonds (1962) and Ray-Chaudhuri (1963), have been studied and applied to cope with special requirements by de Werra (1974) and Höll *et al.* (1978).

The operations research approach

The impact as well as the number of operations research oriented papers seems to be far less. Nevertheless, the timetable problem may be clearly presented, see for example Mihoc-Balaş (1965), as an optimising problem and most of the special requirements are easily included in this description. However, the number of variables and parameters grows rapidly so that standard programs and branch-and-bound techniques of operations research are no longer effective. In addition, integrity constraints for solutions are indispensable. Junginger (1972) gives a reduction of the timetable problem to a 3-dimensional transport problem. Other publications in this direction are by Haley (1962), Carlson and Nemhauser (1966), Morávek (1969) and Kónya (1978). In their complexity considerations, Even, Itai and Shamir (1975) proved, that the multicommodity flow problem is $\mathcal{NP}$-complete, too. Another linear programming approach is due to Lawrie (1969) and Krawczyk (1973).

Other techniques

Detailed analysis of a tree search procedure has been reported in many papers by Lazak. In the heuristic approach, several authors applied random insertions: Fujino (1965), Macon and Walker (1966) and Broder (1966). A theoretically oriented attempt of some sort of long range planning in terms of Boolean matrix iteration of implications was suggested by Schmidt and Ströhlein (1976). Genrich (1966) gave a relational description of the timetable problem. Friedman (1957) applied double integrals.

Future trends

Timetabling by computer is heavily influenced by the devices at hand. We feel that recent developments in computer technology and software engineering have not yet reached the area of timetable programming. A major evolution will, therefore, come in the near future. Timetable programs will probably move from remote handling in huge computing centres to minicomputer systems owned by the school and handled directly by the teachers. Interactive work already reported by Devine and Kumin (1976) and Höll *et al.* (1978) will certainly take place in the coming years. We expect that software support by data base systems for bookkeeping will grow rapidly. Timetables of previous years will be stored and only updated to meet new requirements instead of computing them from the beginning, an idea already proposed by Barraclough (1965). There will be special programs available as tools to be applied interactively by the timetable constructor. As an example consider a diagnostic program using, for instance, some sort of Hungarian method in order to test whether the subproblem is feasible for an isolated participant. There may also be an operator diminishing free hours for classes, and so on.

Related topics

Apart from the original timetable problem, a lot of papers have appeared on related work. For instance, Broder, Cole, Foxley and Lockyer, Peck and Wood published papers on examination scheduling and Friedman, Thornton on stewardess scheduling by airlines. Haynes, McDiarmid, Schultz and de Werra on conference scheduling, Wedekind and Zehnder on scheduling of traffic facilities. A rather broad variety of papers is concerned with student scheduling at (American) universities, e.g. Abell, Mary Almond, Blakesley, Haga, Hartford, Holz, Holzmen, Kónya, Kreczmar, Sherman, Skillings, Smith, Stockman, Wilkes, Winters and Yule.

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Book reviews

Microprocessors: their development and application, 1979; 305 pages. (*ERA Computers and Automation*, £59·00)

This large volume, the second revision of the original 1976 edition, appears a little daunting at first glance. It contains over 600 pages of A4 size, but on closer examination the prospect becomes less intimidating since the main text is contained in about 200 of these pages, the rest being occupied by data sheets and appendices. The (unnamed) authors claim in the introduction that the book is aimed at the electronics design engineer who will be using computing techniques for the first time. He (or she) is assumed to have some knowledge of electronics and digital circuit and system techniques, though not necessarily any detailed knowledge of integrated circuits or computers. An important aspect of the microelectronics industry which is becoming increasingly recognised is that the usefulness of many engineers and established engineering organisations is now in doubt, at least as traditionally accepted. Thus, a volume such as this one, couched in a style to suit the engineering profession, is very welcome, especially as the approach appears sceptical at times in an effort to show a balanced perspective of the subject.

After a chapter sketching the development of microelectronics from the first transistor to the present time (including the major role that military requirements have had in the shaping of the character of the industry) the core of the book describes the range of devices available and provides an account of some of the fundamental attributes of microprocessors and their supporting circuits. This account, although patchy in places (for example, memory mapped input-output methods are not mentioned), is nevertheless pitched at the right level for its intended readership: it is neither too brief to be of value, nor too detailed to be tedious.

Before proceeding to the complementary topic of providing software for the microprocessor hardware, there is a detour into nearly 100 pages of data relating to over 100 microprocessors. However, this survey is not as comprehensive or as useful as it first appears since several of the devices listed have either been discontinued or superceded or are not available in the UK. This survey falls far short of the standards set by other similar surveys, such as that available annually from EDN for only $6.

A surprisingly small section of this massive volume (claimed on its cover to be 'The Complete Guide to Microprocessor Technology' where the use of the definite article is quite unwarranted) is devoted to software. 'Surprisingly' since the acquisition of software knowledge and experience will be more difficult for an electronics engineer than appreciating the intricacies of the hardware. Some contestable statements are made which, bearing in mind the printing history of this book, suggests that the revision of the original document was not carried out with the same enthusiasm as its creation. For example, a list of high level languages for microprocessors omits Pascal and other favourites such as LISP, FORTH and micro-COBOL.

Stepping through the various system and utility programs which may be encountered, the treatment is uneven with, for example, an unnecessary attention to detail in the explanation of assemblers, while omitting to mention the 'linker' utility, a crucial item in a software development system. The text then dances lightly through the use of commercially available modules, development aids and personal computers before presenting some cogent advice on 'getting started'. Having thus reached the end of the main text the reader realises that he is only halfway through the book, and that the remaining 300 or so pages are devoted to detailed explanations of the fabrication technologies and photocopied data sheets from manufacturers. Presenting an explanation of the fabrication processes on this scale is quite unnecessary and positively harmful since it can easily lead the unaware reader (at whom the book is aimed) into erroneously believing that a knowledge of these techniques is required in order to use the devices, whereas all that is required at the application level are the 'black box' characteristics.

The inclusion of over 100 pages of photocopied data sheets has some minor value which could have been considerably enhanced by including tutorial material on understanding, evaluating and comparing the data presented by the various manufacturers. The lack of an index is a serious omission in a work of this nature, but the glossary, although not exhaustive, is adequate, with a few minor errors.

This book then, although oversized (how much more attractive it would be if the data sheets were removed and the format reduced to say, A5) will be of considerable benefit to its intended readership, who are recommended to peruse it before attending any microprocessor courses. Although it appears to be expensive, its cost may well be less than the travelling expenses incurred in attending a course.

H. Quilliam (Guildford)

Software Development: A Rigorous Approach by C. Jones, 1980; 382 pages. (*Prentice-Hall*, £13·95)

The stated aim of the book is to 'teach a method for recording specifications and designs of computer systems'. The title of the book, however, expresses the aim much more precisely—the book is about the development of software rather than computer systems. The approach advocated by the author is 'rigorous without being completely formal'. It has evolved over a period of time in an industrial environment (at the IBM Laboratory, Vienna) where, the author claims, it has been tested in practical software development projects.

The book is intended 'for a course which will bring results of computer science into software development practice'. The subject matter is divided into three parts: the first covers a method for specifying programs for numerical computation, the second extends the method to cover programs for data processing and the third concentrates on the program design. A number of useful appendices and an excellent bibliography are included. The main value of the book is that it provides the reader with a practical method for writing a rigorous software specification which represents a precise record of the software function without giving details of its implementation. The emphasis is placed on the use of abstract data types and on delaying decisions concerning details of data implementation as long as practicable.

The weak point of this otherwise excellent work is, rather ironically, the lack of precision in the use of the English language (e.g. the same concept is often described by different words, each having a slightly different connotation). This is, however, of secondary importance and the book can be highly recommended for courses in software engineering at the M.Sc. level and, if certain chapters are omitted, at the undergraduate level.

George Rzveski (Kingston upon Thames)