Evolutionary MCTS for

Multi-Action Adversarial Games

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# Аннотация

**Оригинал**

Turn-based multi-action adversarial games are games in which each player turn consists of a sequence of atomic actions, resulting in an extremely high branching factor. Many strategy board, card, and video games fall into this category, for which the current state of the art Online Evoilutionary Planning(OEP) — an evolutionary algorithm(EA) that treats atomic actions as genes, and complete actions sequences as genomes. In this paper, we introduce Evolutionary Monte Cralo Tree Search(EMCTS) to tackle this challenge, combining the tree search of MCTS with the sequence-based optinmization of Eas. Experiments on the game Hero Academy show thet EMCTS convincingly outperforms several baselines inclunding OEP and an imporved varinat of OEP introduced in this paper, at different time setting and numbers of atomis actions per turn. EMCTS also scales better than any existing algorithm with the complexity of the problem.

Index Terms — game tree search, Monte Carlo Tree Search, strategy games

**Перевод**

Пошаговые многовариантные состязательные игры - это игры, в которых каждый ход игрока состоит из последовательности атомарных действий, что приводит к чрезвычайно высокому коэффициенту ветвления. Многие настольные игры, карты и видеоигры попадают в эту категорию, для которой в настоящее время используется современное эволюционное-онлайн планирование(ЭОП) - эволюционный алгоритм (ЭА), который обрабатывает атомарные действия как гены, а полные последовательности действий - как геномы. В этой статье мы представляем эволюционный поиск по дереву Монте-Крало (EMCTS) для решения этой проблемы, объединяя поиск по дереву MCTS с оптимизацией последовательностей на основе эволюционных алгоритмов. Эксперименты с игрой Hero Academy показывают, что EMCTS убедительно выигрывает у нескольких базовых алгоритмов, включая OEP и улучшенный вариант OEP, представленные в этой статье, при разных настройках времени и количестве элементарных действий за ход. EMCTS также масштабируется лучше, чем любой существующий алгоритм.

# **I. INTRODUCTION**

Computer programs typically play adversarial games with a form of search, choosing paths to desirable future game states as determined by e.g. a heuristic evaluation function. *Monte Carlo Tree Search* (MCTS) [1], [2] is the state of the art search framework for a variety of classical board games with moderate branching factors of up to a few hundred [3], as well as many card games, video games, and non-game domains [4].  
 However, most *turn-based multi-action adversarial games* – games in which each turn consists of a sequence of atomic actions, instead of just a single action – have much higher branching factors. This class of games includes board games such as Arimaa and Risk, mobile games such as Battle of Polytopia, and PC games such as Civilization, XCOM, Heroes of Might and Magic, and Into the Breach. A turn in a strategy game could for example consist of moving nine units with ten available actions each, resulting in a branching factor of one billion. Vanilla MCTS cannot handle this complexity, even with the help of various techniques for reducing the effective branching factor. Finding a good action sequence for a single turn, even without considering the next turns, is a challenging search problem in such domains. That is the problem we tackle in this paper. While some of the games in this class feature indeterminism (e.g. Risk) or partial observability (e.g. Civilization), our initial focus here is on deterministic multiaction adversarial games with perfect information.

One possible approach is searching a tree in which each edge represents an atomic action instead of a complete turn, resulting in a much smaller branching factor, but also a much deeper tree (see [5] for a similar trade-off). According to Kozelek [6] and Justesen et al. [7] however, vanilla MCTS is often not able to search the tree of its current turn deeply enough, and focuses too much on optimizing the first actions compared to the last actions. MCTS can be enhanced with pruning techniques that make the search spend the same amount of time on each action [8] – but this still suffers from the problem that MCTS has to find the actions of its turn in a fixed order, so that choices on earlier actions can influence later actions but not vice versa. Justesen et al. therefore proposed a different, treeless search approach: *Online Evolutionary Planning* (OEP), an evolutionary algorithm that treats atomic actions as genes and complete turns as genomes [9], [7]. By searching over the space of possible next turns with the help of crossover and mutation, it can optimize each action equally and simultaneously. OEP is the current state of the art in multi-action adversarial games.  
 In this paper, we propose an alternative approach called *Evolutionary MCTS* (EMCTS), combining some of the features of MCTS and evolutionary algorithms. It searches a tree with nodes representing genomes (in multi-action adversarial games: complete turns instead of partial turns, or the states resulting from them), and with edges representing mutations of those genomes (in multi-action adversarial games: mutations of turns instead of additional atomic actions). EMCTS therefore explores the mutation landscape of evolutionary algorithms in a systematic, best-first manner, providing evolution with lookahead search.  
 We use the same testbed game as Justesen et al. [7] in this paper: the turn-based multi-action adversarial game *Hero Academy*. We also introduce an improved variant of OEP called greedy OEP by transferring some ideas from EMCTS to OEP. EMCTS is then compared to vanilla OEP, greedy OEP, and four other baseline search algorithms including two vanilla MCTS variants specifically designed for Hero Academy, at different CPU time per turn and at different numbers of actions per turn.  
 This paper begins with a brief review of relevant related work in Section II. Section III describes our testbed, Hero Academy, outlines the baseline algorithms we are comparing, and introduces Evolutionary MCTS. Section IV presents our experimental setup and results, and Section V gives our conclusions and suggests future work.

# II. BACKGROUND AND RELATED WORK

This section reviews work on MCTS for very large branching factors, on the current state of the art for multi-action  
adversarial games – Online Evolutionary Planning – and on  
previous attempts at combining evolution and tree search.

## *A. Monte Carlo Tree Search*

Monte Carlo Tree Search (MCTS) [1], [2] is a best-first tree search algorithm based on stochastic simulations for state evaluation, which has been successfully applied to a large variety of games and other tasks [4]. The algorithm typically constructs a search tree with nodes representing game states, and edges representing actions leading from one state to another. In a deterministic game and ignoring transpositions, this can also be seen as a tree in which nodes represent the list of actions that have been applied from the root state to reach their respective state – this view will be helpful later. MCTS begins its search at a root node corresponding to the current game state. It then repeats the following four-phase loop until computation time runs out:  
 1. In the selection phase, a *selection policy* is used to traverse the tree until an unexpanded action is chosen. The selection policy should balance the exploitation of states with high value estimates and the exploration of states with uncertain value estimates. In this paper, the popular UCB policy is used [10].  
 2. In the expansion phase, the previously unexpanded action and a node representing its successor state are added to the tree.  
 3. In the rollout phase, a *rollout policy* is used to play out the remaining part of the simulated game, starting from the state represented by the newly added node. This rollout policy can be uniformly random, but can also profit from heuristic game knowledge. In this paper, we use -greedy rollouts, which select a random action with probability , and otherwise follow simple greedy heuristics.  
 4. In the backpropagation phase finally, the value estimates of all states traversed during the simulation are updated with the result of the finished game. Several MCTS variants and enhancements have been proposed over time in order to apply MCTS to games with increasingly higher branching factors.  
 First-play urgency [11] encourages exploitation by providing a value for unvisited child nodes, removing the need for MCTS to visit every child of a node before a selection policy like UCB can be applied. Progressive widening [12] and unpruning [13] approach the branching factor problem in Go by first limiting the number of actions expanded in a new MCTS node, then growing it over time so as to improve value estimates and still guarantee convergence in the limit. For games with much higher branching factors such as real-time strategy (RTS) games, script-based approaches have been developed in order to search over a small number of hand-coded scripts instead of a larger number of atomic actions: Hierarchical Portfolio Search [14] and Script-based UCT [15] fall into this category, as well as the non-MCTS approach of Portfolio Greedy Search [16]. Some previous works have applied MCTS variants to domains with very large or continuous action spaces by making strongly simplifying assumptions such as independence of units in an RTS game [17], or similarity of “close” actions in a physicsbased domain [18]. Often, the assumption is made that each unit can perform one action per time step, as is typical for RTS games. In this paper, we do not assume independence of units, do not tie actions to units, and do not assume the existence of predefined policies or scripts. We do however use a heuristic evaluation function – which is hand-coded in our test domain, but could in future work be automatically learned [3].  
 We are using two specifically adapted variants of MCTS as baselines in our experiments, described in Subsection III-B. The proposed EMCTS is similar to vanilla MCTS in the sense that it uses the same tree search structure of selection, expansion, rollout, and backpropagation, while working on a new, evolution-inspired search space.

## *B. Online Evolutionary Planning*

Evolutionary algorithms (EAs) are a class of optimization  
algorithms inspired by natural selection that has been used  
extensively for evolving and training AI agents for games  
[19], [20]. In the classic, *offline* evolutionary approach, an AI’s  
parameters are evolved using its performance at playing the  
game as a fitness function. No evolution is applied after the  
training has finished and the AI is deployed in the game [21],  
[22], [23], [24].  
*Online* evolution is a newer approach, in which evolutionary  
algorithms are applied during gameplay. This can take the  
form of evolving the AI’s parameters while it is playing [25].  
However, it is also possible to evolve the next *action(s)* to take  
in the currently running game. *Rolling Horizon Evolutionary*  
*Algorithm* (RHEA) [26], [27] for example evolves fixed-length  
future sequences of actions in a single-player game, which are  
compared by simulating them and evaluating the resulting game  
states. When a time limit is reached, the algorithm executes the  
first action in the best action sequence found, and continues  
search on action sequences starting from the next time step  
(“rolling” search horizon).  
*Online Evolutionary Planning* (OEP) [28], [7] is a recent  
evolutionary approach that is applicable to adversarial multiaction games. It optimizes only the action sequence of the  
current turn, without lookahead to future turns of the player or  
the opponent. It can therefore be seen as doing one iteration of  
RHEA at the beginning of each turn, and with a search horizon  
of one turn. The best action sequence found is then executed  
without “rolling” the horizon forward action by action.  
OEP begins its search by creating an initial population of  
genomes, each genome representing a complete turn (fixedlength sequence of actions). Vanilla OEP chooses each of these  
genomes by repeatedly selecting random actions starting from  
the current game state. This population is then improved from

generation to generation, until a given computation time runs  
out. Each generation consists of the following four phases:  
1. All genomes are translated to their respective phenotypes,  
the game states resulting from applying their action sequence  
to the current game state. The fitness of these phenotypes is  
then evaluated with the help of a static heuristic evaluation.  
2. The genomes with the lowest fitness are removed from  
the population. The proportion of genomes to be removed is a  
parameter called the *kill rate*.  
3. The surviving genomes are each paired with a randomly  
chosen different genome, and create an offspring through  
uniform crossover. If this crossover operator leads to an illegal  
action in the offspring, it is repaired by replacement with an  
action from the other parent, or otherwise with a random legal  
action.  
4. A proportion of the offspring, determined by a parameter  
called the *mutation rate*, undergoes mutation. One randomly  
chosen action of the sequence is changed to another action  
randomly chosen from all legal actions. If this leads to illegal  
actions later in the sequence, they are replaced with random  
legal actions as well.  
When the time budget is exhausted, OEP returns the action  
sequence represented by the current best genome, which is then  
executed action by action. In the words of Wang et al. “the  
action selection problem is seen as an optimization problem  
rather than a planning problem” [29]. This is currently the bestperforming approach for turn-based multi-action adversarial  
games, in particular the test domain of this paper: Hero  
Academy [7]. It has also been applied to other problems such  
as micro battles [29] or online build order adaptation [30] in  
RTS games.  
We are using the original OEP, as well as a new improved  
variant, as baselines in our experiments. The proposed EMCTS  
is similar to OEP in the sense that in multi-action adversarial  
games, it also searches a space of complete turns, which are  
connected to each other through the same mutation operator.  
It is different in being a tree search algorithm.

## *C. Hybrids of tree search and evolution*

Several other methods have been published that combine  
ideas from tree search algorithms and evolutionary algorithms.  
Gaina et al. [31] experimented in General Video Game AI  
(GVGAI) with splitting the total search time in two, using  
MCTS in the first half to provide an initial solution, which is  
then refined by RHEA in the second half. This was able to  
outperform RHEA, but not MCTS. Horn et al. [32] hybridized  
MCTS and RHEA in two different ways: By making use of  
limited-depth Monte Carlo simulations in the evaluation of  
RHEA genomes, and by running RHEA and MCTS separately  
and choosing the best solution found by either of them for  
execution. EMCTS on the other hand uses a single search  
algorithm, and a tree search with static state evaluation instead  
of an evolutionary search with rollouts for evaluation. Lucas et  
al. [33] used an evolutionary algorithm to improve the rollout  
policy of MCTS while the search is running. Perez-Liebana  
et al. [34] adapted a similar method for GVGAI, combining  
it with a knowledge base to improve reward calculations of  
given states. While improving MCTS or RHEA performance  
in various single-player games, the algorithms developed for  
the GVGAI framework are not straightforwardly applicable to  
multi-action adversarial games.  
For adversarial games, Hong et al. [35] proposed a strategy  
to evolve paths through a game tree with the help of an  
evolutionary algorithm. While their approach assumes identical  
actions to be available in all states at the same search depth,  
which is not the case in most real-world games including our  
testbed Hero Academy, it gives an interesting indication for  
possible future work that could take opponent actions into  
account.

# III. METHODS

This section briefly describes the game we use as testbed,  
lists the search algorithms we are comparing to, and finally  
presents our approach: Evolutionary MCTS.

## *A. Test Domain: Hero Academy*

**Rules.** Our test domain is a simplified1 Java clone [36] of  
Hero Academy [37], a two-player turn-based tactics game.  
Players can use a variety of combat units, items, and spells  
by first drawing them from a card deck onto their hand, and  
then deploying, casting, or moving them on a battlefield of  
9*×*5 squares. Special squares on this battlefield allow for unit  
deployment, boost the stats of individual units, or represent  
a player’s two crystals. The game is won by the first player  
to either eliminate all enemy units, or to destroy both enemy  
crystals. More details on implementation and rules can be  
found in [28].

Fig. 1: The testbed game Hero AIcademy. The six symbols at the  
bottom represent the current player’s hand, and the numbers below  
the doors represent the deck sizes. One of the red player’s crystals  
has already been destroyed.

A central mechanic of the game are the *action points* (AP).  
For each turn, the player to move receives a number of action  
points – five in the standard form of the game. Each action

1For example, only the “Council” team of units is available.

point can be used for any one atomic action such as deploying  
a unit from the player’s hand onto the battlefield, moving  
a unit on the battlefield, attacking an enemy unit, healing a  
friendly unit, and others. The player can spend any number of  
action points on a single unit, for example by moving it several  
times. With an average of 30-60 actions available per game  
state, depending on the playstyle, the full branching factor  
per turn can be roughly estimated to be 305 *≈* 2*.*4 *×* 106 to  
605 *≈* 7*.*8 *×* 108. Finding the best sequence of actions for any  
given turn is therefore a challenging search problem in itself.  
The order of cards in the deck as well as the opponent’s  
cards are unknown to the Hero Academy player. However, this  
paper focuses on the challenge of multi-action turns, ignoring  
the aspects of hidden information and indeterminism as in [7].  
In line with Justesen et al.’s prior work on Hero Academy,  
we use game knowledge for state evaluation as well as action  
pruning and ordering:  
**State evaluation.** All algorithms compared in this paper  
use the same heuristic evaluation function. This function is a  
linear combination of features such as the current health of  
individual units, whether they are equipped with certain items,  
and whether they are standing on special squares. Improving  
this hand-coded function with machine learning, and testing if  
our conclusions still hold, could be worthwhile future work.  
**Action pruning and ordering.** All algorithms compared in  
this paper use a form of hard pruning, removing a number  
of redundant or provably suboptimal actions from the set of  
available actions considered in any given state. The two MCTS  
variants considered as baselines also make use of static action  
ordering, giving the more promising actions priority in their  
expansion and rollout phases. The heuristics used for this are  
simpler and faster than those of the evaluation function.  
The interested reader can refer to [28] for a full definition of  
the heuristic evaluation function and the pruning and ordering  
strategies.

## *B. Baseline Approaches*

In order to make our results directly comparable to the literature, we are testing our approach against five of the algorithms  
described in [7]. Four of them are tree search techniques, and  
one is Online Evolutionary Planning representing the state of  
the art for Hero Academy.  
**Greedy Action.** The Greedy Action AI chooses the first  
action of its turn with a simple one-ply search of all legal  
actions, maximizing the heuristic evaluation of the immediately  
resulting state. This is repeated for each action point, i.e. for  
all five actions of the turn.  
**Greedy Turn.** The Greedy Turn AI chooses its actions  
by attempting a five-ply depth-first search of the entire turn,  
maximizing the heuristic evaluation of the leaf states resulting  
from full turns. It uses a transposition table in order to avoid  
re-visiting states. Actions are ordered for search with the  
evaluation function, which is especially important since Greedy  
Turn can usually not exhaustively search the entire turn in the  
given time limit.

**Non-exploring MCTS.** This AI is the first MCTS variant  
adapted for multi-action adversarial games in [7]. It searches a  
game tree as shown in Figure 2, in which each edge represents  
an additional action for the turn under consideration (or its  
application). The opponent’s next turn can be reached by a  
tree deeper than five plies, the number of action points. The  
selection policy of this MCTS variant is UCB, and the rollout  
policy deterministically follows the action ordering heuristics.  
It was found to improve performance when rollouts are just  
long enough to complete the current turn of the player to act  
in the leaf node, calling the heuristic state evaluator at the end  
of the turn for a rollout result. The MCTS exploration factor is  
set to *C* = 0 in an attempt to grow a deep enough tree (pure  
exploitation).

Fig. 2: Tree structure as searched by vanilla MCTS and its variants (non-expl. MCTS, BB-MCTS). Nodes represent partial action  
sequences, or the states resulting from them. Edges represent the  
addition of an atomic action to an action sequence, or the application  
of an atomic action to a state. After each node expansion, a rollout  
is performed for evaluation. (We use symbols to represent different  
atomic actions.)

**Bridge-burning MCTS (BB-MCTS).** This MCTS variant  
searches the same kind of tree shown in Figure 2. Instead of  
deterministic rollouts, it uses -greedy rollouts with = 0*.*5,  
which also only reach to the end of the current turn of the  
leaf node. Its exploration factor is *C* = 1*/√*2. In order to  
grow a deep enough tree for multi-action turns however, it  
employs a technique called “bridge burning” in [7] – a reinvention of move-by-move search [8]. We are keeping the  
term “bridge burning” here, as the term “move” is ambiguous  
in Hero Academy, and also because we are going to generalize  
the concept of bridge burning to a different kind of tree in the  
next subsection.  
The idea of BB-MCTS is to split the time budget for the  
current move search into five phases, equal to the number of  
actions per turn. During each phase, the MCTS search proceeds  
normally, but at the end of each phase, the most promising  
action at the root is executed, leading to the root state for  
the next phase. This can be implemented as the hard pruning  
strategy shown in Figure 3.  
**Online Evolutionary Planning.** The OEP baseline is as  
described in Subsection II-B. In our experiments, we use the  
same parameter settings as suggested in [7]: A population size  
of 100, a kill rate of 0.5, a mutation rate of 0.1, and uniform  
crossover and mutation operators.

Fig. 3: The “bridge burning” search strategy (illustration adapted from  
[7]). (a) After phase 1, all branches but the best one are pruned at  
the root. (b,c) After phases 2, 3, *. . . n*, pruning is applied at depth 2,  
3, *. . . n*. The partial tree below the best branch is retained.

Fig. 4: Tree structure of Evolutionary MCTS. Nodes represent  
complete action sequences (genomes), or the states resulting from  
them. Edges represent the mutation of an atomic action within a  
genome. Repairs can be necessary if those mutations can lead to  
illegal genomes. After each node expansion, the evaluation function  
is called instead of a rollout. (We use symbols to represent different  
atomic actions.)

This algorithm is currently the best-performing approach  
for multi-action turn-based games such as Hero Academy.  
Although [7] shows it to be of similar strength to non-exploring  
MCTS and BB-MCTS in the standard form of the game with  
5 action points per turn, OEP was shown to scale better to the  
tougher challenges of Hero Academy using 10 AP or more.  
Our experiments include those exponentially more complex  
variants as well.

## C. Evolutionary MCTS

This subsection proposes our new search algorithm, *Evolutionary MCTS* or *EMCTS*, as applied to playing multi-action  
turn-based adversarial games. It combines the tree search  
of MCTS with the genome-based approach of evolutionary  
algorithms.  
Instead of the vanilla MCTS tree seen in Figure 2, EMCTS  
builds a tree as shown in Figure 4. Instead of starting from  
an empty turn in the root, EMCTS starts from a complete  
sequence of five (or more, depending on the domain) actions  
– just like the genomes of OEP. Instead of growing a tree  
that adds one action to the current sequence with every edge,  
EMCTS grows a tree that mutates the current sequence with  
every edge – using the same mutation operator as OEP. And  
instead of using rollouts to complete the current turn and then  
evaluating it as our MCTS baselines do, we simply evaluate  
the solutions at the leaf nodes2. Backpropagation is unchanged.  
EMCTS does not apply mutations randomly, but can choose  
exactly which action in the sequence to mutate and which other  
legal action to mutate it to3. While OEP turned the planning  
of the action sequence into an optimization problem, EMCTS  
thus takes the evolutionary optimization of the sequence and  
turns it back into a planning problem. It can be seen as tree  
search, but it can also be seen as a systematic exploration of  
the mutation landscape of OEP, giving evolution the benefit of  
lookahead.  
Two questions need to be answered to fully flesh out EMCTS.  
First, where does the root sequence come from? EMCTS needs

2Evaluating at the leaf nodes is a well-known MCTS variant that was  
successfully employed for example in AlphaGo Zero and AlphaZero [3].  
3No crossover operator is used.

a *starting solution* to its search, just like EAs such as OEP  
need a starting population of solutions. Different approaches  
are possible – in this paper, we are using the Greedy Action  
algorithm described above for a quick and greedy initialization  
of the root. Second, what happens when a mutation leads  
to an illegal action sequence? We could filter these out by  
simulating every possible mutation in advance, but that would  
be computationally expensive. Instead, like OEP we are taking  
the classic evolutionary algorithm approach of using a *repair*  
*strategy* – in this paper, we are using the Greedy Action AI  
for repairs as well whenever necessary.  
Note that the use of Greedy Action does not introduce  
additional heuristic knowledge, as all algorithms compared  
in this paper are working with the same evaluation function.  
However, we noticed that like EMCTS, OEP can also be  
significantly improved by using a Greedy Action repair policy  
instead of a random repair policy. This results in higher quality  
repairs on average. And just like EMCTS profits from a greedy  
root genome, OEP can profit from filling 20% of the starting  
population with Greedy Action sequences instead of random  
ones4. This kick-starts the search with higher-quality starting  
solutions. We are calling this new variant *greedy OEP* here,  
as opposed to *vanilla OEP* with random repairs and a purely  
random starting population as described in [28], [9], [7], and  
include it in our experiments for a fair comparison.  
Finally, EMCTS results in an even larger branching factor  
than the vanilla MCTS variants. While the branching factor  
in Hero Academy games between the MCTS baselines was  
measured to be between 30 and 40, the branching factor of  
the mutation tree of EMCTS is about 30 *per action point* – so  
around 150 for the standard settings of the game with five action  
points. We found that an effective way of dealing with this  
is “bridge burning”, just as applied to the regular MCTS tree  
by BB-MCTS. Instead of executing the most promising action  
at the root after every search phase like BB-MCTS, EMCTS  
executes the most promising mutation at the root after each  
phase. The number of bridge burning phases, of successive

4This performed better than filling 1%, 10%, and 50% of the starting  
population with Greedy Action sequences.

searches and prunings/mutations, is the only parameter of  
EMCTS we tuned (see the following section). The MCTS  
exploration factor was set to *C* = 0. The selection policy is  
UCB as in the other MCTS variants.

# IV. EXPERIMENTS AND RESULTS

This section describes our experimental setup for testing the  
proposed Evolutionary MCTS, as well as the results.

## *A. Experimental Setup*

We tested EMCTS in Hero Academy against Greedy Action,  
Greedy Turn, non-exploring MCTS, BB-MCTS, and vanilla  
OEP as proposed in [7], as well as the improved greedy OEP  
as proposed in the previous section. All comparisons were  
performed on the standard settings of the game with 5 action  
points per turn, but also with altered rules allowing 10 AP  
or even 15 AP per turn5. This increases the complexity of a  
single turn exponentially, but gives a stronger indication of  
generalizability to other games which can have higher numbers  
of possible actions per turn. Furthermore, all comparisons were  
done at different time budgets of 200 ms per turn, 1 second  
per turn, and 5 seconds per turn. Each comparison consisted  
of 400 games, with EMCTS playing 200 games as the first  
player and 200 games as the second player. The map used is  
shown in Figure 1. Games that had no winner after 200 turns  
were counted as draws, i.e. half a win for each player.  
All algorithms used the parameter settings described in  
Section III. The number of “bridge burning” phases for EMCTS  
was determined in preliminary experiments and set to 20 for  
200 ms, 40 for 1 second, and 100 for 5 seconds per turn time  
controls. The number of phases for BB-MCTS were identical  
to the AP per turn, since it searches the type of tree shown in  
Figure 2 and does not profit from deeper searches. As no other  
algorithm was modified based on the AP per turn, EMCTS  
was also not specifically tuned for different AP.

## *B. Results*

Table I shows the performance of the proposed Evolutionary  
MCTS against the five baselines and the improved greedy  
Online Evolutionary Planning.  
EMCTS is significantly stronger than all baselines (Greedy  
Action, Greedy Turn, BB-MCTS, non-expl. MCTS, and vanilla  
OEP) at all time controls and all numbers of action points  
per turn. Its relative strength increases with the complexity of  
the search problem as measured in action points per turn. The  
newly proposed greedy OEP is a dramatic improvement over  
vanilla OEP as described in [7], but still significantly weaker  
than EMCTS at all action points at 200 ms per turn, and at all  
action points except for the lowest setting (5) at 1 s and 5 s per  
turn, where the two algorithms perform similarly. The results  
therefore show that Evolutionary MCTS is highly effective at a

*520 or even 25 AP as in [7] were not included. As the authors noted, such  
high numbers of AP make it possible to win the game within very few turns,  
and make the winner very strongly depend on who gets the first turn. Strength  
differences between AIs are therefore harder to measure. More significant rule  
changes would have to be made to balance the game with such high AP*

*TABLE I: Win rates of EMCTS vs. all baselines at different time  
controls. 400 games per data point. Asterisks indicate significantly  
stronger play by EMCTS: \*p < 0.05, \*\*p < 0.01, \*\*\*p < 0.001*

variety of time controls, and scales better with the complexity  
of the domain than all other tested approaches.  
Note that there is a tradeoff for “bridge burning” EMCTS  
between doing more phases (pruning all but the best mutation  
and continuing search from there), and having more time for  
each phase (to identify the best mutation). With search time,  
both the optimal number of phases as well as the optimal time  
per phase seem to increase. The settings found to perform best  
in our experiments have such high numbers of phases, and such  
little time for them, that EMCTS could be seen as a type of  
local search [38] or (1*, λ*)-Evolution Strategy [39]. At longer  
time settings though, deeper trees can form, and EMCTS turns  
into a new kind of genome-based planning, or evolution with  
lookahead. These connections are worth exploring more deeply  
in future work.

# V. CONCLUSIONS AND FUTURE WORK

This paper proposes a new algorithm for playing turnbased adversarial games, where each turn consists of a  
sequence of multiple actions. Such action sequences, common  
in strategy games, lead to the challenge of extremely large  
branching factors per turn. This is difficult to handle even for  
selective tree search methods such as MCTS, which typically  
search a tree of atomic actions, and specifically developed  
evolutionary algorithms such as OEP, which optimize entire  
action sequences.

Our new algorithm, called *Evolutionary MCTS* (EMCTS), is  
based on the idea of combining the tree search of MCTS with  
the sequence-based optimization of evolutionary algorithms.  
Instead of searching a vanilla MCTS tree, EMCTS searches  
a tree in which each edge mutates one action in a complete  
action sequence. Experiments on the game Hero Academy  
show that EMCTS convincingly outperforms several baselines  
from the literature, including the state of the art OEP and an  
improved variant of OEP introduced in this paper, at different  
time settings and numbers of actions per turn. EMCTS also  
scales better than any existing algorithm with the complexity  
of the problem. It is therefore the currently strongest algorithm  
for playing Hero Academy, and a promising candidate for other  
turn-based multi-action games such as Civilization, XCOM,  
Heroes of Might and Magic, or Into the Breach.  
Several directions appear interesting for future work. First,  
the comparison between Evolutionary MCTS and the baseline  
algorithms could be deepened, including experiments with  
different initialization and repair strategies, different evaluation  
functions, more careful tuning of algorithm parameters such  
as OEP’s population size, mutation rate, and kill rate, and  
possible improvements to MCTS methods such as stronger  
rollout policies. Second, various aspects of EMCTS could  
be considered in more detail, such as speed optimizations  
– it currently only evaluates roughly 20% as many action  
sequences per second as OEP. Mutations for expansion could  
for example be generated lazily in the tree nodes, and various  
MCTS enhancements could be used to improve their ordering.  
Third, the performance of EMCTS in other games could be  
tested, such as strategy games with longer matches and larger  
numbers of units. We are planning to apply it to Battle of  
Polytopia, a mobile turn-based strategy game in which armies  
can grow to 15 to 20 units or more in the late game. Unlike Hero  
Academy, Battle of Polytopia does not allow for any unit to  
move more than once per turn; however, additional complexity  
arises from units whose actions themselves consist of several  
atomic parts such as moving, attacking, and retreating. An  
interesting challenge for the application to commercial games is  
that the existence of a heuristic state evaluation function cannot  
generally be assumed, requiring machine learning approaches.  
Just like OEP, EMCTS could also be generalized to other  
problems such as micro battles [29] or online build order  
adaptation [30] in RTS games. In the former scenario, the  
genomes would consist of a list of scripts representing simple  
policies assigned to each unit, instead of a list of atomic  
actions for the player. In the latter scenario, the genomes  
would be candidate build orders, i.e. fixed-length sequences  
of future units and buildings to construct. Fourth, the problem  
of considering future actions of the opponent has not been  
tackled successfully yet, neither by OEP nor by EMCTS.  
Generalizing to larger classes of games will also require dealing  
with indeterminism and partial observability. And last but not  
least, the algorithmic similarities between Evolutionary MCTS  
and certain local search algorithms and evolutionary algorithms  
deserve further study, in order to further explore the idea of  
“evolution with lookahead”.

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**Раскрытие технологии:**

**Оригинал**

**Перевод**