SELECTED BIBLIOGRAPHY ON COMBINATORIAL GAMES AND SOME RELATED MATERIAL

Aviezri S. Fraenkel

Department of Applied Mathematics & Computer Science
The Weizmann Institute of Science
Rehovot 76100, Israel
email: *fraenkel@wisdom.weizmann.ac.il*
http://eris.wisdom.weizmann.ac.il/~fraenkel/fraenkel.html

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1. What are Combinatorial Games? What are they Good For?

Roughly speaking, the family of *combinatorial games* consists of 2-player games with perfect information (no hidden information as in some card games), no chance moves (no dice) and outcome restricted to (lose,win), (tie,tie) and (draw,draw) for the two players who move alternately. Tie is an end position such as in tic-tac-toe, where no player wins, whereas draw is a dynamic tie, i.e., any position from which a player has a nonlosing move, but cannot force a win. Both the easy game of Nim and the seemingly difficult chess are examples of combinatorial games. We use the shorter terms *game* and *games* below to designate combinatorial games.

Amusing oneself with games may sound like a frivolous occupation. But the fact is that the bulk of interesting and natural mathematical problems which are hardest in complexity classes beyond *NP*, such as *P*space, *E*xtime and *E*xspace, are 2-player games; occasionally even 1-player games (puzzles) or even 0-player games (Conway's "Life"). Two of the reasons for this high complexity are outlined below. Before that we note that in addition to a natural appeal of the subject, there are applications or connections to various areas, including complexity, logic, graph and matroid theory, networks, error-correcting codes, surreal numbers, on-line algorithms and biology.

But when the chips are down, it is this "natural appeal" which compels both amateurs and professionals to become addicted to the subject. What is the essence of this appeal? Perhaps it is rooted in our primal beastly instincts; the desire to corner, torture, or at least dominate our peers. An intellectually refined version of these dark desires, well hidden under the façade of scientific research, is the consuming strive "to beat them all", to be more clever than the most clever, in short — to create the tools to defeat them all. Reaching this goal is particularly satisfying and sweet in the context of combinatorial games, in view of their inherent high complexity.

2. Why are Combinatorial Games Hard?

Decision problems such as Traveling Salesperson (Is there a round tour through specified cities of cost $\leq C$?) or graph hamiltonicity are *existential*: "Is there…?", involving a single existential quantifier. In mathematical terms an existential problem boils down to finding a path, in a large "decision-tree" of all possibilities, which satisfies specified properties. The above two problems, as well as thousands of other interesting and important combinatorial-type problems are NP-*complete*. This means that they are *conditionally intractable*, i.e., the best way to solve them seems to require traversal of most if not all of the decision tree, whose size is exponential in the input size of the problem. No better method is known to date at any rate, and if an efficient solution will ever be found for any NP-complete problem, then all NP-complete problems will be solvable efficiently.

The decision problem whether White can win if White moves first in a chess game, on the other hand, has the form: "$\exists\forall\exists\forall\cdots$: White wins?", i.e., is there a move of White such that for every move of Black there is a move of White$\cdots$ such that White can win? Here we have a large number of alternating quantifiers rather than a single existential one. We are looking for an entire subtree rather than just a path in the decision tree. The problem for generalized chess on an $n \times n$ board is in fact Extime-complete, which is a *provable intractability*. Most games are at least Pspace-hard.

Put in simple language, in analyzing an instance of Traveling Salesperson, the problem itself is passive: it does not resist your attempt to attack it, yet it is difficult. In a game, in contrast, there is your opponent, who, at every step, attempts to foil your effort to win. It's similar to the difference between an autopsy and surgery. Einstein, contemplating the nature of physics said, "Der Allmächtige ist nicht boshaft; Er ist raffiniert" (The Almighty is not mean; He is sophisticated). NP-complete existential problems are perhaps sophisticated. But your opponent in a game can be very mean!

Another reason for the high complexity of games is connected with the fundamental notion of *sum* (disjunctive compound) of games. A sum is a finite collection of disjoint games; often very basic, simple games. Each of the two players, at every turn, selects one of the games and makes a move in it. If the outcome is not a draw, the sum-game ends when there is no move left in any of the component games. If the outcome is not a tie either, then in *normal* play, the player first unable to move loses and his opponent wins. The outcome is reversed in *misère* play.

The *game-graph* of a game is a directed graph whose vertices are the positions of the game, and (u, v) is an edge if and only if there is a move from position u to position v. It turns out that the game-graph of a sum has size exponential in the combined size of the input game-graphs! Since sums occur naturally and frequently, and since analyzing the sum entails reasoning about its game-graph, we are faced with a problem which is *a priori* exponential, quite unlike most present-day interesting existential problems.

3. Breaking the Rules

As the experts know, some of the most exciting games are obtained by breaking some of the rules for combinatorial games, e.g., permitting a player to pass a bounded or unbounded number of times, relaxing the requirement that players play alternately, or permitting a number of players other than 2. But by far the most fruitful tampering with the rules seems to be to permit sums of games which are not quite fixed (which explains why misère play of sums of games is much harder than normal play) or not quite disjoint (Welter) or the game does not seem to decompose into a sum (Geography or Poset Games).

On the other hand, permitting a payoff function different from (0,1) = (lose,win) or (1/2,1/2) = (draw,draw) usually, but not always, leads to games which are not considered to be combinatorial games, or to borderline cases.

4. Why is the Bibliography Vast?

In the realm of existential problems, such as sorting or Traveling Salesperson, most present-day interesting decision problems can be classified into tractable, conditionally intractable, and provably intractable ones. There are exceptions, to be sure, e.g. graph isomorphism and primality testing, whose complexity is still unknown. But these are few. It appears that, in contrast, there is a very large set of games whose complexities are hard to determine. The set of these games is termed *Wonderland*, because we are wondering about the complexity classification of its members. Only few games have been classified into the complexity classes they belong to. Today, most games belong to Wonderland, and despite recent impressive progress, the tools for reducing Wonderland are still few and inadequate.

To give an example, many interesting games have a very succinct input size, so a polynomial strategy is often more difficult to come by (Octal games; Grundy's game). Succinctness and non-disjointness of games in a sum may be present simultaneously (poset games). In general, "breaking the rules" and the alternating quantifiers add to the volume of Wonderland. We suspect that the large size of Wonderland, a fact of independent interest, is the main contributing factor to the bulk of the bibliography on games.

5. Why isn't it Larger?

The bibliography below is a partial list of books and articles on combinatorial games and related material. It is partial not only because I constantly learn of additional relevant material I did not know about previously, but also because of certain self-imposed restrictions. The most important of these is that only papers with some original and nontrivial mathematical content are considered. This excludes most historical reviews of games and most, but not all, of the work on heuristic or artificial intelligence approaches to games, especially the large literature concerning computer chess. I have, however, included the compendium Levy [1988], which, with its 50 articles and extensive bibliography, can serve as a first guide to this world. Also some papers on chess-endgames and clever exhaustive computer searches of some games have been included.

On the other hand, papers on games which break some of the rules of combinatorial games are included liberally, as long as they are interesting and retain a combinatorial flavor. These are vague and hard to define criteria, yet combinatorialists usually recognize a combinatorial game when they see it. Besides, it is interesting to break also this rule sometimes! Adding borderline cases is acknowledged in the "related material" postfixed to the title of this bibliography. We have included some references to 1-player games, e.g., towers of Hanoi and peg-solitaire, but hardly any on 0-player games (such as Life). We have also included papers on various applications of games, especially when the connection to games is substantial or the application is important.

In 1990, *Theoretical Computer Science* has inaugurated a Mathematical Games Section whose main purpose is to publish papers on combinatorial games. The "Aims and Scope" and the names and addresses of the Mathematical Games Section editors are printed in the first issue of every volume of TCS. Prospective authors are cordially invited to submit their papers (in triplicate), to one of the editors whose interests seem closest to the field covered by the paper. This forum is beginning to become a focal point for high-class research results in the field of combinatorial games, thus increasing the bibliography at a moderate pace.

6. Cold and Hot Versions

The game bibliography below is very dynamic in nature. Previous versions have been circulated to colleagues for many years, intermittently, since the early 80's. Prior to every mailing updates were prepared, and usually also afterwards, as a result of the comments received from several correspondents. The listing can never be "complete". Thus also the present form of the bibliography is by no means complete.

Because of its dynamic nature, it is natural that the bibliography now became a "Dynamic Survey" in the Dynamic Surveys (DS) section of the *Electronic Journal of Combinatorics* (ElJC) and *The World Combinatorics Exchange* (WCE). The ElJC and WCE are on the World Wide Web (WWW), and the DS can be accessed via the Uniform Resource Locator (URL):

http://ejc.math.gatech.edu:8080/Journal/Surveys/index.html

It contains a copy of the *cold* version of the bibliography, together with the date of the latest modification.

Any document on the WWW may contain short text portions (underlined, or colored) which are *hypertext*, i.e., each such portion contains a hidden link to another relevant document. Clicking with your mouse on this *hot* hypertext brings up that document onto your screen, wherever in the world it may physically reside. Portions of that document may also be hot (clickable), and so the entire world is hyperlinked into a web, i.e., virtualized into a complex mosaic, all at your fingertips. In fact, a good way to access the WWW is via its interface *Mosaic*!

It is thus natural to have also a *hot* version of the bibliography. In it, the bibliographic items are hypertext, and so clicking on a hot item retrieves the document itself, displaying it on your screen for browsing, reading or downloading. A hot version is currently under construction.

7. Hot and Cold Help

For the hot version to grow into a bibliography of practical value, we need the links to the bibliographic items. These links are mainly of two types.

- Links to papers published in refereed electronic journals, proceedings or books published by scientific societies or commercial enterprises directly from authors' TEX-files. At this time there are only few of these, but that is likely to change rapidly.
- Links to the documents in the authors' own home directories or ftp archives.

Authors and readers who have this information are requested to send it to me. Note that some copyright questions may be involved. Each author should clear those prior to submitting the hyper-links to me. Authors should send *updates* of the links to the Managing Editor of ElJC at `calkin@math.gatech.edu` . Updates should be sent whenever there is a change in the link, due e.g., to host and/or directory changes; even if a file is replaced by a compressed version of it, since its name changed!

Regarding the cold and hot versions alike, I wish to ask the readers to continue sending to me corrections and comments; and inform me of significant omissions, remembering, however, that it is a *selected* bibliography. I prefer to get reprints, preprints or URL's, rather than only titles, whenever possible.

8. Idiosyncrasies

Due to the changes announced in the previous section, hard copies of the bibliography will not be mailed out any more, with the possible exception of a few copies to individuals without access to the Internet.

Most of the bibliographic entries refer to items written in English, though there is a sprinkling of Danish, Dutch, French, German, Japanese, Slovakian and Russian, as well as some English translations from Russian. The predominance of English may be due to certain prejudices, but it also reflects the fact that nowadays the *lingua franca* of science is English. In any case, I'm soliciting also papers in languages other than English, especially if accompanied by an abstract in English.

Three correspondents, including myself, have expressed the opinion that the value of the bibliography would be enhanced if it would be transformed into an annotated bibliography. This may be done sometime in the future.

On the administrative side, Technical Reports, submitted papers and unpublished theses have normally been excluded; but some exceptions have been made. Abbreviations of book series and journal names follow the *Math Reviews* conventions. Another convention is that de Bruijn appears under D, not B; von Neumann under V, not N, McIntyre under M not I, etc. The bibliography, with 400 items, was the master bibliography of *Proc. Sympos. Appl. Math.* **43**, 1991 (R.K. Guy, ed.), Amer. Math. Soc., Providence, RI.

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