

Theory of Computer Games

電腦對局理論

Tsan-sheng Hsu

徐讚昇

tshsu@iis.sinica.edu.tw

<http://www.iis.sinica.edu.tw/~tshsu>

Goal

- Course name: Theory of Computer Games

● 電腦對局理論

- 十二週年!!!
- Prerequisite: Computer Programming, **Linux/Unix**, C/C++, and Data Structure and Algorithms.
 - **Enjoy playing classical board games!**
 - **Heavy programming projects!**
- Goal: This course introduces techniques for computers to play various games which include Chinese chess and Go.
- Disclaimers:
 - **NOT** yet a course on game theory.
 - **NOT** yet a course on video games.
 - **NOT** yet a course on war game simulations.
- Web page:
<http://www.iis.sinica.edu.tw/~tshsu/tcg/2018>

About this course

- Time and Place: Every Thursday from 2:20pm to 5:20pm at Room 105 (NTU CSIE building).

Sep 13 20 27

Oct 4 11 18 25

- Dates: Nov 1 8 15 22 29

Dec 6 13 20 27

Jan 3 17

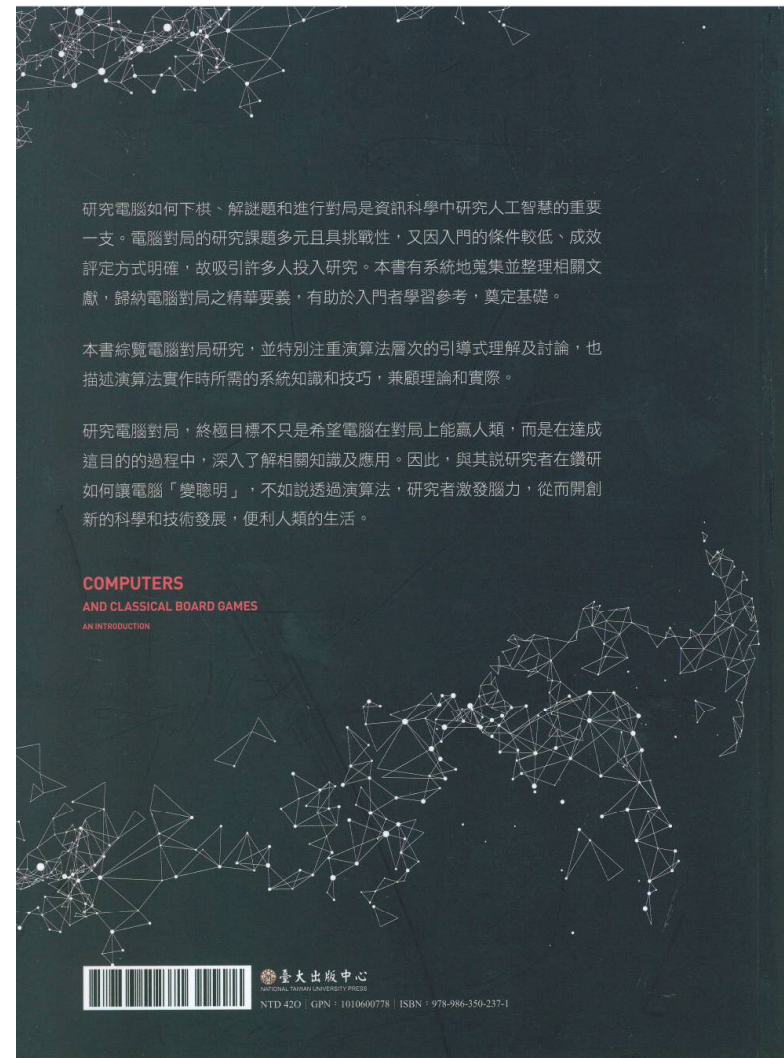
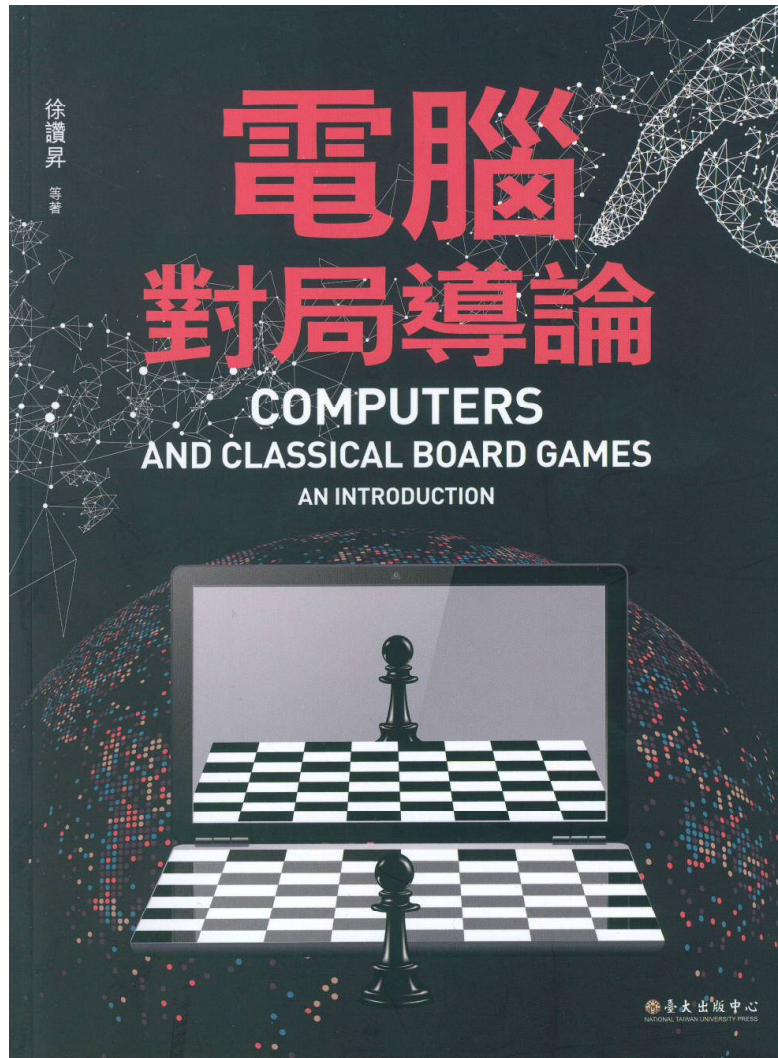
- Format:

- Lectures.
- Presentations for homework projects (optional).
- Invited lectures: TBA.

- Class materials

- textbook: 電腦對局導論, 臺大出版中心, June 2017 ; ISBN: 978-986-350-237-1
- Class notes
- Collection of papers

Textbook



勘誤表: <http://www.iis.sinica.edu.tw/~tshsu/tcg/errata.pdf>

電腦對局導論

Computers and classical board games: An Introduction
2017年6月一版

勘誤表

日期：2018年1月9日

頁碼/位置	內容	
	修改前	修改後
p. I 序一的第二段	預官退伍之後，讚昇出國到美國德州奧斯汀大學深造，專攻演算法研究。	預官退伍之後，讚昇出國到美國德州大學奧斯汀校區深造，專攻演算法研究。
p. I 序一的第三段	2005年8月，讚昇與我共同主辦第十屆國際電腦奧林匹亞大賽和 CG2005 電腦對局國際會議，開啓 ICGA 國際電腦對局學會在亞洲地區舉辦活動的新頁。	2005年8月，讚昇與我共同主辦第十屆國際電腦奧林匹亞大賽和 CG2005 電腦對局國際會議，開啓 ICGA 國際電腦對局學會在亞洲地區舉辦活動的新頁。
演算法目錄之15	15 F' (position p)	15 F' (position p , integer $depth$)
演算法目錄之16	16 G' (position p)	16 G' (position p , integer $depth$)
演算法目錄之17	17 F (position p)	17 F (position p , integer $depth$)
演算法目錄之18	18 $F2'$ (position p , value $alpha$, value $beta$)	18 $F1'$ (position p , value $alpha$, value $beta$)
演算法目錄之19	19 $G2'$ (position p , value $alpha$, value $beta$)	19 $G1'$ (position p , value $alpha$, value $beta$)
演算法目錄之20	20 $F2$ (position p , value $alpha$, value $beta$)	20 $F2$ (position p , value $alpha$, value $beta$, integer $depth$)
演算法目錄之36	36 $F4.4'$ (position p , value $alpha$, value $beta$, integer $depth$, Boolean <u>do_null</u>)	36 $F4.4'$ (position p , value $alpha$, value $beta$, integer $depth$, Boolean <u>in_null</u>)
演算法目錄之37	37 $F4.5'$ (position p , value $alpha$, value $beta$, integer $depth$, Boolean <u>do_lmr</u>)	37 $F4.5'$ (position p , value $alpha$, value $beta$, integer $depth$, Boolean <u>in_lmr</u>)
演算法目錄之59	59 $F2.1'$ (position p , value $alpha$, value $beta$)	59 $F3.1'$ (position p , value $alpha$, value $beta$)
演算法目錄之60	60 $Star1_F2.1'$ (position p , node n , value $alpha$, value $beta$)	60 $Star1_F3.1'$ (position p , node n , value $alpha$, value $beta$)
p. 7 的 1.4 節	Barbara Liskov 2008年)	Barbara Liskov (2008年)
p. 9 的 1.4.4 節	因為西洋棋被認為是相當複雜且具有高度智慧的行為表現，1997年IBM的深藍超級電腦 (Deep Blue Supercomputer) 打敗人類的西洋棋棋王Garry Kasparov 被視為電腦弈棋研究中最為重要里程碑之一。	因為西洋棋被認為是相當複雜且具有高度智慧的行為表現，1997年IBM的深藍超級電腦 (Deep Blue Supercomputer) 打敗人類的西洋棋棋王Garry Kasparov 被視為電腦弈棋研究中最重要里程碑之一。
p.11 的 1.5.2 節	目前觀察到一個謎題必須至少要有 NP 完備的難度才會耐玩。	目前觀察到一個謎題必須至少要有 NP 完備的難度才會耐玩。

Acknowledgements

- **Thanks to the students of this course for providing constructive feedbacks on the slides.**
 - **Classes of 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016 and 2107.**
- **Special thanks to the following persons.**
 - **Yuh-Jie Chen (class of 2008)**
 - **Jenny Chang (class of 2011)**
 - **Jessica Lin (class of 2011)**
 - **許祐程 (TA of the 2012 class)**

Evaluation (1/3)

■ Homework (30%)

● One homework project about single-agent search (15%)

- ▷ *About single agent search, single-person project, Linux/Unix knowledge is **required**.*
- ▷ *Implement different techniques learned from the class and compare the results.*

● One homework project about Monte-Carlo simulation (15%)

- ▷ *A 2-player game with a strong Monte Carlo flavor, single-person project, Linux/Unix knowledge is **required**.*
- ▷ *Your program against TA's program, and against all other students.*

■ Written exam: midterm exam (30%)

Evaluation (2/3)

- **Final project (40%)**
 - An alpha-beta based computer game program for Chinese Dark Chess.
 - ▷ *A sample code with GUI will be provided.*
 - ▷ *The usage of this sample code is restricted for anything related to this course only.*
 - The 12th NTU-TCG Cup.
 - A whole day tournament, attendance is **required!!**
 - Submitted package: Code + documents.
- **Class participation (bonus)**

Evaluation (3/3)

- **Presentation/Report of a research paper on game tree search.**
 - **If we have more than 16 students, then**
 - ▷ *Bonus for selected students who are obviously falling behind.*
 - If we have less than 17 students, then**
 - ▷ *This is required for each student.*
 - ▷ *This will be 10% of your score in which case the two programming homework each take 10%.*
 - **If time allows, give an in-class presentation.**
 - ▷ *Discussion before presentation.*
 - ▷ *30-minute talk.*
 - ▷ *≤ 30 slides in PDF format.*
 - ▷ *10–15 minutes of Q & A.*
 - ▷ *Each student asks ≥ 1 non-trivial question.*
 - ▷ *Submit your revised set of slides one week later.*
 - **If time does not allow, submit a written report.**
 - ▷ *Pick a paper related to the course.*
 - ▷ *Write a report with at least 1000 words in PDF format.*
 - ▷ *Summary of results in the paper.*
 - ▷ *Comments about this paper, its strength, weakness and potential improvements.*

Lecturing format

- **For each topic**
 - **The first and most influential papers are introduced.**
 - **A list of recent and latest papers is provided for further readings and/or topics for presentations.**

Course at a glance (1/2)

- Introduction: an A.I. oriented overview
- Single-player games
 - Basic techniques
 - Advanced techniques
- **Homework 1: October**
- Two-player perfect information games
 - Survey
 - Introduction from Chess's point of view
 - Alpha-beta and its extensions
- **Midterm exam: November**

Course at a glance (2/2)

- Two-player perfect information games
 - Monte-Carlo based method
- **Homework 2: December**
- **Practical considerations**
 - Memorizing knowledge
 - ▷ *Transposition tables*
 - ▷ *Endgame databases*
 - Advanced pruning techniques
 - Parallelization (?)
 - The graph-history interaction (GHI) problem
 - Opponent model (?)
 - Timing control
 - Hardware enhancements (?)
- **Conclusion**
- **Final project: January**

Introduction and an A.I. oriented overview

- **Relations between computer games and Artificial Intelligence.**
 - Why we study computer games?
 - Why we play or study games?
- **History [SvdH02] [Sha50a]**
 - The Turk, a chess playing “machine” at 1780’s [LN82]
 - The endgame playing machine at 1910’s [McC04]
 - C. E. Shannon (1950) [Sha50b] and A. Samuel (1960) [Sam60]
- **Games that machines have beaten human champions [SvdH02] [Sch00]**
 - Chess [CHH02]
 - Othello [Bur97]
 - Checker [SLLB96]
 - Go [SHM⁺16]
 - ...

Single-player games

- **Games that can be played by one person [DH09]**
 - combinatorial games such as 15-puzzle or Sudoku
 - other solitaire
- **Classical approaches [Kor85] [KF02] [CS98]**
 - Brute-force, BFS, DFS and its variations including DFID
 - Bi-directional search
 - A*
 - IDA*
 - IDA* with databases
- **Disk-based approach [KS05]**

Two-player perfect information games (1/2)

- A survey of current status [vdHUvR02]
- The original Computer Chess paper by C.E. Shannon [Sha50a] in 1950.
- Classical approaches
 - ▷ *Alpha-beta search and its analysis* [KM75]
 - ▷ *Scout and Negascout* [Pea80] [Rei83] [Fis83]
 - ▷ *MTD(f): Best-first fixed-depth search* [PSPdB96] [Pea80] if time allowed
- Enhancements to the classical approaches
 - ▷ *Aspiration search*
 - ▷ *Quiescence search* [Bea90]
 - ▷ *Move ordering and other techniques* [Sch89] [AN77] [Hsu91]
 - ▷ *Further pruning techniques* [SP96] including null move pruning and late move reduction
 - ▷ *Proof-number search* [AvdMvdH94] if time allowed

Two-player perfect information games (2/2)

- **Monte-Carlo game tree search [BPW⁺12]**
 - Original ideas [Bru93]
 - Best first game tree growing
 - UCT
 - Pruning techniques
 - ▷ *Online knowledge [BH04] [YYK⁺06]*
 - ▷ *Offline knowledge [ST09] [HCL10a]*
 - ▷ *Deep learning [SHM⁺16]*
- **Case study:**
 - Computer Chinese chess [YCYH04]
 - Computer Chinese dark chess [CSH10] if time allowed

Practical considerations (1/2)

- **Transposition tables**
 - Recording prior-search results to avoid researching
 - Design of a good hash function
 - ▷ *Zobrist's hash function [Zob70]*
- **Open-game [Hya99] [Bur99] and endgame databases [Tho86] [Tho96] [WLH06]**
 - Off-line collecting of knowledge
 - Computation done in advance
- **Parallelization**
 - Parallel alpha-beta based game tree search [Bro96] [FMM94] [HM02] [HSN89] [Hya97] [Man01]
 - Parallel Monte-Carlo game tree search [CJ08] [CWvdH08]
- **The graph-history interaction (GHI) problem [Cam85] [BvdHU98] [WHH05]**
 - The value of a position depends on the path leading to it.
 - ▷ *Position value is dynamic and static.*

Practical considerations (2/2)

- **Opponent model [CM96]**
 - How to take advantage of knowing the playing style of your opponent.
- **Timing and resource usage control [Hya84] [HGN85] [MS93]**
 - Using time wisely
 - ▷ *Use too little time in the opening may be fatal.*
 - ▷ *Use too much time in opening may be fatal, too.*
 - ▷ *Knowledge from real tournament environments [vV09].*
 - ▷ *For Monte-Carlo type of search [HCL10b].*
- **Hardware enhancements [DL04]**

Other games – if time allowed

- **Games with imperfect information and stochastic behaviors [FBM98]**
 - Backgammon
 - Bridge
- **Multi-player games [Stu06]**
 - Poker
 - Majon

Concluding remarks

- Search chance nodes
- How to put everything together?
- How to test your implementation?
- How to measure the strength?

Resources (1/6)

■ ICGA web site

- <http://ticc.uvt.nl/icga/>
- Formally as ICCA (International Computer Chess Association)
 - ▷ *Between 1977 and 2001.*
- International Computer Games Association
 - ▷ *Since 2002.*
- Host of Computer Olympiad
 - ▷ *International competition of games played by computers*
 - ▷ *1989 at London, United Kingdom (1st)*
 - ▷ *...*
 - ▷ *2004 at Ramat-Gan, Israel (9th)*
 - ▷ *2005 at Taipei, Taiwan (10th)*
 - ▷ *...*
 - ▷ *2011 at Tilburg, the Netherlands (16th)*
 - ▷ *2013 at Yokohama, Japan (17th)*
 - ▷ *2015–2017 at Leiden, the Netherlands (18–20th)*

Resources (2/6)

- **TCGA web site**
 - Taiwan Computer Games Association
 - Since 2011.
 - <http://tcga.ndhu.edu.tw>
 - Annual June conference and tournaments
- **TAAI game tournaments**
 - Taiwan AI Association
 - ▷ <http://www.taai.org.tw/TAAI/>
 - Annual conference since 2001
 - Annual November game tournament since 2009

Resources (3/6)

■ Proceedings of IJCAI

- International Joint Conference on Artificial Intelligence
- Covers all areas of A.I.
- Computer games occupy only a small session now
- Since 1969, odd numbered of years

■ Proceedings of AAAI

- Association for the Advancement of A.I.
- Covers all areas of A.I.
- Computer games occupy only a small session now
- Since 1980

Resources (4/6)

■ Proceedings of the ACG conference

- Advances in Computer Games International Conference
- Every (if possible) odd numbered of year
 - ▷ ...
 - ▷ 1999 at Paderborn Germany (9th)
 - ▷ 2003 at Graz, Austria (10th)
 - ▷ 2005 at Taipei, Taiwan (11th)
 - ▷ 2009 at Pamplona, Spain (12th)
 - ▷ 2011 at Tilburg, the Netherlands (13th)
 - ▷ 2015, 2017 at Leiden, the Netherlands (14th,15th)

■ Proceedings of the CG conference

- Computers and Games International Conference
- Since 1998, **almost** even numbered of years
 - ▷ 1998 (1st), 2000, 2002, 2004, 2006, 2008, 2010 (7th), 2013 (8th), 2016 (9th), 2018 (New Taipei City, Taiwan)

Resources (5/6)

- **Proceedings of IEEE CIG**
 - Computational Intelligence and Games International Conference
 - Since 2005, every year.
 - Video game, classical games, ...
- **Proceedings of the Computer Games Workshop (CGW)**
 - Since 2012, every year.
 - Classical games, 2017 with IJCAI at Melbourne, Sunday August 20th, 2017.

Resources (6/6)

- **Artificial Intelligence**
 - Flagship journal
 - Since 1970
- **ICGA journal**
 - Quarterly publication since 1977
- **The A.I. magazine**
 - Journal for AAAI
 - Since 1980
- **IEEE Transactions on Computational Intelligence and A.I. in Games**
 - An IEEE journal
 - Quarterly publication since 2009
 - Since, 2017, IEEE Transactions on Games.

Collection of papers

References

- [ACBF02] P. Auer, N. Cesa-Bianchi, and P. Fischer. Finite-time analysis of the multiarmed bandit problem. *Machine Learning*, 47:235–256, 2002.
- [AHH11] B. Arneson, R. Hayward, and P. Henderson. Solving Hex: Beyond humans. In H. Jaap van den Herik, H. Iida, and A. Plaat, editors, *Lecture Notes in Computer Science 6515: Proceedings of the 7th International Conference on Computers and Games*, pages 1–10. Springer-Verlag, New York, NY, 2011.
- [AN77] Selim G. Akl and Monroe M. Newborn. The principal continuation and the killer heuristic. In *ACM '77: Proceedings of the 1977 annual conference*, pages 466–473, New York, NY, USA, 1977. ACM Press.

- [AvdHH91] L. V. Allis, H. J. van den Herik, and I.S. Herschberg. Which games will survive? In D.N.L. Levy and D.F. Beal, editors, *Heuristic Programming in Artificial Intelligence 2: The Second Computer Olympiad*, volume 2, pages 232–243. Ellis Horwood, Chichester, England, 1991.
- [AvdMvdH94] L. V. Allis, M. van der Meulen, and H. J. van den Herik. Proof-number search. *Artificial Intelligence*, 66(1):91–124, 1994.
- [Bal83] Bruce W. Ballard. The *-minimax search procedure for trees containing chance nodes. *Artificial Intelligence*, 21(3):327 – 350, 1983.
- [Bea90] D. F. Beal. A generalised quiescence search algorithm. *Artificial Intelligence*, 43:85–98, 1990.
- [BH04] B. Bouzy and B. Helmstetter. Monte-Carlo Go developments. In H. Jaap van den Herik, Hiroyuki Iida, and Ernst A. Heinz, editors, *Advances in Computer Games, Many Games, Many Challenges, 10th*

International Conference, ACG 2003, Graz, Austria, November 24-27, 2003, Revised Papers, volume 263 of *IFIP*, pages 159–174. Kluwer, 2004.

- [Bou04] Bruno Bouzy. Associating shallow and selective global tree search with Monte Carlo for 9x9 Go. In *Lecture Notes in Computer Science 3846: Proceedings of the 4th International Conference on Computers and Games*, pages 67–80, 2004.
- [BPW⁺12] Cameron B Browne, Edward Powley, Daniel Whitehouse, Simon M Lucas, Peter Cowling, Philipp Rohlfshagen, Stephen Tavener, Diego Perez, Spyridon Samothrakis, Simon Colton, et al. A survey of monte carlo tree search methods. *Computational Intelligence and AI in Games, IEEE Transactions on*, 4(1):1–43, 2012.
- [Bro96] M.G. Brockington. A taxonomy of parallel game-tree searching algorithms. *ICCA Journal*, 19(3):162–174, 1996.
- [Bru93] B. Bruegmann. Monte Carlo Go. unpublished manuscript, 1993.

- [Bur97] Michael Buro. The othello match of the year: Takeshi murakami vs. logistello. *Icca Journal*, 20(3):189–193, 1997.
- [Bur99] M. Buro. Toward opening book learning. *International Computer Game Association (ICGA) Journal*, 22(2):98–102, 1999.
- [BvdHU98] D. M. Breuker, H. J. van dan Herik, and J. W. H. M. Uiterwijk. A solution to the GHI problem for best-first search. In H.J. van den Herik and H. Iida, editors, *Lecture Notes in Computer Science 1558: Proceedings of the 1st International Conference on Computers and Games*, pages 25–49. Springer-Verlag, New York, NY, 1998.
- [Cam85] M. Campbell. The graph-history interaction: on ignoring position history. In *Proceedings of the 1985 ACM annual conference on the range of computing : mid-80's perspective*, pages 278–280. ACM Press, 1985.
- [Che00] K. Chen. Some practical techniques for global search in Go. *International Computer Game Association (ICGA) Journal*, 23(2):67–74, 2000.

- [CHH02] Murray Campbell, A Joseph Hoane, and Feng-hsiung Hsu. Deep blue. *Artificial intelligence*, 134(1):57–83, 2002.
- [CHP⁺09] G. Chaslot, J.-B. Hoock, J. Perez, A. Rimmel, O. Teytaud, and M. Winands. Meta monte-carlo tree search for automatic opening book generation. In *The IJCAI-09 Workshop on General Game Playing General Intelligence in Game-Playing Agents (GIGA'09)*, 2009.
- [CJ08] T. Cazenave and N. Jouandeau. A parallel Monte-Carlo tree search algorithm. In H. Jaap van den Herik, X. Xu, Z. Ma, and M. H.M. Winands, editors, *Lecture Notes in Computer Science 5131: Proceedings of the 6th International Conference on Computers and Games*, pages 72–80. Springer-Verlag, New York, NY, 2008.
- [CLHH06] B.-N. Chen, P.F. Liu, S.C. Hsu, and T.-s. Hsu. Abstracting knowledge from annotated chinese-chess game records. In H. Jaap van den Herik, P. Ciancarini, and H.H.L.M. Donkers, editors, *Lecture Notes in Computer Science 4630: Proceedings of the 5th International Conference on Computers and Games*, pages 100–111. Springer-Verlag, New York, NY, 2006.

- [CLHH08] B.-N. Chen, P.F. Liu, S.C. Hsu, and T.-s. Hsu. Knowledge inferencing on Chinese chess endgames. In H. Jaap van den Herik, X. Xu, Z. Ma, and M. H.M. Winands, editors, *Lecture Notes in Computer Science 5131: Proceedings of the 6th International Conference on Computers and Games*, pages 180–191. Springer-Verlag, New York, NY, 2008.
- [CLHH10] B.-N. Chen, P.F. Liu, S.C. Hsu, and T.-s. Hsu. Conflict resolution of Chinese chess endgame knowledge base. In H. Jaap van den Herik and P. Spronck, editors, *Lecture Notes in Computer Science 6048: Proceedings of the 12th Advances in Computer Games Conference*, pages 146–157. Springer-Verlag, New York, NY, 2010.
- [CLHH11] B.-N. Chen, P.F. Liu, S.C. Hsu, and T.-s. Hsu. Knowledge abstraction in Chinese chess endgame databases. In H. Jaap van den Herik, H. Iida, and A. Plaat, editors, *Lecture Notes in Computer Science 6515: Proceedings of the 7th International Conference on Computers and Games*, pages 176–187. Springer-Verlag, New York, NY, 2011.
- [CLHH12] B.-N. Chen, B.-F. Liu, S.-C. Hsu, and T.-s. Hsu. Aggregating

consistent endgame knowledge in Chinese chess. *Knowledge-Based Systems*, 34:34–42, 2012.

- [CM96] David Carmel and Shaul Markovitch. Learning and using opponent models in adversary search. Technical Report CIS9609, Technion, 1996.
- [Cou06] Rémi Coulom. Efficient selectivity and backup operators in Monte-Carlo tree search. In *Lecture Notes in Computer Science 4630: Proceedings of the 5th International Conference on Computers and Games*, pages 72–83. Springer-Verlag, 2006.
- [CS98] J. Culberson and J. Schaeffer. Pattern databases. *Computational Intelligence*, 14(3):318–334, 1998.
- [CS11] T. Cazenave and A. Saffidine. Score bounded Monte-Carlo tree search. In H. Jaap van den Herik, H. Iida, and A. Plaat, editors, *Lecture Notes in Computer Science 6515: Proceedings of the 7th International Conference on Computers and Games*, pages 93–104. Springer-Verlag, New York, NY, 2011.

- [CSH10] B.-N. Chen, B.-J. Shen, and T.-s. Hsu. Chinese drak chess. *International Computer Game Association (ICGA) Journal*, 33(2):93–106, 2010.
- [CTH12] H.-J. Chang, M.-T. Tsai, and T.-s. Hsu. Game tree search with adaptive resolution. In H. Jaap van den Herik and A. Plaat, editors, *Lecture Notes in Computer Science 7168: Proceedings of the 13th Advances in Computer Games Conference*, pages 306–319. Springer-Verlag, New York, NY, 2012.
- [CtSU⁺06] Guillaume Chaslot, Jahn takeshi Saito, Jos W. H. M. Uiterwijk, Bruno Bouzy, and H. Jaap Herik. Monte-Carlo strategies for computer Go. In *Proceedings of the 18th BeNeLux Conference on Artificial Intelligence*, pages 83–91, Namur, Belgium, 2006.
- [CWvdH08] G. M.J.-B. Chaslot, M. H.M. Winands, and H. J. van den Herik. Parallel Monte-Carlo tree search. In H. Jaap van den Herik, X. Xu, Z. Ma, and M. H.M. Winands, editors, *Lecture Notes in Computer Science 5131: Proceedings of the 6th International Conference on Computers and Games*, pages 60–71. Springer-Verlag, New York, NY, 2008.

- [DH01] E. Demaine and R. A. Hearn. Playing games with algorithms: Algorithmic combinatorial game theory. Technical report, Massachusetts Institute of Technology, USA, 2001. <http://arxiv.org/abs/cs.CC/0106019>, last revised 22 April 2008.
- [DH09] E Demaine and B Hearn. Games, puzzles, and computation. *AK Peters: I-IX*, pages 1–237, 2009.
- [DL04] C. Donninger and U. Lorenz. The chess monster Hydra. In Jürgen Becker, Marco Platzner, and Serge Vernalde, editors, *Field Programmable Logic and Application, 14th International Conference , FPL 2004, Leuven, Belgium, August 30-September 1, 2004, Proceedings*, volume 3203 of *Lecture Notes in Computer Science*, pages 927–932. Springer, 2004.
- [DL05] C. Donninger and U. Lorenz. Innovative opening-book handling. In H. Jaap van den Herik, Shun-Chin Hsu, Tsan-sheng Hsu, and H.H.L.M. Donkers, editors, *Lecture Notes in Computer Science 4250: Proceedings of the 11th Advances in Computer Games Conference*, pages 1–10, New York, NY, 2005. Springer-Verlag.

- [EM10] Markus Enzenberger and Martin Müller. A lock-free multi-threaded Monte-Carlo tree search. In H. Jaap van den Herik and P. Spronck, editors, *Lecture Notes in Computer Science 6048: Proceedings of the 12th Advances in Computer Games Conference*, pages 14–20. Springer-Verlag, New York, NY, 2010.
- [FBM98] I. Frank, D. A. Basin, and H. Matsubara. Finding optimal strategies for imperfect information games. In *AAAI/IAAI*, pages 500–507, 1998.
- [Fis83] John P. Fishburn. Another optimization of alpha-beta search. *SIGART Bull.*, (84):37–38, 1983.
- [FMM94] Rainer Feldmann, Peter Mysliwietz, and Burkhard Monien. Studying overheads in massively parallel min/max-tree evaluation. In *SPAA*, pages 94–103, 1994.
- [Gin99] Matthew L. Ginsberg. Gib: Steps toward an expert-level bridge-playing program. In *In Proceedings of the Sixteenth International Joint Conference on Artificial Intelligence (IJCAI-99)*, pages 584–589, 1999.

- [GS07] Sylvain Gelly and David Silver. Combining online and offline knowledge in UCT. In *Proceedings of the 24th international conference on Machine learning, ICML '07*, pages 273–280, New York, NY, USA, 2007. ACM.
- [HAH09] P. Henderson, B. Arneson, and R. B. Hayward. Solving 8x8 Hex. In *Proceedings of IJCAI*, pages 505–510, 2009.
- [HCL10a] S. C. Huang, R. Coulom, and S. S. Lin. Monte-Carlo simulation balancing applied to 9x9 Go. *International Computer Game Association (ICGA) Journal*, 33(4):191–201, 2010.
- [HCL10b] S. C. Huang, R. Coulom, and S. S. Lin. Time management for Monte-Carlo tree search applied to the game of Go. In *International Workshop on Computer Games (IWCG)*. 2010. Hsinchu, Taiwan, Nov 18–20, 2010.
- [Hei00] E. A. Heinz. *Scalable Search in Computer Chess*. Vieweg, 2000. ISBN: 3-528-05732-7.

- [HGN85] R. M. Hyatt, A. E. Gower, and H. L. Nelson. Using time wisely, revisited (extended abstract). In *Proceedings of the 1985 ACM annual conference on the range of computing : mid-80's perspective*, pages 271–271. ACM Press, 1985.
- [HL02] T.-s. Hsu and P.-Y. Liu. Verification of endgame databases. *International Computer Game Association (ICGA) Journal*, 25(3):132–144, 2002.
- [HM02] R. M. Hyatt and T. Mann. A lockless transposition-table implementation for parallel search. *International Computer Game Association (ICGA) Journal*, 25(1):36–39, 2002.
- [HSN89] Robert M. Hyatt, Bruce W. Suter, and Harry L. Nelson. A parallel alpha/beta tree searching algorithm. *Parallel Computing*, 10(3):299–308, 1989.
- [Hsu91] S.-C. Hsu. Searching techniques of computer game playing. *Bulletin of the College of Engineering, National Taiwan University*, 51:17–31, 1991.

- [Hya84] R. M. Hyatt. Using time wisely. *International Computer Game Association (ICGA) Journal*, pages 4–9, 1984.
- [Hya97] R. M. Hyatt. The dynamic tree-splitting parallel search algorithm. *ICCA Journal*, 20(1):3–19, 1997.
- [Hya99] R. M. Hyatt. Book learning — a methodology to tune an opening book automatically. *International Computer Game Association (ICGA) Journal*, 22(1):3–12, 1999.
- [JS79] Wm. Woolsey Johnson and William E. Story. Notes on the ”15” puzzle. *American Journal of Mathematics*, 2(4):pp. 397–404, 1879.
- [Jui99] Hugues Juille. *Methods for Statistical Inference: Extending the Evolutionary Computation Paradigm*. PhD thesis, Department of Computer Science, Brandeis University, May 1999.
- [KF02] R. E. Korf and A. Felner. Disjoint pattern database heuristics. *Artificial Intelligence*, 134:9–22, 2002.

- [KM75] D. E. Knuth and R. W. Moore. An analysis of alpha-beta pruning. *Artificial Intelligence*, 6:293–326, 1975.
- [KM04] A. Kishimoto and M. Müller. A general solution to the graph history interaction problem. In *Proceedings of Nineteenth National Conference on Artificial Intelligence*, pages 644–649, 2004.
- [KMN02] Michael Kearns, Yishay Mansour, and Andrew Y Ng. A sparse sampling algorithm for near-optimal planning in large markov decision processes. *Machine Learning*, 49(2-3):193–208, 2002.
- [Kor85] R. E. Korf. Depth-first iterative-deepening: An optimal admissible tree search. *Artificial Intelligence*, 27:97–109, 1985.
- [KPS08] G. Kendall, A. Parkes, and K. Spoerer. A survey of NP-complete puzzles. *International Computer Game Association (ICGA) Journal*, 31(1):13–34, 2008.
- [KS05] R. E. Korf and P. Schultze. Large-scale, parallel breadth-first search. In *Proceedings of AAAI*, pages 1380–1385, 2005.

- [KT08] Hideki Kato and Ikuo Takeuchi. Parallel Monte-Carlo tree search with simulation servers. In *13th Game Programming Workshop (GPW-08)*, November 2008.
- [LN82] David Levy and Monroe Newborn. Chess machines. In *All About Chess and Computers*, pages 1–23. Springer Berlin Heidelberg, 1982.
- [Man01] Valavan Manohararajah. Parallel alpha-beta search on shared memory multiprocessors. Master’s thesis, Graduate Department of Electrical and Computer Engineering, University of Toronto, Canada, 2001.
- [McC04] Pamela McCorduck. Machines who think: A personal inquiry into the history and prospects of artificial intelligence, ak peters. *Natick, Mass*, 2004.
- [MS93] Shaul Markovitch and Yaron Sella. Learning of resource allocation strategies for game playing. In R. Bajcsy, editor, *Proceedings of the 13th International Joint Conference on Artificial Intelligence (IJCAI-93)*, pages 974–979, 1993.

- [Neu28] J v Neumann. Zur theorie der gesellschaftsspiele. *Mathematische Annalen*, 100(1):295–320, 1928.
- [Pea80] J. Pearl. Asymptotic properties of minimax trees and game-searching procedures. *Artificial Intelligence*, 14(2):113–138, 1980.
- [Pea82] J. Pearl. The solution for the branching factor of the alpha-beta pruning algorithm and its optimality. *Communications of ACM*, 25(8):559–564, 1982.
- [Pea84] J. Pearl. *Heuristics: intelligent search strategies for computer problem solving*. Addison-Wesley, 1984.
- [PSPdB96] Aske Plaat, Jonathan Schaeffer, Wim Pijls, and Arie de Bruin. Best-first fixed-depth minimax algorithms. *Artificial Intelligence*, pages 255–293, 1996.
- [Rei83] A. Reinefeld. An improvement of the scout tree search algorithm. *ICCA Journal*, 6(4):4–14, 1983.

- [Ric83] Elaine Rich. *Artificial Intelligence*. McGraw-Hill, Inc., New York, NY, USA, 1983.
- [RTT11] A. Rimmel, F. Teytaud, and O. Teytaud. Biasing Monte-Carlo simulations through RAVE values. In H. Jaap van den Herik, H. Iida, and A. Plaat, editors, *Lecture Notes in Computer Science 6515: Proceedings of the 7th International Conference on Computers and Games*, pages 59–68. Springer-Verlag, New York, NY, 2011.
- [SA83] David J Slate and Lawrence R Atkin. Chess 4.5-the northwestern university chess program. In *Chess skill in Man and Machine*, pages 82–118. Springer, 1983.
- [Sam60] A. Samuel. Programming computers to play games. *Advances in Computers*, 1:165–192, 1960.
- [Sam67] A. Samuel. Some studies in machine learning using the game of checkers. *IBM J. Res. Develop.*, 11:601–617, 1967.
- [SBB⁺07] Jonathan Schaeffer, Neil Burch, Yngvi Bjornsson, Akihiro Kishi-

moto, Martin Muller, Robert Lake, Paul Lu, and Steve Sutphen. Checkers Is Solved. *Science*, 317(5844):1518–1522, 2007.

- [SCA03] AysePinar Saygin, Ilyas Cicekli, and Varol Akman. Turing test: 50 years later. In JamesH. Moor, editor, *The Turing Test*, volume 30 of *Studies in Cognitive Systems*, pages 23–78. Springer Netherlands, 2003.
- [Sch89] J. Schaeffer. The history heuristic and alpha-beta search enhancements in practice. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 11(11):1203–1212, 1989.
- [Sch00] Jonathan Schaeffer. The games computers (and people) play. *Advances in Computers*, 52:190–268, 2000.
- [Sha50a] C. E. Shannon. Programming a computer for playing chess. *Philosophical Magazine*, 41(314):256–275, 1950.
- [Sha50b] Claude E Shannon. Xxii. programming a computer for playing chess. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, 41(314):256–275, 1950.

- [SHM⁺16] David Silver, Aja Huang, Chris J Maddison, Arthur Guez, Laurent Sifre, George Van Den Driessche, Julian Schrittwieser, Ioannis Antonoglou, Veda Panneershelvam, Marc Lanctot, et al. Mastering the game of go with deep neural networks and tree search. *Nature*, 529(7587):484–489, 2016.
- [SLLB96] Jonathan Schaeffer, Robert Lake, Paul Lu, and Martin Bryant. Chinook the world man-machine checkers champion. *AI Magazine*, 17(1):21, 1996.
- [SP96] J. Schaeffer and A. Plaat. New advances in alpha-beta searching. In *Proceedings of ACM Conference on Computer Science*, pages 124–130, 1996.
- [ST09] David Silver and Gerald Tesauro. Monte-carlo simulation balancing. In *Proceedings of the 26th Annual International Conference on Machine Learning, ICML '09*, pages 945–952, New York, NY, USA, 2009. ACM.
- [Sta07] T. Stam. Solving Mahjong solitaire positions, 2007. BSc thesis.

- [Sti89] L. Stiller. Parallel analysis of certain endgames. *ICCA Journal*, 12(2):55–64, 1989.
- [Sti91] L. Stiller. Some results from a massively parallel retrograde analysis. *ICCA Journal*, 14(3):91–93, 1991.
- [Stu06] N. Sturtevant. Current challenges in multi-player game search. In H. Jaap van den Herik, Y. Björnsson, and N. S. Netanyahu, editors, *Lecture Notes in Computer Science 3846: Proceedings of the 4th International Conference on Computers and Games*, pages 285–300. Springer-Verlag, New York, NY, 2006.
- [SvdH02] J. Schaeffer and H. J. van den Herik. Games, computers, and artificial intelligence. *Artificial Intelligence*, 134:1–7, 2002.
- [SWvdH⁺08] M. P.D. Schadd, M. H.M. Winands, H. J. van den Herik, G. N.J.-B. Chaslot, and J. W.H.M. Uiterwijk. Single-player Monte-Carlo tree search. In H. Jaap van den Herik, X. Xu, Z. Ma, and M. H.M. Winands, editors, *Lecture Notes in Computer Science 5131: Proceedings of the 6th International Conference on Computers and Games*, pages 1–12. Springer-Verlag, New York, NY, 2008.

- [TBBS53] Alan M Turing, MA Bates, BV Bowden, and C Strachey. Digital computers applied to games. *Faster than thought*, 101, 1953.
- [Tho86] K. Thompson. Retrograde analysis of certain endgames. *ICCA Journal*, 9(3):131–139, 1986.
- [Tho96] K. Thompson. 6-piece endgames. *ICCA Journal*, 19(4):215–226, 1996.
- [vdHUVR02] H. J. van den Herik, J. W. H. M. Uiterwijk, and J. van Rijswijk. Games solved: Now and in the future. *Artificial Intelligence*, 134:277–311, 2002.
- [vV09] R. Šolak and R. Vučković. Time management during a chess game. *International Computer Game Association (ICGA) Journal*, 32(4):206–220, 2009.
- [WH05] I.-C. Wu and D.-Y. Huang. A new family of k -in-a-row games. In H. Jaap van den Herik, Shun-Chin Hsu, Tsan sheng Hsu, and H.H.L.M. Donkers, editors, *Lecture Notes in Computer Science*

4250: Proceedings of the 11th Advances in Computer Games Conference, pages 180–194, New York, NY, 2005. Springer-Verlag.

- [WHH05] K.-c. Wu, S.-C. Hsu, and T.-s. Hsu. The graph history interaction problem in Chinese chess. In H. Jaap van den Herik, Shun-Chin Hsu, Tsan-sheng Hsu, and H.H.L.M. Donkers, editors, *Lecture Notes in Computer Science 4250: Proceedings of the 11th Advances in Computer Games Conference*, pages 165–179, New York, NY, 2005. Springer-Verlag.
- [Win84] Patrick Henry Winston. *Artificial Intelligence (2Nd Ed.)*. Addison-Wesley Longman Publishing Co., Inc., Boston, MA, USA, 1984.
- [WLH06] P.-s. Wu, P.-Y. Liu, and T.-s. Hsu. An external-memory retrograde analysis algorithm. In H. Jaap van den Herik, Y. Björnsson, and N. S. Netanyahu, editors, *Lecture Notes in Computer Science 3846: Proceedings of the 4th International Conference on Computers and Games*, pages 145–160. Springer-Verlag, New York, NY, 2006.
- [YCYH04] S.-J. Yen, J.-C. Chen, T.-N. Yang, and S.-C. Hsu. Computer

Chinese chess. *International Computer Game Association (ICGA) Journal*, 27(1):3–18, 2004.

- [YHM⁺11] Takayuki Yajima, Tsuyoshi Hashimoto, Toshiki Matsui, Junichi Hashimoto, and Kristian Spoerer. Node-expansion operators for the UCT algorithm. In H. Jaap van den Herik, H. Iida, and A. Plaat, editors, *Lecture Notes in Computer Science 6515: Proceedings of the 7th International Conference on Computers and Games*, pages 116–123. Springer-Verlag, New York, NY, 2011.
- [YLP01] J. Yang, S. Liao, and M. Pawlak. A decomposition method for finding solution in game Hex 7x7. In *Proceedings of International Conference on Application and Development of Computer games in the 21st century*, pages 93–112, November 2001.
- [YYK⁺06] Haruhiro Yoshimoto, Kazuki Yoshizoe, Tomoyuki Kaneko, Akihiro Kishimoto, and Kenjiro Taura. Monte Carlo Go has a way to go. In *AAAI*, 2006.
- [Zob70] A. L. Zobrist. A new hashing method with applications for game playing. Technical Report 88, Department of Computer Science,

University of Wisconsin, Madison, USA, 1970. Also in *ICCA journal*, vol. 13, No. 2, pp. 69–73, 1990.