CS5010
Artificial Intelligence Principles: Induction Lecture

Ognjen Arandjelović (Oggie)

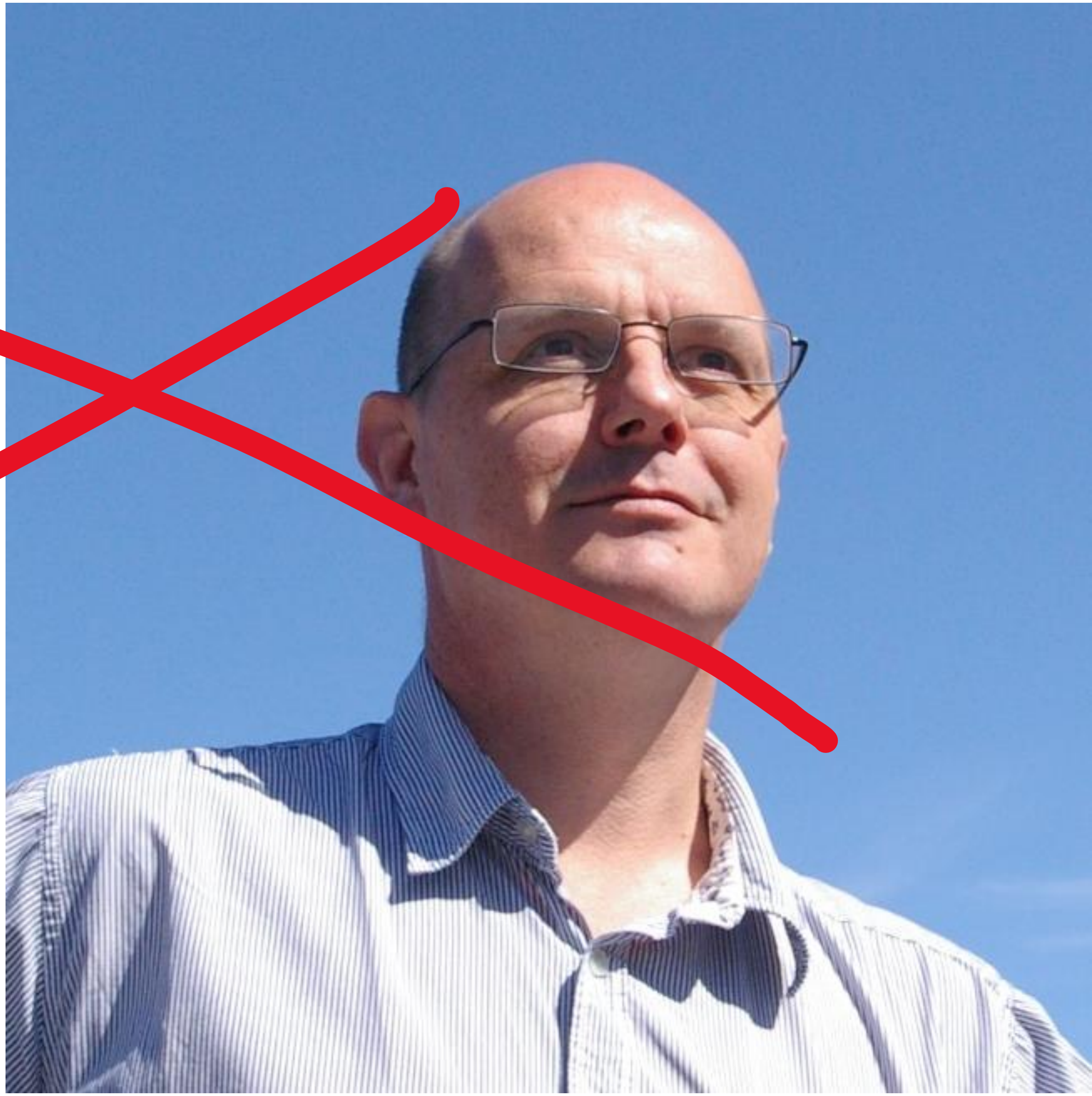
Key Policy Points

- You are assumed to be familiar with the whole student handbook
- Read the Good Academic Practice policy
- Check that coursework submitted to MMS has been received successfully, and that it's the right piece of coursework
- Coursework submitted after deadline is subject to automatic penalty
- Any special circumstances must be documented immediately through the self-certification system, and followed up with coordinator if you are seeking any allowance
- You must be available in St Andrews for the entire exam period

[*info.cs.st-andrews.ac.uk/student-handbook/key-points.html*](info.cs.st-andrews.ac.uk/student-handbook/key-points.html)

Lecturer

- Tom Kelsey
  - 1.16 Jack Cole Building
  - 01334 463249
  - twk@st-andrews.ac.uk
  - https://tom.host.cs.st-andrews.ac.uk/
  - I don’t set office hours but feel free …
  - to try my office to see if I am there
  - or email me with a query
  - or email me to arrange a time to meet
  - We have Teams sessions on Thursdays



Lecturer

- Ognjen Arandjelović
  - 0.09 Jack Cole Building
  - 01334 462428
  - oa7@st-andrews.ac.uk
  - https://oa7.host.cs.st-andrews.ac.uk/
  - Seldom in the office these days, for obvious reasons…
  - Better:
    - email me with a query
    - email me to arrange a time to meet
  - In-person sessions on Monday (4pm, from Week 2)

Assessment

- P01 is an essay
  - worth 30% of the module
  - Due Week 4
- P02 is also an essay
  - Worth 30% of the module
  - Due week 10
- The remaining 40% will be an open book style examination

MMS has the exact details and is the authorized source

Planning and quality control is an ongoing process between Me, Kasim, Jon and the external examiner

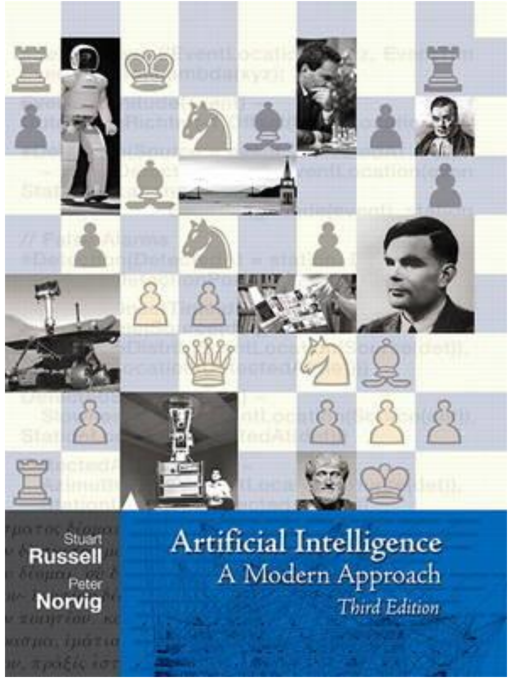
If in doubt about taking this module….

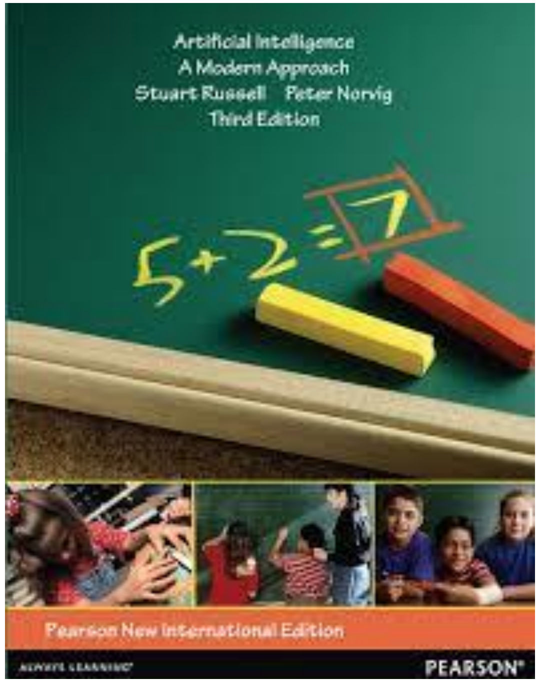
- Some people asked me about the level of maths in this module
- A good way to assess this is to look at old exam papers
- E.g. the 2016/17 paper for this module is available
    - Representative of what to expect
    - Coverage may be slightly different this year
- Obviously you don't need to know ANY of this material yet
- But if you can't imagine ever being able to answer questions like that, this module may not be for you
- https://www.st-andrews.ac.uk/students/academic/examinations/pastpapers/

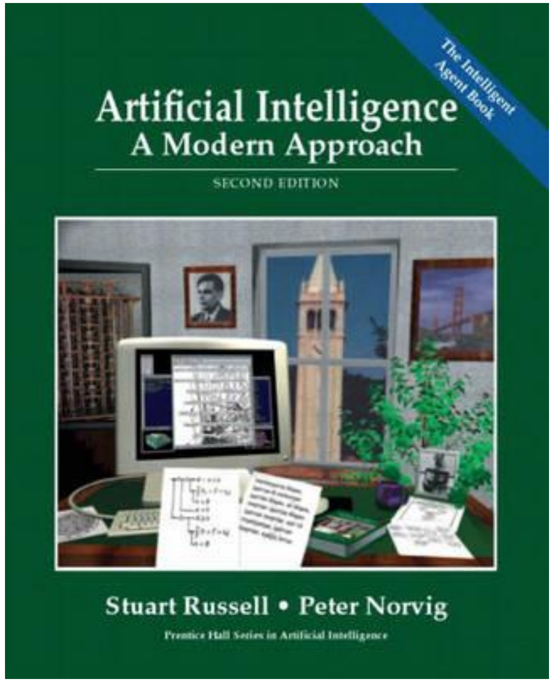
Textbooks

- No book is required but one is highly recommended:
- “Artificial Intelligence: A Modern Approach”
  - Stuart Russell and Peter Norvig
  - 3rd Edition, 2009
    - But earlier editions should be ok
    - Chapter references etc to 3rd edition so watch out!
    - ISBN 0-13-604259-7
    - Book website: http://aima.cs.berkeley.edu/
- Covers all the topics in this module
  - Most in more detail than I can
  - Most (but not all) material I teach will be somewhere in the textbook, possibly in a different form

Textbooks


Stuart
Russell
Peter
Norvig
Artificial Intelligence
A Modern Approach
Third Edition


Artificial Intelligence
A Modern Approach
Stuart Russell Peter Norvig
Third Edition
5+2=7
Pearson New International Edition
PEARSON


The Intelligent Agent Book
Artificial Intelligence
A Modern Approach
SECOND EDITION
Stuart Russell • Peter Norvig
Prentice Hall Series in Artificial Intelligence

Topics in this module

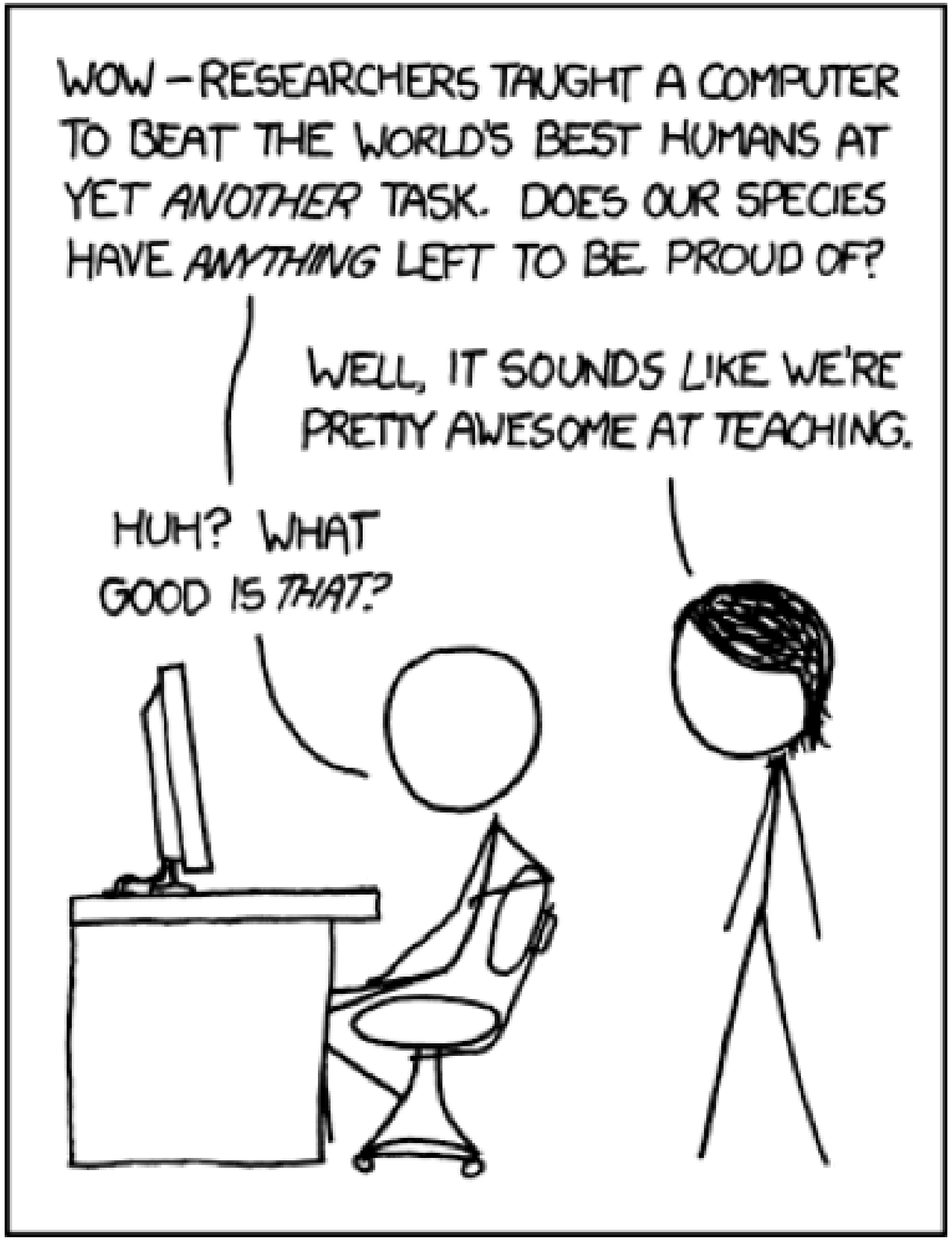
- History and Philosophy of AI
- Machine Learning
- Search
- Automated Reasoning
- Bayesian probabilistic reasoning

Ok that’s the boring stuff done

- Now I want to persuade you that you’ve made a great choice of module and that AI is an incredibly amazing topic
- And that much of it is based on the fundamentals we will cover in this module

Artificial Intelligence: Celebration lecture

Adapted from a talk by Ian Gent



xkcd webcomic

4 May 2011
http://xkcd.com/894/

The Thesis of this Lecture

- Artificial Intelligence is an incredible achievement of humanity
- We should celebrate it
- It is amazing
- From nothing it’s achieved incredible feats and changed the world

Some Amazing Things in AI

- Computer Go
- There is no valid sudoku problem with 16 clues
- Computers can win general knowledge quizzes against champions with questions in English
- Robbins Algebras are Boolean Algebras
- 6-player poker

KOTAKU AU

Xbox PlayStation Nintendo PC Mobile In Real Life Retro

Someone Is Destroying Online Go, And Nobody Knows Who It Is

Alex Walker
Jan 4, 2017, 12:30pm · Filed to: ai

Share

Image: Shutterstock

Right now, there's a player lurking in the depths of the online Go scene that is laying was to some of the best players in the world. It's called Master, and nobody knows who it is.

Xbox PlayStation Nintendo PC Mobile In Real Life Retro

The Mystery Account Destroying Online Go Was Google's

Alex Walker
Jan 5, 2017, 8:00am · Filed to: ai

Share

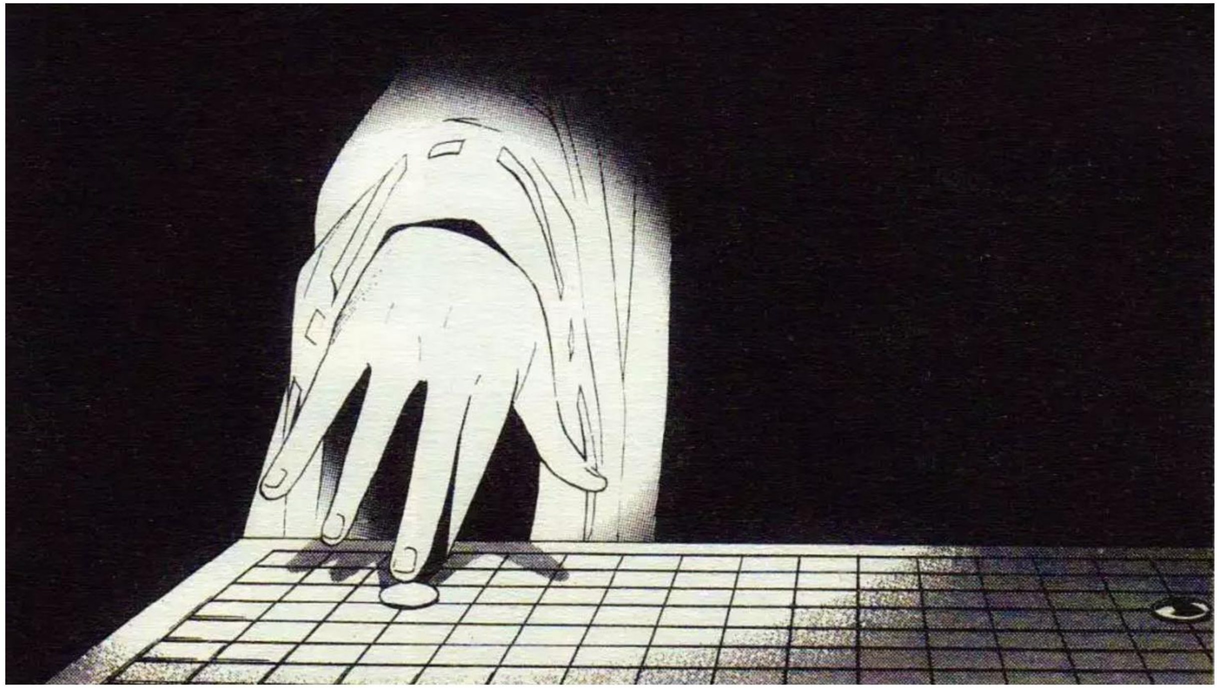


Image: Photobucket (u/lacygrey)

Yesterday I reported on how a mystery account called "Master" had been tearing up the world of online Go, and nobody knew who it was. But in an update posted on Twitter earlier this morning, Google has admitted that the mystery account "Master", as well as a second account "Magister", was their world-beating AlphaGo bot all along.

http://www.kotaku.com.au/2017/01/google-the-mystery-account-destroying-online-go-was-ours/

AlphaGo vs Lee Sedol

- Match played in March 2016 between…
- AlphaGo
  - Program created by Google
- Lee Sedol
  - One of the best Go Players in the world
  - Winner of 18 major championships
- Best of 5 games
- AlphaGo won 4-1

Lee Sedol in 2012

How is this amazing magic done?

- Using the amazing power of amazing AI
- I might be overusing the word amazing
- But still, it’s amazing, right?
- We are here to find out how this kind of thing is done

Will we teach you how to build world class computer Go programs?

No

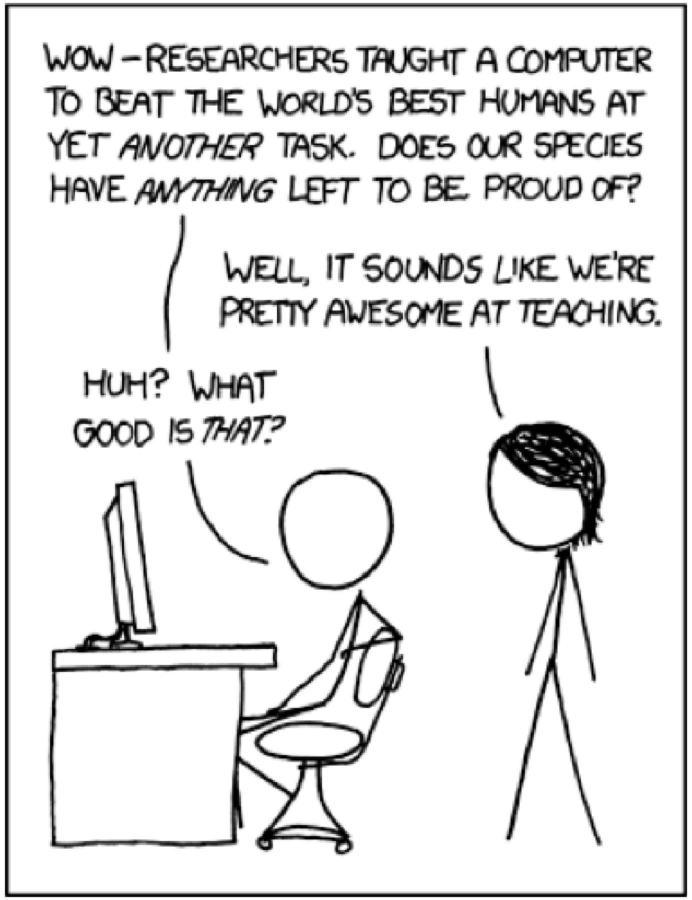
Sorry about that

But we *will* teach you the basics of (some of) the key technologies underlying it

Two main technologies behind AlphaGo

- Monte Carlo Tree Search
- Deep Learning

- Paper about AlphaGo after it beat a weaker (but still professional) human:
  - "Mastering the Game of Go with deep neural networks and tree search"
  - David Silver (& 19 other authors)
  - Nature 529, pages 484–489 doi:10.1038/nature16961
- http://www.nature.com/nature/journal/v529/n7587/full/nature16961.html



Some Amazing Things in AI

- Computer Go
- There is no valid sudoku problem with 16 clues
- Robbins Algebras are Boolean Algebras
- Computers can win general knowledge quizzes against champions with questions in English
- 6-player poker

Sudoku and amazing AI

- Sudoku is a popular puzzle
- Put a number 1-9 in each small square
- Some numbers (clues) are already filled in.
- You not allowed the same number twice in
  - The same row
  - The same column
  - The same 3x3 box

			7					
1								
			4	3		2		
								6
			5		9			
						4	1	8
				8	1			
		2					5	
	4					3		

Image Gordon Royle, theconversation.com

Sudoku and amazing AI

- For a Sudoku puzzle to be "valid" there should be just one solution
  - Not 2 solutions
  - Obviously not zero
- This example has 17 "clues"
- Can you solve it?

			7					
1								
			4	3		2		
								6
			5		9			
						4	1	8
				8	1			
		2					5	
	4					3		

Image Gordon Royle, theconversation.com

Sudoku and amazing AI

- For a Sudoku puzzle to be "valid" there should be just one solution
  - Not 2 solutions!
  - Obviously not zero!
- This example has 17 "clues"
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			7					
1								
			4	3		2		
								6
			5		9			
						4	1	8
				8	1			
		2					5	
	4					3		

Image Gordon Royle, theconversation.com

Spoiler alert

- Here is the solution
- Oops – a bit late for the spoiler alert!
- Solving Sudokus is not a major problem in AI
- To be precise:
  - By the time Sudoku became popular, lots of AI techniques were mature enough to solve them easily
- So why is Sudoku amazing for AI?

2	6	4	7	1	5	8	3	9
1	3	7	8	9	2	6	4	5
5	9	8	4	3	6	2	7	1
4	2	3	1	7	8	5	9	6
8	1	6	5	4	9	7	2	3
7	5	9	6	2	3	4	1	8
3	7	5	2	8	1	9	6	4
9	8	2	3	6	4	1	5	7
6	4	1	9	5	7	3	8	2

Image Gordon Royle, theconversation.com

Sudoku and amazing AI

- This example has 17 “clues”
- There are more than 49,000 valid puzzles known with 17 clues
  - Not even counting renumbering, and reordering columns etc
- Is there a valid sudoku with 16 clues?

			7					
1								
			4	3		2		
								6
			5		9			
						4	1	8
				8	1			
		2					5	
	4					3		

Image Gordon Royle, theconversation.com

Spoiler alert

- No.
- There is no valid sudoku with 16 clues.
- This was proved in 2012
- Richard Elwes called this result one of ["the top 10 mathematical achievements of the last 5ish years, maybe"]

			7					
1								
			4	3		2		
								6
			5		9			
						4	1	8
				8	1			
		2					5	
	4					3		

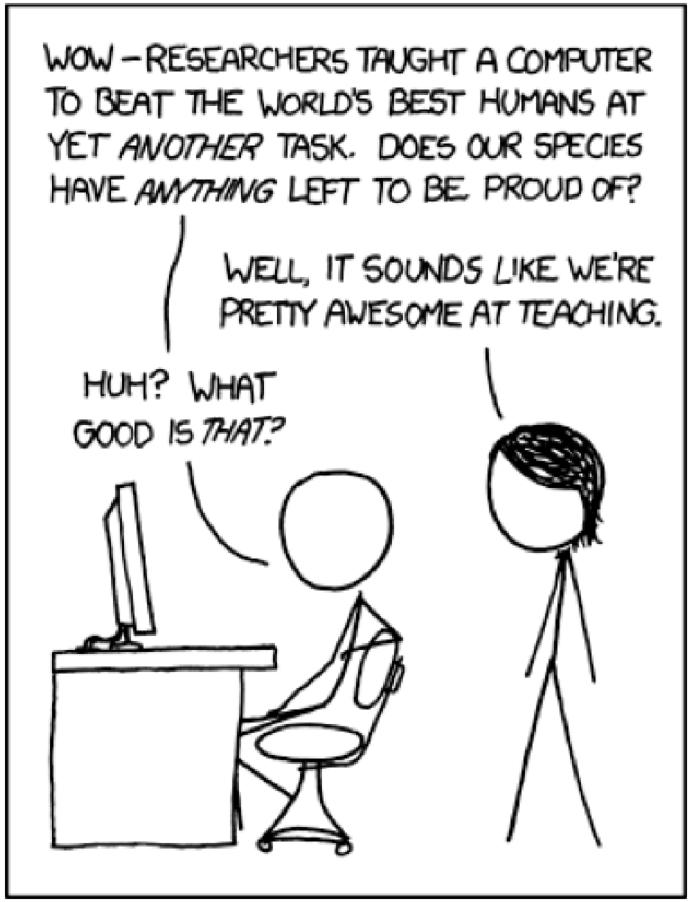
Image Gordon Royle, theconversation.com

Almost done here…

- Almost done in St Andrews
  - Chris Jefferson and Max Neunhoffer bid for 8000 CPU-years from Google to do it
    - But Google didn't give them the CPU time
- Actually done at Ireland's High Performance Computing Centre
  - about 800 CPU-years (in 2011)
    - (So Chris and Max overestimated it or had less efficient methods)
- "There is no 16-clue Sudoku: Solving the Sudoku minimum number of clues problem"
  - G McGuire, B Tugemann, G Civario
  - arXiv preprint arXiv:1201.0749
  - 2012

How Was It Done?

- This definitely is one of those “Wikipedia sized proofs”.
- Bits of maths
    - E.g. Symmetry
        - To avoid trying the same thing twice
    - Facts about Sudoku mathematicians have worked out
- A clever way to rule out lots of things at once
    - There are lots more potential Sudoku *puzzles* (sets of clues) than *solutions (*filled grids)
    - Figure out constraints that apply to the filled in grids that stops valid puzzles for them having 16 clues.
- Search
    - Needs *a lot* of search
    - Special purpose algorithms for this problem
    - But still basically backtracking search like we will study



Related work was done here…

The Semigroups of Order 10

Andreas Distler[1], Chris Jefferson[2], Tom Kelsey[2], and Lars Kotthoff[2]

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[2] School of Computer Science,
University of St Andrews, KY16 9SX, UK

Abstract. The number of finite semigroups increases rapidly with the number of elements. Since existing counting formulae do not give the complete number of semigroups of given order up to equivalence, the remainder can only be found by careful search. We describe the use of mathematical results combined with distributed Constraint Satisfaction to show that the number of non-equivalent semigroups of order 10 is 12,418,001,077,381,302,684. This solves a previously open problem in Mathematics, and has directly led to improvements in Constraint Satisfaction technology.

Keywords: Constraint Satisfaction, Mathematics, semigroup, Minion, symmetry breaking, distributed search

1 Introduction

An important area of investigation is the determination of the number of solutions of a given finite algebraic problem. It is often the case that we are interested in the number of classes of solutions under some type of equivalence relation, since this gives the number of structural types rather than distinct objects. In certain cases, these numbers can be found by deriving counting formulae. It may also be possible, on an *ad hoc* basis, to derive enumerative constructions of larger objects from smaller ones. In both these cases, no systematic computer search is required – the numbers are calculated from mathematical proofs using the structures of the underlying problem.

There is no guarantee, of course, that the use of formally-proven formulae will work for all problems. It may be that no suitable formulae is available. In this event, the only method left is to carefully search for solutions, ensuring that none is missed and none is counted more than once. Examples include the search for all distinct transitive graphs on n vertices [23, 24], all binary self-dual codes of length 32 [2], all ordered trees with k leaves [32], and all non-equivalent semigroups up to order 9 and monoids up to order 10 [6, 7, 9, 17, 26, 28, 30]. Large-scale studies often involve a combination of enumeration by formula and computer search. The tautomer enumeration problem [18] from Cheminfomatics is an illustrative example. Commercial and academic software packages used to solve this type of problem typically use a suite of transformation

The Monoids of Orders Eight, Nine & Ten

Andreas Distler[1] and Tom Kelsey[2]

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North Haugh, St Andrews, KY16 9SS, UK
andreas@mcs.st-andrews.ac.uk
[2] School of Computer Science, Jack Cole Building,
North Haugh, St Andrews, KY16 9SX, UK
tom@cs.st-andrews.ac.uk

Abstract. We describe the use of symbolic algebraic computation allied with AI search techniques, applied to the problem of the identification, enumeration and storage of all monoids of order ten or less. Our approach is novel, using computer algebra to break symmetry and constraint satisfaction search to find candidate solutions. We present new results in algebraic combinatorics: up to isomorphism and anti-isomorphism, there are 858,977 monoids of order eight; 1,844,075,697 monoids of order nine and 52,991,253,973,742 monoids of order ten.

1 Introduction

The aim of this paper is to find all solutions to a class of problems in algebraic combinatorics. This is a well-known research area: it is natural when discussing, for example, various types of latin squares to try to resolve the question of how many of each type exist. As well as obtaining the correct answer in terms of number of solutions, we aim to store each solution so that they can be analysed in terms of their structure by algebraists. This second aim means that we are not searching for a purely constructive solution to the enumeration problem; we want to generate and store a canonical example from each equivalence class of solutions.

The On-Line Encyclopedia of Integer Sequences [1] contains numerous examples of known initial sequences of enumerations of algebraic and combinatorial structures. The sequence that this paper extends is A058133: the numbers of monoids of order n, considered to be equivalent when they are isomorphic or anti-isomorphic. Currently values for $n \leq 7$ are available online, values for $n = 8$ and 9 were given in [2], the value for $n = 10$ is a new result.

A monoid is an algebraic structure equipped with a closed and associative binary operator, and an identity element. The formal definition used throughout this paper is the following:

Definition 1. *A* monoid *is a tuple* $\langle M, *, e\rangle$ *where* M *is a set;* $* : M \times M \to M$ *satisfies* $x * (y * z) = (x * y) * z \quad \forall x, y, z \in M$*; and the* identity $e \in M$ *satisfies* $x * e = x = e * x \quad \forall x \in M$.

If $\langle M, *, e\rangle$ *is a monoid, and* $|M| = n$*, then* $\langle M, *, e\rangle$ *has* order n.

Enumerate the ways a 10x10 grid can be completed with values 0,1,2,…9 such that

1. Multiplication is associative
2. All symmetry is broken

- Search space is 10^{100}
- CPU centuries needed, even after most solutions found using discrete maths
- Answer: 12,418,001,077,381,302,684

- AI is the Computer Science approach to decision making
- Logic, search, uncertainty, learning
- Algorithms, heuristics

Distler *et al.*, 2009; Distler *et al.*, 2012

Some Amazing Things in AI

- Computer Go
- There is no valid sudoku problem with 16 clues
- Robbins Algebras are Boolean Algebras
- Computers can win general knowledge quizzes against champions with questions in English
- 6-player poker

All Robbins Algebras are Boolean Algebras

- Hard to make this sound as amazing as Computer Go I suppose
- But it is pretty amazing
- Why?
- Well let me tell you what it is first.
- Then I’ll tell you why it’s amazing

Boolean Algebra

∨	**0**	**1**
0	0	1
1	1	1

a	**0**	**1**
¬*a*	1	0

From Wikipedia

- Remember Boolean Algebra from CS2002?
  - ∨ (for OR)
  - ¬ (for NOT)
  - Various laws relating them
- I hope I do because I am teaching it again soon to this year's class!
- Actually that is just *one example* of a Boolean Algebra
  - With two values 0 & 1
- Here is one with four values
  - They can have infinitely many values
- General Boolean Algebras obey certain axioms
  - Which I won't bother to repeat

∨	**0**	**a**	**b**	**1**
0	0	a	b	1
a	a	a	1	1
b	b	1	b	1
1	1	1	1	1

x	**0**	**a**	**b**	**1**
¬*x*	1	b	a	0

From Wikipedia

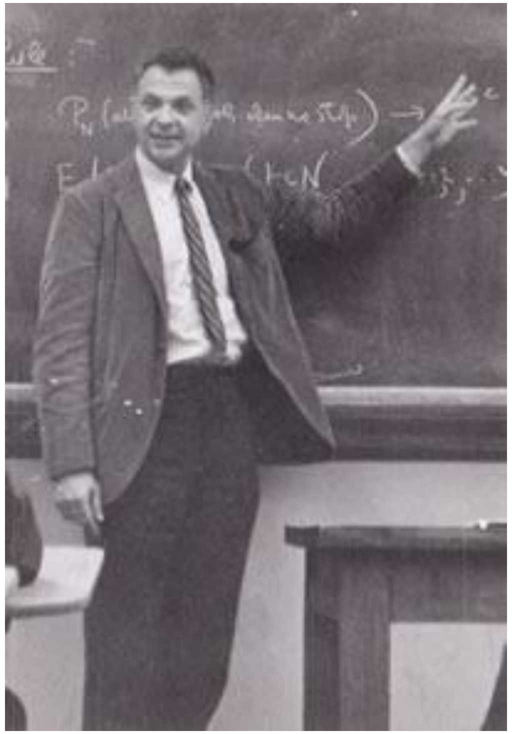
Robbins Algebra

- A Robbins algebra contains two operations: a binary and a unary
  - $\vee$
  - $\neg$
- A Robbins algebra must obey these rules
  - Associativity

    $a \vee (b \vee c) = (a \vee b) \vee c$
  - Commutativity

    $a \vee b = b \vee a$
  - Robbins' Equation

    $\neg(\neg(a \vee b) \vee \neg(a \vee \neg b)) = \neg a$
- Robbins' Conjecture:
  - Every Robbins algebra is a Boolean algebra
  - Conjectured 1930
  - Worked on by great mathematicians like Robbins, Tarski
  - Proved using AI techniques in 1996



From Wikipedia

Herbert Robbins in 1966

Robbins Algebra: *Yes but why is it amazing??*

- A Robbins algebra contains two operations: a binary and a unary
  - ⋁
  - ¬
- A Robbins algebra must obey these rules
  - Associativity

    $a \lor (b \lor c) = (a \lor b) \lor c$
  - Commutativity

    $a \lor b = b \lor a$
  - Robbins' Equation

    $\neg(\neg(a \lor b) \lor \neg(a \lor \neg b)) = \neg a$
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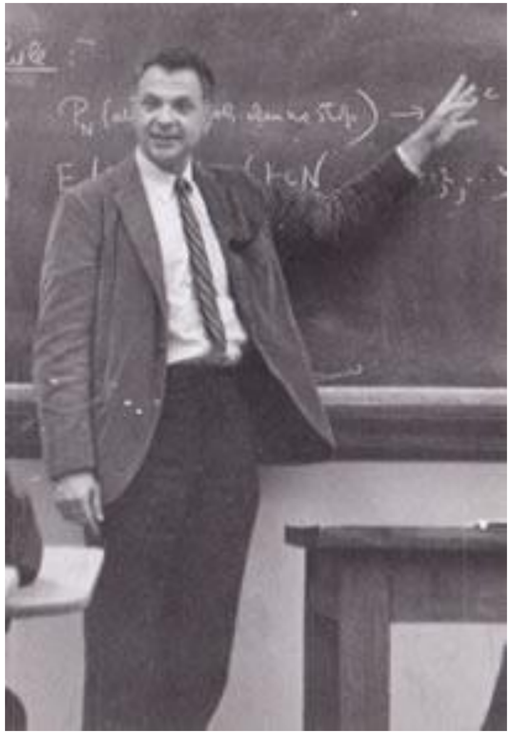

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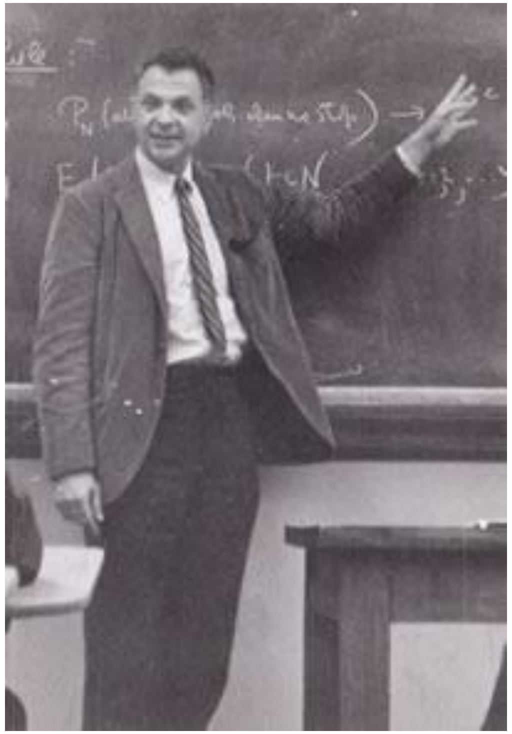
- Robbins' Conjecture:
  - Every Robbins algebra is a Boolean algebra
  - Conjectured 1930s
  - Worked on by great mathematicians like Robbins, Tarski
  - ***AND NOT KNOWN TO BE TRUE UNTIL…***
  - Proved using AI techniques in 1996

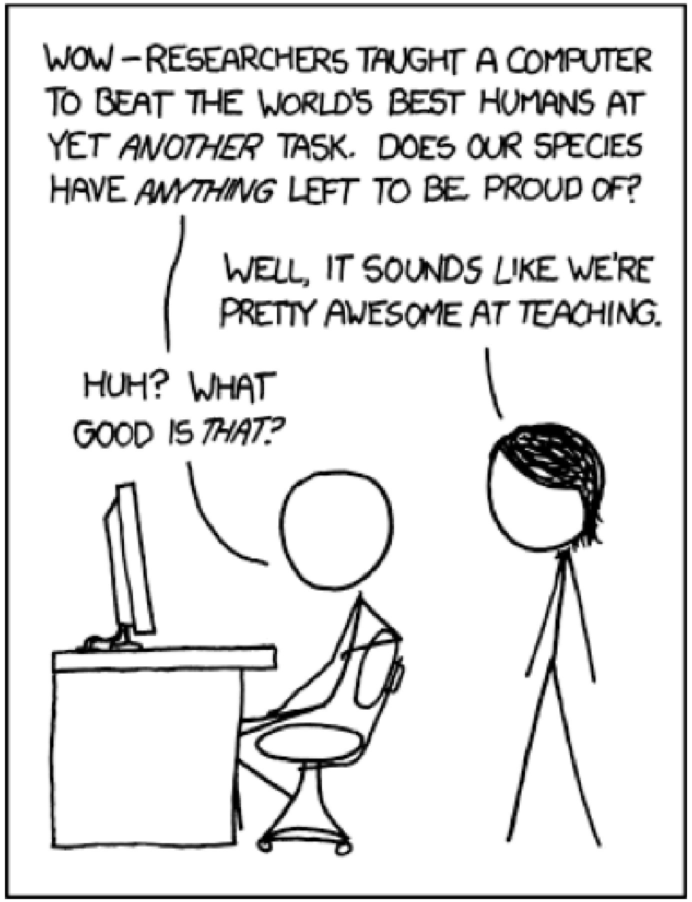


From Wikipedia

Herbert Robbins in 1966

Robbins Algebra: *Yes but why is it amazing??*

- A major maths result first proved by machine
  - Proof is not particularly big
  - But finding it was *hard*
  - Obviously hard for humans since they failed
- Mathematics has often been seen as one of the key components of intelligence
  - E.g. one of Gardner's "nine types of intelligence"
    - https://en.wikipedia.org/wiki/Theory_of_multiple_intelligences
  - And often seen as *more* important than 1/9
- Now computers can outperform great mathematicians
  - At least in certain areas

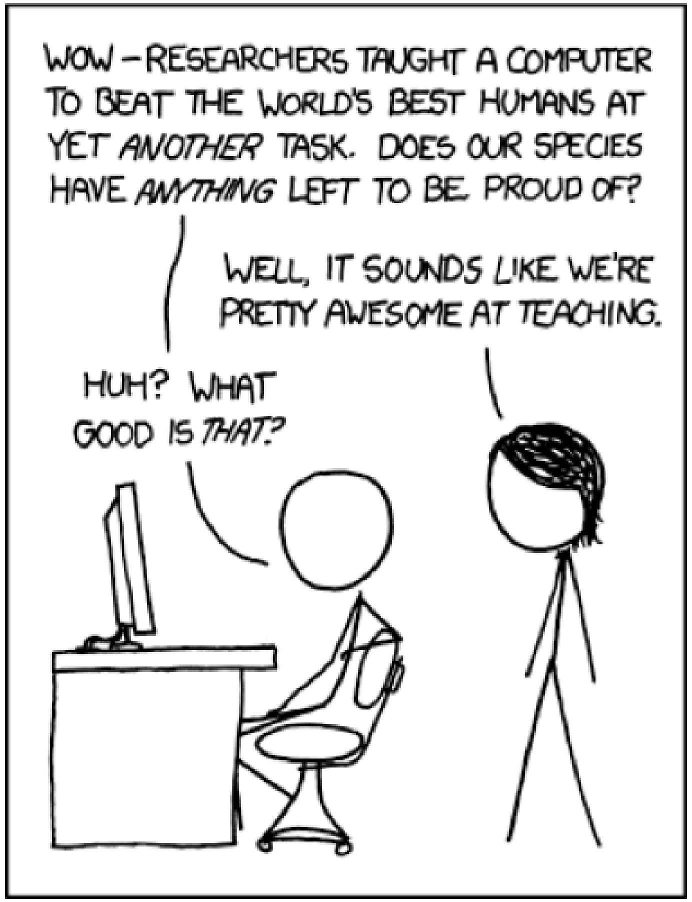


Some technologies in Robbins Algebra proof

- Automated Theorem Proving
- Search

- Computer proof took about 5 CPU-weeks in 1996
- Used Automated theorem proving system "EQP"

- Reference
  - "Solution of the Robbins Problem"
  - WILLIAM McCUNE
  - *Journal of Automated Reasoning* **19:** 263–276, 1997



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IBM Watson wins Jeopardy

- *Jeopardy!* is a US general knowledge quiz show
  - Weird reverse where questions are “answers”
- Example:
  - Topic: “A, B, or C”
  - Question: “Originally, it was a cheap movie shown in addition to the main feature”
  - Answer: “What is B?”
- Top champions have become rich playing this:
  - Ken Jennings won 74 matches and $2,500,000
  - Brad Rutter won $4,350,000
- IBM built an AI to play these two superchampions
  - Winner to get $1,000,000
  - Match played 14 Jan 2011
  - IBM’s “Watson” won

From Wikipedia

Why is this amazing?

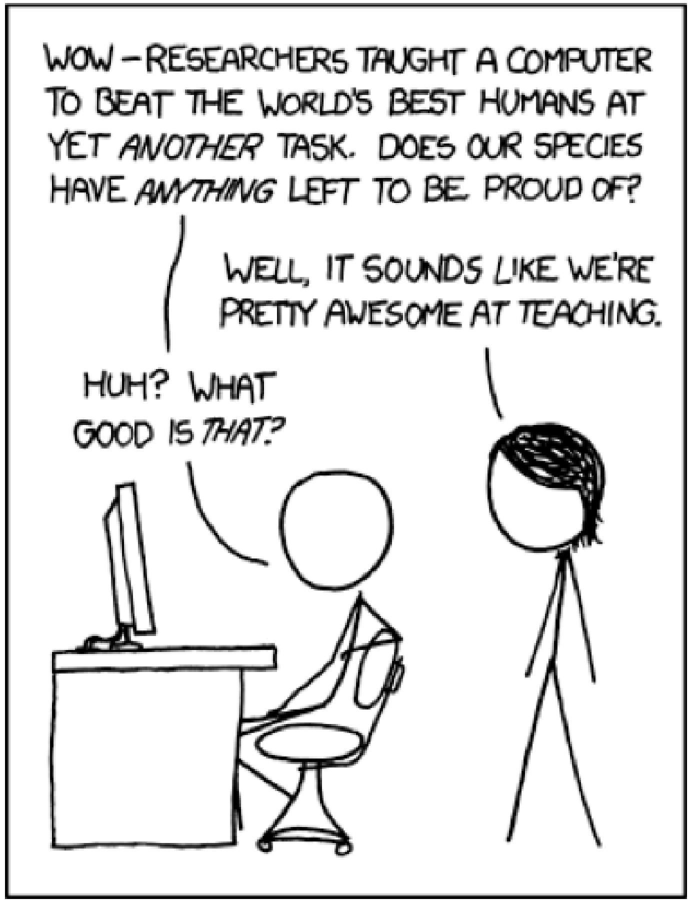
- The game being played is a real game played over thousands of episodes by humans with the same rules
  - The questions are in English, not formalised in any other way
  - The game was set up to be entertaining to people watching
  - Clues are often a bit punning or hard to work out what the question is
- The fact it’s *general knowledge* is important
  - You can’t win just by specialised chess programming
- Remember – it’s still a specialised program
  - i.e. programmed to play the game of *Jeopardy!*
  - Watson now being tested in other areas like medical diagnosis
    - But this involves a lot of new work, not just asking different questions

How did it do it?

- Let’s ask one of the human competitors:
- “The computer's techniques for unraveling Jeopardy! clues sounded just like mine. That machine zeroes in on key words in a clue, then combs its memory for clusters of associations with those words. It rigorously checks the top hits against all the contextual information it can muster: the category name; the kind of answer being sought; the time, place, and gender hinted at in the clue; and so on. And when it feels "sure" enough, it decides to buzz. This is all an instant, intuitive process for a human Jeopardy! player, but I felt convinced that under the hood my brain was doing more or less the same thing.”
  - *Ken Jennings – one of the human champions*

How did it do it?

- Many many AI techniques combined
  - Knowledge representation
  - Bayesian probabilistic reasoning
  - Natural language processing
  - Machine learning
  - Automated reasoning
- Stored all of Wikipedia (and lots of other stuff)
  - Not on internet but 4TB storage
  - Massive preprocessing
  - So as part of its preprocessing it analysed much of Wikipedia



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6-player Poker

- Go, Chess, 2-player poker, backgammon and StarCraft
- All zero-sum games – if you win I lose
- Most have perfect knowledge
- 6-player poker is harder, in a sense
- Nash equilibria are hard to formalise and/or interpret
- Imperfect information
- Too many decision points to reason about individually

Pluribus

- Brown and Sandholm developed a program, dubbed Pluribus, that learned how to play six-player no-limit Texas hold'em by playing against five copies of itself
- When pitted against five elite professional poker players, or with five copies of Pluribus playing against one professional, the computer performed significantly better than humans over the course of 10,000 hands of poker
  - *Science* 30 Aug 2019:
    Vol. 365, Issue 6456, pp. 885-890
    DOI: 10.1126/science.aay2400

How did they do it?

- Counterfactual reasoning (CFR) – simulate what would happen if any player modifies their strategy
- Monte Carlo CFR (MCCFR) that samples actions in the game tree rather than traversing the entire game tree on each iteration
- Depth limited search
- Develop a strategy for all hands, then implement it for the actual cards held
- Search, learning, logic and uncertainty all vital components

Why is this amazing?

- A successful AI for chess is a great achievement
- But chess is not like real life
- In poker one has limited knowledge and some insights from probabilities
- But the other humans could be bluffing with weakness or laying a trap with strength
- Solving this problem would be much closer to real-world intelligence
  - And Pluribus is a very good attempt at a solution

Topics in this module

- History and Philosophy of AI
- Search
- Automated Reasoning
- Bayesian reasoning
- Machine Learning

Next time:

- Some Attacks on AI