

Combinatorial Games: Selected Bibliography With A Succinct Gourmet Introduction

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

Roughly speaking, the family of *combinatorial games* consists of two-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: 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. And so is Go. 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 that are hardest in complexity classes beyond *NP*, such as *Pspace*, *Exptime* and *ExpSPACE*, are two-player games; occasionally even one-player games (puzzles) or even zero-player games (Conway's "Life"). Two of the reasons for the high complexity of two-player games 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” that compels both amateurs and professionals to become addicted to the subject. What is the essence of this appeal? Perhaps the urge to play games 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 local, national or international tournaments or 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 *Math-master* them all in hot *combinatorial combat*! 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 graph hamiltonicity and Traveling Salesperson (Is there a round tour through specified cities of cost $\leq C$?) are *existential*: they involve a single existential quantifier (“Is there...?”). In mathematical terms an existential problem boils down to finding a path, in a large “decision-tree” of all possibilities, that 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: Is there a move of White such that for *every* move of Black there is a move of White such that for *every* move of Black there is a move of White ... such that White can win? Here we have a large number of alternating existential and universal 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 Exptime-complete, which is a *provable intractability*. Most nonpolynomial 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 the 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 that is *a priori* exponential, quite unlike many 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, such as permitting a player to pass a bounded or unbounded number of times, i.e., relaxing the requirement that players play alternately; or permitting a number of players other than two. But by far the most fruitful tampering with the rules seems to be to permit sums of games that 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).

But permitting a payoff function other than $(0, 1) = (\text{lose}, \text{win})$ or $(\frac{1}{2}, \frac{1}{2}) = (\text{draw}, \text{draw})$ usually, but not always, leads to games that 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 the exceptions are few. It appears that, in contrast, there is a very large set of games whose complexities are hard to determine. We call the set of these games *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 that 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! We have included some references to one-player games, e.g., towers of Hanoi, n -queen problems, 15-puzzle and peg-solitaire, but only few zero-player games (such as Life and games on “sand piles”). 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* 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 invited to submit their papers by email (postscript is preferred) or snailmail (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 contributing to the increase of the bibliography.

6 The Dynamics of the Literature

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 became a “Dynamic Survey” in the Dynamic Surveys (DS) section of the *Electronic Journal of Combinatorics* (EJJC) and *The World Combinatorics Exchange* (WCE). The EJJC and WCE are on the World Wide Web (WWW), and the DS can be accessed at

<http://www.combinatorics.org/Surveys/index.html>

The journal itself can be found at

<http://www.combinatorics.org/>

There are mirrors at various locations. Furthermore, the European Mathematical Information Service (EMIS) mirrors this Journal, as do all of its mirror sites (over thirty of them). See

<http://www.emis.de/tech/mirrors.html>

Hereby I 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 URLs, rather than only titles — whenever possible.

Material on games is mushrooming on the Web. The URLs can be located using a standard searcher, such as Alta Vista.

7 Idiosyncrasies

Due to the facts stated in Section 6, hard copies of the bibliography are not 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.

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.

Earlier versions of this bibliography have appeared, under the title “Selected bibliography on combinatorial games and some related material”, as the master bibliography for the book *Combinatorial Games*, AMS Short Course Lecture Notes, Summer 1990, Ohio State University, Columbus, OH, *Proc. Symp. Appl. Math.* **43** (R. K. Guy, ed.), AMS 1991, pp. 191–226 with 400 items, and in the *Dynamic Surveys* section of the *Electronic J. of Combinatorics* in November 1994 with 542 items (updated there at odd times). It also appeared as the master bibliography in: *Games of No Chance*, Proc.

MSRI Workshop on Combinatorial Games, July, 1994, Berkeley, CA (R. J. Nowakowski, ed.), MSRI Publ. Vol. 29, Cambridge University Press, Cambridge, pp. 493–537, under the title *Combinatorial games: selected bibliography with a succinct gourmet introduction*, containing 666 items.

8 Suggestions and Questions

Two correspondents and myself have expressed the opinion that the value of the bibliography would be enhanced if it would be transformed into an annotated bibliography. Do you think this should be done?

One correspondent has suggested to include a list of combinatorial games people, with email addresses and URLs, where available.

One correspondent and myself think that the bibliography has, after the August 1995 update, become somewhat unwieldy:

1. Should henceforth new additions be kept in separate files? Disadvantage: machine searching will have to be done on several (.tex) files, and visual search on several .ps files. However, some of the older updates may be merged with the main part, after a while.

2. The bibliography could be broken up into sections of related papers. Thus, zero-person and one-person games could be in one section, games of imperfect information or those with chance moves in another, complexity papers in a third, partizan games in another, impartial games in still another, etc. The disadvantage here is that some papers will belong to several sections. For example, papers dealing with complexity aspects of impartial games, or of games with imperfect information. This could be amended by using crossreferences to other sections, at the price of some further unwieldiness.

3. Neither of these two avenues looks particularly attractive. Any suggestions on this or other points?

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