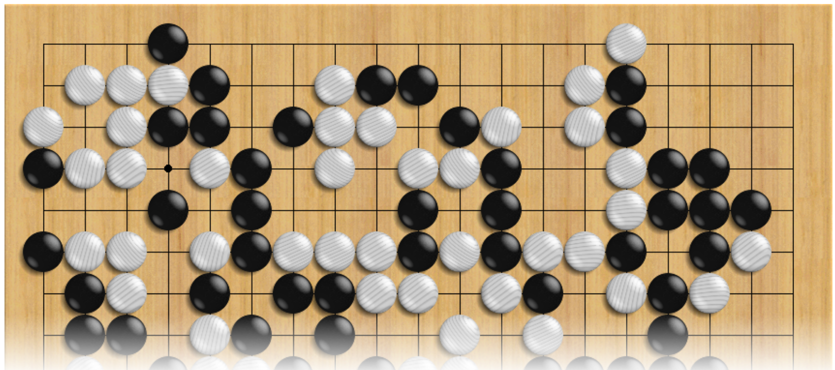
"The rules of Go are so elegant, organic, and rigorously logical that if intelligent life forms exist elsewhere in the universe, they almost certainly play Go."
Edward Lasker, chess master



Igo Math

Natural and Artificial Intelligence and the Game of Go

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Course Description

Go is a board game of superlatives. Most ancient (originated 3000-4000 years ago), most abstract (minimal set of rules, single aim of gaining territory), most complex (extreme high number of patterns, variations and game plays), most peaceful (winning is by gaining more territory, not by annihilation; games end in agreement), most beautiful (black and white stones on a grid laid over the natural grains of wood). It is one of the highest art form of logical and intuitive thinking combined. Renewed interest in the game was sparked by a somewhat unexpected event: a computer program won against the world champion player in 2016.

How can machine intelligence surpass human intellect? How do we think when we play Go? Do we now have a complete understanding of the game of Go? The course will answer these questions by studying the game and its computational aspects by using mathematics as a tool.

Learning Outcomes

Scholarly investigation of a game require mathematical and computational formalism. Fortunately, this is not some advanced material, but 'low-hanging fruits' of several parts of mathematics (e.g. graph theory, probability, algebra, combinatorics) and artificial intelligence concepts (e.g. game trees, minimax algorithm, neural networks). On the successful completion of this course, it is expected that the students will be able to:

1. play the game and solve elementary Go problems (tsumegos)[1], appreciate its aesthetics and its rich cultural heritage;
2. identify the cognitive processes involved in playing, and understand the difference between amateur and professional players;
3. represent games as tree structures, and solve simple games by applying the minimax search algorithm
4. use techniques of combinatorics to enumerate all possible plays for simple games, understand the role of symmetry as a mathematical tool
5. sense the difference between computationally hard and easy problems;
6. understand probabilistic sampling techniques, and Monte-Carlo simulations;
7. grasp the ideas of machine learning and neural networks, and assess their impacts.

Tentative Schedule

The schedule of the course is designed around motivating questions that naturally arise when approaching the game.

Week	Topics
1	**Introduction.** *What is Go?* The rules of Go. *How was it invented/discovered?* History. *How to play Go?* Tactics and strategy.
2	**Learning and improving.** *How can one become a better player? What do professional players do?* Go problems (tsumegos). Metacognition. Go proverbs.
3	**Go ratings.** *How to measure progress in learning? How to rank players?* Traditional kyu and dan system, winning probabilities and the handicap system. Élő rating.
4	**Game tree representation.** *How to describe gameplays in a precise manner?* AI concepts: search space and evaluation function. Graph theory. Tree structure to linear text – the SGF file format.
5	**Minimax algorithm.** *How to solve a game?* Search algorithms in classical AI. Heuristics.
6	**Computational complexity.** *What makes a problem difficult for a computer? What are combinatorial explosions?* Polynomial and exponential growth rates of execution times of programs.

[1]This course is a scholarly activity, which happens to have a component allocated for playing, since experiencing the game is a necessary requirement for studying it. However, the course does not guarantee that students will become strong players.

7	**Enumerative combinatorics.** *What is the size of the game tree? How many legal positions are there?*
8	**Symmetry as a compression tool.** Shapes on the board rotated and reflected, switching colors.
9	**MIDTERM TEST**
10	**Statistical methods and probabilistic sampling.** Randomness as a tool for dealing with hard problems. Monte Carlo simulations.
11	**Architecture of a Go playing program.**
12	**Neural networks.** The inner workings of the AlphaGo system. AlphaGo Zero, reinforcement learning.
13	**The impact of AlphaGo.** *What happens next?* Responses by Go players. Parallels to the more general phenomenon of automation.
14	**Variants of Go.** *Why the rules of Go are so special?* The notion of emergence. Exploring the 'space' of games in the neighbourhood of Go. Irregular Go boards, Go in higher dimensions, more than two players.
15	**FINAL EXAM**

Textbooks

There are many excellent books about Go, but only a few (and rather technical) research monographs on the mathematics of Go. There is no established textbook about the mathematics of Go. Therefore, lecture notes and handouts will be provided.

Assessment Components

Growth diary 10% Written records of events and stages of understanding the game and its theory, maintained by the students throughout the semester, guided by timed questions

Classroom activities 20% Continuous evaluation of participation in gameplays and paired problem solving, emphasis will be put on sharing thought processes, explanations and helping others will be rewarded. Playing skills are not assessed in this course; but attendance is mandatory.

Homework problems 20% Selected mathematical exercise problems.

Midterm & final exams 50% (25 %each) Paper based exams containing questions similar to homework assignments and problems discussed in class.

Delivery Format

Guided and independent problem solving and instructed gameplays. Go equipment will be available in classroom. Mathematical content will be presented in lecture format but in the context of practical problems.

Requirements

Knowing how to play the game is *not* a requirement, the basic rules can be learnt in 5 minutes. The course is self-contained. The mathematics part of is built up from first principles. Therefore, minimal math background, like regular high school math, suffices.

Software & Resources

online-go `https://online-go.com` – for playing the game online (both real-time and turn-based), solving problems; the site also has introductory material `https://online-go.com/learn-to-play-go` and exercises for beginners `https://online-go.com/puzzle/2625`.

Sabaki `https://sabaki.yichuanshen.de/` – cross-platform Go board and SGF editor, it can use different AI engines (such as GnuGo `https://www.gnu.org/software/gnugo/`)

Sensei's Library `https://senseis.xmp.net` – a collaborative web site for all Go related information.

Further Reading

Go

Peter Shotwell: **Go! More than a game**, 2003. One of the many excellent beginner Go books, distinguished by describing the historical, art and scientific context as well.

Literature

Hermann Hesse: **The Glass Bead Game**, 1943. Inspired by Go (though the game in the book is different and its rules are not defined precisely), the book describes a society that values scholarly activity highly. It is a fictional biography of a player.

Psychology

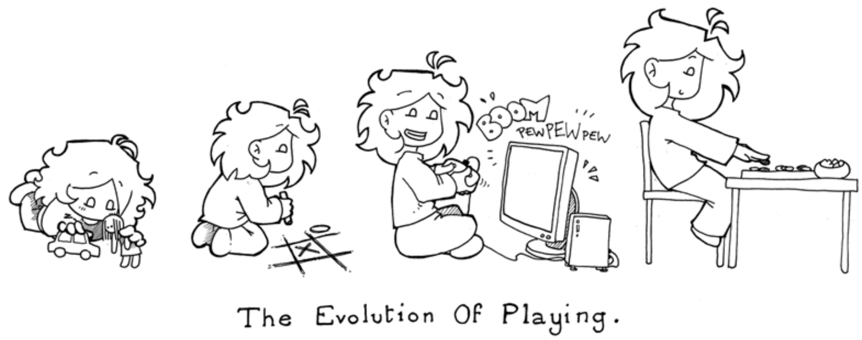
Fernand Gobet, Jean Retschitzki, Alex de Voogt: **Moves in mind** 2004. An excellent review of psychological studies of abstract board games (with main focus on chess).

Math & Computing

Peter Norvig, Stuart Russell: **Artificial Intelligence: A Modern Approach, 3rd Edition** 2009. De facto standard textbook on AI.

Documentary

The Surrounding Game https://www.surroundinggamemovie.com/ 2017 The first feature film about the game.



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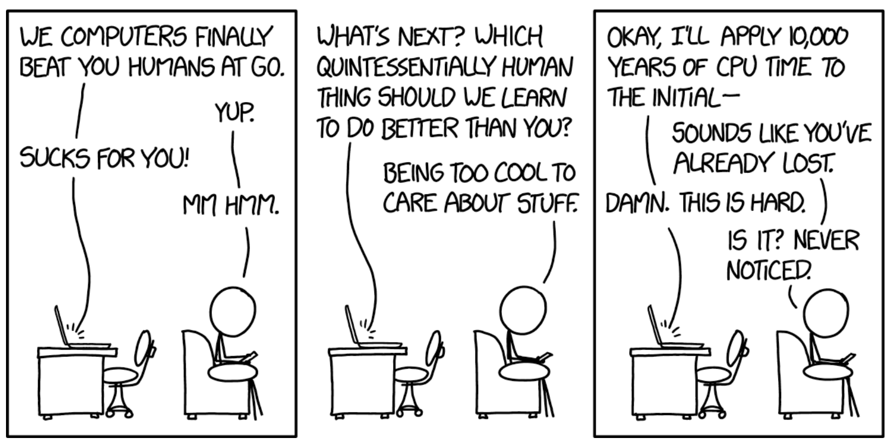

https://xkcd.com/1875/