Evolutionary Approach to Collectible Card Game
Arena Deckbuilding using Active Genes

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Abstract—In this paper, we evolve a card-choice strategy for
the arena mode of Legends of Code and Magic, a programming
game inspired by popular collectible card games like Hearthstone
or TES: Legends. In the arena game mode, before each match, a
player has to construct his deck choosing cards one by one from
the previously unknown options. Such a scenario is difficult from
the optimization point of view, as not only the fitness function
is non-deterministic, but its value, even for a given problem
instance, is impossible to be calculated directly and can only
be estimated with simulation-based approaches.

We propose a variant of the evolutionary algorithm that uses a
concept of an active gene to reduce the range of the operators only
to generation-specific subsequences of the genotype. Thus, we
batched learning process and constrained evolutionary updates
only to the cards relevant for the particular draft, without
forgetting the knowledge from the previous tests.

We developed and tested various implementations of this
idea, investigating their performance by taking into account the
computational cost of each variant. Performed experiments show
that some of the introduced active-genes algorithms tend to learn
faster and produce statistically better draft policies than the
compared methods.

Index Terms—Evolutionary Algorithms, Collectible Card
Games, Deck Building, Game Balancing, Strategy Card Game
AI Competition, Legends of Code and Magic

I. INTRODUCTION

Currently, not only classical boardgames like Chess [1] and
Go [2] are used as grand challenges for AI research. It has
been recently shown that such a role may be taken by modern
computer games. So far presented approaches that beat the
best human players in Dota 2 [3] and StarCraft II [4] are one of
the most spectacular and media-impacting demonstrations of AI
capabilities.

The weight is put on particular game features that make
designing successful AI players especially tricky, e.g., imper-
fect information, randomness, long term planning, and massive
action space. One of the game genres containing all these game
features is Collectible Card Games [5].

Recently, numerous research has been conducted in this
domain, focusing mainly on development of MCTS-based
agents, and creating the deck recommendation systems that
will choose the right set of cards to play. The Hearthstone
AI Competition [6], with the goal to develop the best agent
for the game Hearthstone, [7] was organized during the IEEE
CIG/COG conferences in 2018 and 2019. The Strategy Card
Game AI Competition based on programming game Legends of
Code and Magic (LOCM) [8], designed especially for handling
AI vs. AI matches and played in the arena mode, was hosted
in 2019 by IEEE CEC and IEEE COG. The AAIA’17 Data
Mining Challenge: Helping AI to Play Hearthstone [9] was
focused on developing a scoring model for predicting win
chances of a player, based on single-game state data.

This work is the first approach to build a deck recommenda-
tion system for the arena mode. As in the other modes players
can use their full collection of cards, in arena they draw a deck
from a random selection of cards before every game. Such a
task is characterized by an even larger domain (considering
all possibilities of available choices), higher non-determinism
(the additional card selection phase is non-deterministic), and
harder opponent prediction.

We propose variants of the evolutionary algorithm that
uses a concept of an active gene to reduce the range of the
operators only to specific subsequences of the genotype that
changes from generation to generation. In other words,
our batched learning constrains evolutionary updates only to
the cards relevant for the particular draft. Individuals forming
the next population are no longer simply selected among the
parents/offspring populations, but instead, they are merged
from the specific subsets of their representatives.

We have conducted a series of experiments in LOCM to
estimate the performance of multiple variants of designed
algorithms and compare them with several baselines. Algo-
rithms learn on a small sample of random drafts (available
card choices) and are tested on a larger number of other drafts,
using large number of game simulations to estimate the fitness
value in such a highly non-deterministic environment. The
results show that some of the introduced active genes variants
perform better than other tested approaches, i.e., they tend to
draw stronger decks from the same available card choices.

II. BACKGROUND

A. Collectible Card Games

Collectible Card Game (CCG) is a broad genre of both
board and digital games. Starting with Magic: The Gathering
decks of similar games have been created. The Elder Scrolls: Legends (MtG) [10] in the early 90s, or more recent Hearthstone [7] and The Elder Scrolls: Legends (TESL) [11], a huge number of similar games have been created.

The mechanics differ between games, but basics are similar. Two players with their decks draw an initial set of cards into their hands. Then the actual play begins. A single turn consists of a few actions, like playing a card or using an onboard card. The game ends as soon as one of the players wins, most often by getting their opponent’s health to zero.

A typical CCG characterizes with a large number of playable cards (over 1,000 in TESL and almost 20,000 in MtG), which causes an enormous number of possible deck compositions. This leads to even bigger in-play search space, as the player does not know the order of his next draws, the content of the opponent’s deck, nor his in-hand cards. Such numbers tend to increase the amount of problems related with the imperfect information and randomness.

It is also common to observe a metagame level of such games. It describes the popularity of certain decks or cards. On a top-level, meta creates a possibility to compare different decks on a larger scale. Most often, it boils down to a “rock-paper-scissors” scheme, but with more possible types.

B. Related Work

The problem of creating decks that will be effective for some given meta (usually understood as a currently dominating set of opposing decks) is one of the key challenges for CCG domain [5]. In [12], the Hearthstone decks are evolved and tested for their strength via playing against a small number of predefined human-created decks. A similar task, but in a much more complicated domain of Magic: The Gathering has been approached, also via evolution, in [13]. A neural network-based approach to deckbuilding in Hearthstone has been presented in [14]. More in-depth analysis of Hearthstone deck space and the impact of various factors on the process of their evolution can be found in [15]. All the above research is focused on the constructed game mode, i.e., a static card selection, from unrestricted sets of available cards.

The topic closely correlated with deckbuilding is how to design the cards in CCG to be balanced [16]. In [17], evolution is used to propose changes to the cards that will result in better balance. In [18], several experiments using a modification of MAP-Elites algorithm for design and rebalancing of Hearthstone have been presented.

So far, no research has been aimed at the arena mode of CCGs. Methods for estimating card values that could be useful in arena play have not been subject to a proper investigation, although they are popular among human game players. There exist dedicated web pages and game-helping software that recommends cards (e.g., [19], [20]). The data they are based on is continuously updated and consists of a mix of expert domain knowledge, mathematical formulas, and remarks made by players on public forums.

C. Legends of Code and Magic

Legends of Code and Magic (LOCM) [8] is a small implementation of a Collectible Card Game, designed to perform AI research. Its advantage over the real card game AI engines is that it is much simpler to handle by the agents, and thus allows testing more sophisticated algorithms and quickly implement theoretical ideas.

All card effects are deterministic. Thus the non-determinism is introduced only by the ordering of cards and unknown opponent’s deck. The game board consists of two lanes (similarly as in The Elder Scrolls: Legends), so it favors deeper strategic thinking. Fig. 1 shows the visualization in the middle of the game. Also, LOCM is based on the fair arena mode, i.e., before every game, both players create their decks secretly from the symmetrical yet limited choices. The card choices for the players are different every game, but both players have the same decisions in this phase. This is not true in arena mode in existing computer games, where every created deck is used in several games versus players that had other options to choose from. The deckbuilding in LOCM is more dynamic and, although the concept of meta is still applicable, it can be countered by the specific choices of drafts, reducing the overall strength of usual human-created top-meta decks.

The game in a slightly simplified (one-lane) form was used in August 2018 as a CodinGame platform contest, attracting more than 2,000 players (or rather AI programmers) across the world [21]. The Strategy Card Game AI Competition based on LOCM was hosted in 2019 by IEEE CEC and IEEE COG [8].

III. METHODOLOGY

A. Problem Specification

Consider two players, A and B, playing in a constructed mode. Before every game, they have to choose their decks, i.e., subsets of available cards additionally fulfilling some game-specific constraints (e.g., no more than three copies of the same card). Then, A and B play against each other, using their playing algorithms and their chosen decks (randomly shuffled).

Thus, the goal of A is to choose deck and algorithm such that it performs best over every possible combination of the opponent’s choices. (In practice, as the number of such combinations is huge, a much smaller set of meta opponent decks is considered, as they are well-performing and have a higher chance of appearance.)
However, considering the arena mode, the task becomes slightly different. Now, the player \( A \) has to build his deck given a set of choices in the so-called draft phase. Usually, it consists of turns in which \( A \) has to pick one of randomly given cards, and he is not aware of the future options. Thus, the player’s goal is to choose the best draft strategy, i.e., such that performs best for every draft options and every possible opponent.

In the deckbuilding problem, we fix the algorithms used by the players, treating them as given, and focus on optimizing the policy of choosing the cards. Either a static as in constructed mode, or dynamic, depending on the given draft options, in arena.

1) Domain: Consider a set of all possible cards in the game \( \mathcal{C} \). For Legends of Code and Magic, \( |\mathcal{C}| = 160 \). During the draft phase, a player collects 30 cards for his deck in turns, in each turn choosing one of 3 given cards. Thus, given that all draws are independent and a card cannot be repeated within a single turn, the number of possible drafts for LOCM is \( (160 \times 159 \times 158)^{30} \approx 1.33 \times 10^{198} \).

During the draft, a player knows his previous decisions but is unaware of future choices. Thus, when learning the best draft policy, we search for the best function from the following domain (simplified to repeating cards):

\[
(\mathcal{C} \cup \{\perp\})^{30} \times \mathcal{C}^3 \rightarrow \{1, 2, 3\},
\]

where \( \perp \) denotes a choice that is yet to make (remaining draft turns). We assume the cards to choose from are ordered, so it is enough to pick the position of the card.

This task can be significantly simplified by discarding the information about previous choices (which removes, e.g., taking to account card synergies or controlling a mana curve), and reduces the domain of possible draft strategies to

\[
\mathcal{C}^3 \rightarrow \{1, 2, 3\}.
\]

In this work, for practical reasons, we represent a draft policy as the pure card-value assignment: in each turn, the card with the highest value is chosen. Such an approach is popular policy as the pure card-value assignment: in each turn, the card with the highest value is chosen. Such an approach is popular

2) Fitness Function: The difficulty with estimating the quality of card selection policy comes from the multiple sources of simplifying assumptions and randomness. Even approximated fitness functions, using fixed playing algorithms, are flawed not only because of unknown distribution of opponent strategies, but also the nondeterminism in the games themselves, causing the value of the function to be less reliable.

In such a case, a reasonable approach is to combine simulation-based estimations with numbers. First, sample the largest possible portion of possible drafts. Second, estimate fitness based on the performance of candidate policies on those sample drafts, using a large number of simulated games.
C. Baseline Evolutionary Algorithm

The goal of the evolution is to improve the quality of draft policies encoded as chromosomes. A straightforward approach is to use all available training data in each generation.

A genotype is represented as a constant-size vector of doubles. Every gene (from 1 to |C| = 160) encodes a priority of the associated card (estimated card value). Thus, during the draft phase, a card with the highest priority is chosen each turn.

As before, let \( n \) be the size of the population, and \( d_t \) the number of available training drafts. The schema of the baseline evolutionary algorithm \( \text{Evo}_\text{base} \) goes as follows.

The population is initialized with the random values between 0.0 and 1.0. To evaluate the population, we play \( s_g \) games between every two individuals for each of \( d_t \) drafts (with side change after half of the games). Then, we use tournament selection (best of random 4 individuals) to select \( \frac{n}{2} \) parents based on the number of wins. The standard uniform crossover is used. Mutation rate \( m = 0.05 \) is the probability of changing each gene into a new random number. The elitism size is 2. Thus, to compute \( g \) generations, this algorithm has to play \( C_{\text{Evo}_\text{base}} \) games, where

\[
C_{\text{Evo}_\text{base}} = n \times (n - 1) \times s_g \times d_t \times (1 + g).
\]

IV. Active Genes Algorithm

Evaluating each generation using all of the available test drafts, while being the most robust, is also time-consuming and may force the evolution to be insubstantial within the constrained computational budget.

Alternatively, we propose an approach where each generation is responsible for learning how to play only one of the available test drafts. Such a method allows not only evolving more generations within the same budget but also observing a more detailed influence of single genes (cards) on the performance of the agents in particular scenarios (drafts). To emphasize the benefit of this gene-to-draft-to-outcome correspondence even more, and partially make up for the loss of generality it creates, evolutionary operators will be applied selectively, differently in each generation.

We say a gene is active in a given generation if the card it encodes appears within the draft choices. For the sake of evaluation of this generation, all the other genes are considered irrelevant. Thus, in this generation, we can perform crossover and mutation only on the active genes. Moreover, this will prevent the destruction of the so-far gained knowledge encoded in the inactive genes, which has already proven itself through the previous generations.

The major drawback of this approach is that we lose a uniform metric that can be used to compare parents and children across the generations. Thus, to select \( \frac{n}{2} \) pairs of parents, we run actual games to test how they perform on the current generation draft. For each parent we perform a tournament of size \( s_t \text{Size} = 4 \), playing \( s_t \text{Games} = 10 \) games each round. Selected parents create offspring in the same manner as in the \( \text{Evo}_\text{base} \) algorithm (uniform crossover, constant mutation rate).

Now, we calculate fitness values for the offspring population. This is done in \( s_t \) rounds, where in each round we score the population by the so-far wins and then play \( s_g \) games (with side change) between consecutive pairs in order.

The remaining part, selection, is in our approach substituted by a merge operation. To create each of \( n \) individuals of the next population, we use a fitness-based roulette to select a child from the offspring, and a parent from the parents’ population. For parents, the fitness values of their generation are used.

We investigated three variants of the merging procedure. First, called \( AG \), uses active genes most straightforwardly. The resulting individual contains values of the active genes copied from the child and inherits the rest from its parent. Thus, the newest knowledge is considered the most important.

Alternatively, \( AG_{\text{weights}} \) is the variant of \( AG \) that uses the weighted sum instead. Such a variant aims to be more conservative and improve individuals gradually, preserving the already gained knowledge even more. The proportion we found working is 0.75 of the parent gene and 0.25 of the child gene, instead of the original 0 and 1 in \( AG \).

For comparison, we also test \( AG_{\text{all}} \) variant, which is based on the same scheme but does not take advantage of active genes (i.e., it treats all genes as active). Instead, it discards the parent, and only the child gene values are copied.

Essentials of the pseudocode for these algorithms are presented in Fig. 1. Here, we assume that \( g = d_t \), which is in line with most of the conducted experiments. More sophisticated variants, using the same pseudocode but breaking this assumption, are described separately in Section V-C. The main procedure, \( \text{EVOLVE} \), progresses through each generation learning \( d_t \) drafts, creating random drafts using \( \text{RANDOMDRAFTS} \), calculating the children population using \( \text{CREATEOFFSPRING} \), and merging them, as described above, using \( \text{MERGEALL} \). Depending on the variant, \( \text{MERGEONE} \) selects an appropriate behavior, where \( \text{LERP} \) is the linear interpolation function. The \( \text{SCORE} \) procedure simulates a single game and updates the scores (win counts) accordingly.

Thus, the cost of \( g \) generations using these algorithms is:

\[
C_{AG} = C_{AG_{\text{weights}}} = C_{AG_{\text{all}}} = n \times g \times (s_t \text{Size} \times (s_t \text{Size} - 1) \times s_t \text{Games} + s_r \times s_g \times d_t)
\]

V. Experiments

Source code for the described experiments is available in a public GitHub repository [23]. All performed experiments were run on a single CPU-Optimized DigitalOcean droplet with 16 GB of RAM and 8 standardized vCPUs.

A. Algorithm Comparison

We compared the overall results obtained by the Contest\(_1 \), Contest\(_2 \), Random, Random\(_t \), \text{Evo}_\text{base} \), \( AG \), \( AG_{\text{all}} \), and \( AG_{\text{weights}} \) algorithms. To ensure the robustness of our approach, we have tested two playing strategies – random and greedy. We did not test more advanced strategies due to the computational time constraints.
Algorithm 1 Active genes algorithm variants pseudocode.

```plaintext
procedure EVOLVE(options)
    old ← RANDOMPOPULATION(n)
    for generation ← 1, g do
        drafts ← RANDOMDRAFTS()
        new ← CREATEOFFSPRING(drafts, old)
        old ← MERGEALL(old, new, drafts, options)
    return old

procedure CREATEOFFSPRING(drafts, old)
    new ← EMPTYPOPULATION()
    for individual ∈ new do
        parents ← SELECTPARENTS(drafts, old)
        children ← Crossover(parents)
        individual ← MUTATE(children)
    SCOREPOPULATION(drafts, new)
    return new

procedure SELECTPARENTS(drafts, population)
    tournament ← SAMPLE(population, s_{tSize})
    for all draft ∈ drafts do
        for all a ∈ tournament do
            for all b ∈ tournament do
                if a ≠ b then
                    for game ← 1, s_{tGames} / 2 do
                        SCORE(a, b, draft)
                        SCORE(b, a, draft)
        return BEST2BYSORE(tournament)

procedure SCOREPOPULATION(drafts, population)
    for round ← 1, s_r do
        SORTBYSORE(population)
        for all draft ∈ drafts do
            for i ← 1, 3, 5, …, n do
                a, b ← population[i], population[i + 1]
                SCORE(a, b, draft)
                SCORE(b, a, draft)

procedure MERGEALL(old, new, drafts, options)
    merged ← EMPTYPOPULATION()
    for all individual ∈ merged do
        a, b ← ROULETTE(old), ROULETTE(new)
        individual ← MERGEONE(a, b, drafts, options)
    return merged

procedure MERGEONE(new, old, drafts, options)
    if AG all then
        cardIds ← ALLCARDIDS
    else
        cardIds ← CARDIDSIN(drafts)
        merged ← CLONE(old)
    for all id ∈ cardIds do
        old[id] ← LERP(new[id], old[id], options.weight)
    return merged
```

The first one uniformly picks a random action sequence, while the latter selects the best actions, one at a time, according to a material heuristic. A complete summary of their relative performance is presented in Tables I and II.

While both competition-based heuristic Contest 1 gains fewer wins than loses, Contest 2 seems to be the second most robust choice from considered strategies. What is interesting, during the one-lane LOCM contest [22] Contest 1 was established as the meta, outperforming other solutions, including Contest 2.

Scores of both random players are worse than those obtained by any evolution-based approach, which is a clear indication that the learning process gives a definite advantage.

Additionally, on Fig. 3, we visualized the process of evolution for $Evo_{base}$, $AG$, $AG_{all}$, and $AG_{weights}$. For each of the presented algorithms, the best five individuals from each generation played 50 games on 250 random drafts against Contest 1, Contest 2, and three random individuals. The results reported on this chart are higher than in the tables mentioned before, as the random opponents tend to be less skilled on average.

Surprisingly, the performance of the straightforward evolution $Evo_{base}$ is below 50% when using the random player. Also, the correlation between performance on the training and evaluation drafts is the worst (yellow line on the Fig. 2). Each of its generations took significantly longer to compute, so only a few of them can be finished within the assumed computation budget. It might be the case that their number is too low to observe learning. Nevertheless, a few non-exhaustive experiments we had additionally performed showed that the score does not raise significantly even with a far greater computational budget or using different parameters. This variant generates average solutions during the first generation that it cannot further improve.

As expected, $AG_{all}$ performs poorly. Using only offspring genes results in constant forgetting, which is visible in its evolution process. On the contrary, the remaining active genes-based approaches, $AG$ and $AG_{weights}$, learn step-by-step from low scores. Both need about four times the cost of the initial $Evo_{base}$ generation to start performing better, but the process does not finish there. They continue learning, which supports the assumption of the advantage of batched learning and selective genetic operators. The variant with weighted merge achieves significantly better results versus all opponents, especially using the greedy playing algorithm. In particular, it tends to achieve better performance faster, as it is easier to stabilize at good gene values by weighted sum than it is by gene replacing.

Although the improvements of a single percent using random players do seem small, it is a common thing in such a noisy environment as CCGs, and even that leads to a long-term gain. Especially, when it translates into more significant improvement for better player strategies. For comparison, using greedy players for both evolution and evaluation leads to more diversified results, emphasizing the difference between the learning algorithms.
Fig. 3. Process of evolution for AG, AG_all, AG_weights, and Evo_base using random (left chart) and greedy (right chart) players. Computation cost (number of simulated games) on x axis, average performance versus Contest1, Contest2, and three random strategies on y axis.

Moreover, a comparison between Tab. I, Tab. II and Fig. 3 shows that even a small advantage over the better performing opponents yields a significant advantage over the less skilled ones.

B. Analysis of AG_weights Learning

In Fig. 4, we visualized the performance of overall-best against generation-best individuals during a sample AG_weights run to analyze the learning progress. It shows how the all-time top five individuals per 200 generations (the first generation is an entirely random one) perform against the top five individuals of each of the generations on all training drafts.

As we can observe, champions from later generations tend to perform better on average, which is consistent with the previous observations. All tested champions are significantly strong at first because the first generation did not have time to learn. As the learning progresses and the individuals from the following generations are getting better, the scores of the champions tend to be lowering.

It is worth noticing that the best genotypes of each generation tend to be lowering. It is worth noticing that the best genotypes of each generation tend to be lowering.
C. Investigating Active Genes Approach

The performance of active genes evolution correlates with the number of training drafts used to evaluate a single population. More drafts imply that a more significant part of the genotype is active and being affected by the operators. On the other hand, with a limited number of drafts per generation, the quality of the evaluation is limited, and some knowledge may be lost during evolution. Thus, we introduced two additional variants of AGweights algorithm.

The first one, called AGweights/\(Kd\), where \(K\) is the number of drafts, affects parent tournament and merge phases, in both places adding a loop over the used drafts. To keep the computational cost and the number of drafts the same, this variant runs for \(g/K\) generations compared to AGweights.

The second variant called AGweights/\(Kg\), where \(K\) is the number of repetitions, bases on reusing the same drafts \(K\) times, leaving the evolution framework as-is. To ensure comparable computation cost, as the variant runs for \(g\times K\) generations, the number of games in each generation is accordingly lower.

Analyzing the results from Fig. 5, the average performance of AGweights/\(4g\) is the lowest. The budget allowed too few evaluations to make one-generation learning reliable enough. However, less restricted variant AGweights/\(2g\), although not the top one, performs reasonably well, achieving higher performance than our Evo baseline evolution without problems (compare with Fig. 3 for random player).

There is no significant difference between the performance of AGweights/\(2d\) and AGweights/\(4d\). Both performs similarly, slightly worse than the two leading algorithms. When we compare the difference between those approaches in terms of percent of the genome that is active, we get that it is \(\sim 56\%\) for AGweights, \(\sim 79\%\) for AGweights/\(2d\), and \(\sim 95\%\) for AGweights/\(4d\).
Evolution based on active genes usually performs better when the number of such genes is lower, but this trend is less visible in \( AG_{weights} \) variant. In LOCM, proportion of active genes depends on the generation method used to prepare drafts. (This is similar to the dropout regularization technique in the artificial neural networks.)

Additionally, we performed two more experiments concerning the trade-off between the number of generations and the number of plays during the evaluation, using larger \( K \) values. Both yielded similar but noisier results, therefore have been not included in the paper.

VI. CONCLUSION

This paper presents initial research towards the problem of deckbuilding in the arena mode of Collectible Card Games. This can be seen as a complementary problem for the standard CCG deckbuilding, where the set of available cards is known in advance. As the domain is characterized by vast state space and omnipresent non-determinism, a straightforward approach to learn draft strategies via an evolutionary algorithm is not very successful and leaves much room for improvements.

In our work, we propose an active genes approach, a variant that learns gradually, generation-to-generation. Learning in each generation is based only on the partial training data, and genetic operators are applied selectively only on a subset of genes that is currently considered as relevant. The selection operator is substituted by merge, performed between selected pairs consisting of parent and offspring.

We have tested our approach in programming game Legends of Code and Magic, which is used in the Strategy Card Game AI Competition. We designed a few variants of the algorithm and conducted experiments show that usually they perform better than the baseline. Some of them achieve average results that are even significantly better, taking into account that in such a noisy environment as CCG (especially in arena mode), even a small increase in win percentage is a substantial gain leading to overall success in a longer timeline.

What is also important, most of the presented approaches learn very fast in terms of our cost measure (which is the number of required game simulations). Given a fast simulation engine available on the Strategy Card Game AI Competition package [24], it requires about half a minute for a random player to achieve a decent performance on an average run.

For future work, we mainly plan to test active genes family of algorithms on other similar domains, e.g., in Hearthstone. From the game balancing point of view, it would also be interesting to compare policies obtained by one-lane and two-lane versions of LOCM, and how policies trained for one playing algorithm works for the others.

We also aim to develop methods that will improve reliability in terms of achieved performance. This includes using more sophisticated simulated agents (at the expense of computation time) and merging a few runs to perform multiple levels of evolution automatically. We would also like to investigate more algorithm variants and understand what influence on the behavior of the agents has an algorithm that prepares draft choices. Finally, we would like to test how our approach affects agent performance compared to the other solutions presented at the Strategy Card Game AI Competition.

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