A Game That Stymies AI

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Catch-Up is a simple 2-person game in which player A successively chooses numbers from a set, without replacement, that are added to the numbers A already has until their sum equals or exceeds player B's sum—after which B does the same, and the players alternate their choices. The game ends when all numbers have been chosen, and one player's sum equals or exceeds its opponent's sum, making it the tied or absolute winner. Unlike chess or go, no AI or deep-learning program has been found that consistently beats an opponent—say, 90% or more of the time—who randomizes its choices of numbers, whereas making random moves in Chess or Go would be disastrous. Has AI met its match in its strongest fields, computation and learning?

AI has succeeded spectacularly in fields of specialized learning, such as playing chess or go, and in finding patterns in visual displays, such as identifying when a human organ is diseased or otherwise abnormal. It has done much less well in situations requiring generalized learning, such as in understanding a text, including one that it may be able to expertly translate from one language into another. Worse, acting human-like by expressing—and, especially, feeling— appropriate emotions seems well beyond AI's capacity.

AI's panoply of tools, such as neural networks, have helped to fuel recent advances, including the design of self-driving cars and trucks. Such advances require enormous computational power as well as smart algorithms to put this power to good use. With uncanny accuracy, AI has been able to identify driving situations in which it is safe to proceed, slow down, speed up, turn, stop, or choose myriad variations on these basic actions.

It is surprising, therefore, to discover a game, Catch-Up, whose absurdly simple rules and a particular strategy have so far foiled AI's ability to outplay human players, whom it has trounced in much more complex games like Chess and Go. This is especially ironic when the human player makes random choices, which would be disastrous against an AI opponent in Chess or Go. I will suggest reasons why this is the case later, but first let's take a look at Catch-Up and what constitutes optimal play in this game.

Catch-Up and Optimal Play

Catch-Up has five rules of play:

1. Two players alternately choose numbers, without replacement, from the set of natural numbers, $\{1, 2, 3, \ldots, n\}$.
2. The first player to choose one or more numbers, is P1, and the second player is P2. At the outset, P1 chooses one of the n original numbers.

3. Thereafter, P1 and P2 successively choose one or more numbers, but each must stop—and turn play over to the other player—when the sum of its numbers equals or exceeds its opponent's previous sum.
4. The goal of the players is to have a higher sum than an opponent—and by as much as possible—or that failing, to have the same sum. If neither of these goals is achievable, a player prefers to lose by as small amount as possible.
5. The game ends when all numbers have been chosen, and one player's sum equals or exceeds its opponent's sum, making it the tied or absolute winner.

We illustrate these rules and optimal play in two simple cases, ignoring the trivial case in which there is only the number 1, which P1 will choose and win:

1. If the numbers are {1, 2}, P1 will choose 2, and P1 cannot catch up and so loses by 2-1.
2. If the numbers are {1, 2, 3}, there are three cases:
   a. If P1 chooses {3}, P2 will choose {1, 2} in either order and guarantee a 3-3 tie.
   b. If P1 chooses {2}, P2 will choose {1, 3}, in that order, and

guarantee a 4-2 win, which is better for P2 than choosing only {3} and obtaining a 3-3 tie after P2 subsequently chooses {1}.

• If P1 chooses {1}, P2 will choose {3} and guarantee a 3-3 tie after P1 subsequently chooses {2}.

Clearly, P1 can force a tie in the cases 2a and 2c, whereas in case 2b P1 will lose when P2 plays optimally. This makes it nonoptimal for P1 to choose {2} initially but instead to choose {1} or {3}.

In asking what P1 should do at the outset, we first determine what is optimal for P2 to do subsequently and then determine the consequences for P1. In the {1, 2, 3} example, P1 cannot force a win, as it can in the {1, 2} case, but it can force a tie by choosing {1} or {3} initially.

The thought process underlying optimal play of Catch-Up is called *backward induction*, a venerable idea going back more than 100 years that is now most used in the solution of sequential games. The idea is to work from the end of the game back to the beginning, assuming at each stage that the priority of the players is as given by the goal of the players in rule 4. We assume that each player, looking ahead, anticipates that it and its opponent will make optimal choices when it is each's turn to choose from the set of numbers still available.

Applying computer-assisted backward induction to all sets of natural numbers from $n = 2$ to 20, I and my coauthors of a 2015 article in *Game and Puzzle Design*, http://game.engineering.nyu.edu/wp-content/uploads/2015/10/catch-up-a-game-in-which-the-lead-alternates-2015.pdf found that when the sum of all numbers is odd, as it is when $n = 2$ (1+2 = 3), optimal play results in a win by either P1 or P2 by a difference in their sums of 1 (2-1 = 1). But when the sum of the numbers is even, as it is when $n = 3$ (1+2+3 = 6), optimal play results in a tie (1+2 = 3).

Initially, I thought, when the sum of the numbers is odd, P1, by going first, might always be able to force a win, but this is not the case. When $n =$ 9, 10, 14, or 18, P2 can force a win, whereas when $n =$ 5, 6, 13, or 17, P1 can force a win. In all other cases up to $n = 20$, optimal play produces a tie. Thus, unlike Chess, in which there is a consensus that optimal play—if it is ever discovered—will lead either to a win for white or a draw, backward-induction calculations for Catch-Up show that neither P1 nor P2 wins or ties more than the other, at least up to $n = 20$.[1]

Randomization Vs. AI

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[1] For a playable version of Catch-Up on the computer, see http://game.engineering.nyu.edu/projects/catch-up/

In our 2015 article, my coauthors and I compared the performance of a player who randomizes its choices to three other strategies (more on these shortly). To illustrate what randomization means, assume $n = 5$, so the numbers at the start are {1, 2, 3, 4, 5}. Randomization works as follows:

P1's first choice

P1 chooses each of the 5 numbers with probability 1/5.

P2's first choice

For purposes of illustration, assume that P1 chooses {3}. Then there are 8 possible subsets of the remaining numbers whose sum equals or exceeds 3 by one number.

{4} / {5} / {1, 2} / {1, 4} / {1, 5} / {2, 1} / {2, 4} / {2, 5}

Randomizing these choices means that P2 chooses each with probability 1/8.

In 6 of these cases, the subsets comprise two numbers, wherein the first number—either 1 or 2—is less than 3, so a second number, which is the second number in each subset, is needed to make the sum for P2 equal to or greater than 3. After P2 chooses one of the 8 subsets at random, either 2 or 3 numbers remain.

P1's second choice

Next P1 will choose again, and at random, a subset of the remaining numbers such that, when they are added to P1's present score of 3, equals or exceeds P2's score. Depending on the numbers that P1 chooses when it makes a second choice, P2 may or may not have a second choice that equals or exceeds P1's last total.

In summary, when a player randomizes, it chooses with equal probability any of the subsets of available numbers that equal or exceed an opponent's last total. In our 2015 article, we tested it against three strategies, none using AI, in which an opponent, at each of its turns, may (1) maximize its score, increasing its lead by as much as possible; (2) minimize its score, decreasing its lead by as much as possible, or (3) use the maximum number of numbers possible, reducing the numbers available to its opponent by as much as possible.

How do these strategies do against random when $n = 10$? A randomizing player won the following percentages of 100,000 games against each of these three kinds of opponents: (1) 41.7%, (2) 60.9%, and (3) 46.5%, suggesting that its performance was middling. The most decisive win score from matching each strategy, including random, against every other is that strategy (2) beat strategy (1) in 79.7% of games.[2]

Problems of AI in Catch-Up

Can an AI player, called AI, do better against a randomizing player, called RD, than any of the non-AI strategies? It would seem yes if AI can learn to make optimal choices by using backward induction.

The rub is that backward induction may not be learnable by AI, because it's a human discovery based on reasoning backwards from a last move. While this move can be determined if the players make optimal choices at every stage, this is not what RD does. Because RD's choices are unpredictable, AI cannot backward induct from a known last move of the game.

To be sure, after every (unpredictable) move of RD, AI can consider all possible moves from that point onward and determine what is optimal for it to do for every contingency that can arise. This optimal strategy may

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[2] Because the sum of the first 10 natural numbers is odd (55), we know that either P1 or P2 can force a win, based on backward induction, which turns out to be P2 by 28 to 27. This cannot readily be shown by hand; but in the simpler case of the first 5 natural numbers, it is not difficult to show that P1 can force a win by choosing 3 initially. Whichever of the 8 possible strategies that P2 can choose to equal or exceed 3 (see previous section), whatever choice P2 makes, P1 can force a win. For example, if P2 chooses {2, 5}, P1 will choose {1, 4} and win by 8 to 7; similarly, if P2 chooses {1, 2} and ties P1, P1 will then choose {5} and win by the same score when P2 must choose 4.

change radically after each random move of RD, but this is not the fundamental problem. More fundamental is whether it is possible, from playing against itself hundreds of thousands or millions of times, that any pattern resembling what backward induction prescribes can be learned.

It's not evident that this is possible when AI's opponent is RD, because there is no rhyme or reason to RD's choices.[3] Indeed, any regularity that AI detects in RD's play will be a chimera.

But for argument's sake, assume that AI is able to infer that RD is making random choices. Then AI's optimal strategy would be to stop trying to learn and instead use backward induction. But no extant AI strategy I am familiar with allows for this option.

Even if this option were allowed, however, applying backward induction may not be feasible. Because the number of possible choices of a player in Catch-Up increases exponentially with n, no present or foreseeable computer will be able to find optimal strategies in Catch-Up for, say, $n = 100$, just as Chess has proved impregnable to this determination. (This is not true of checkers; in 2007, it was shown that optimal strategies always produce a draw in this game.)

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[3] RD's strategy is somewhat akin to the use of optimal mixed (random) strategies in 2-person, zero-sum games, in which the value of the game is the same regardless of what strategy an opponent chooses.

Unlike Catch-Up, however, a player that randomizes its moves in Chess will lead to its quick demise (i.e., checkmate) against even an amateur player, not to mention one that uses an AI program. This has not proved true in Catch-Up, suggesting that RD vs. AI poses a real challenge to AI for two reasons: (1) AI may not be able to surmise that its opponent is RD, and what pattern in its play it does infer may be chimerical; (2) even if AI is able to infer that RD is making random choices and that backward induction would be optimal, it may not be feasible, except toward the end of a game when most numbers have already been chosen.

But this would not be an AI strategy, which has proved so effective in Chess and Go. It would rather be to use an idea from over 100 years ago, backward induction, which has nothing to do with learning either from experience or observing the results of playing a game many, many times.

In short, Catch-Up—and perhaps other behavior that reflects random processes in the natural world or applies them in the play of certain games—may be beyond the reach of AI. What distinguishes Catch-Up from Chess and Go, as well as other 2-person zero-sum games that in principle are solvable by backward induction, is that randomness in Catch-Up is the Achilles heel of AI.