

# Variable-Processor Cup Games

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## Abstract

The problem of scheduling tasks on  $p$  processors so that no task ever gets too far behind is often described as a game with cups and water. In the  $p$ -processor cup game on  $n$  cups, there are two players, a filler and an emptier, that take turns adding and removing water from a set of  $n$  cups. In each turn, the filler adds  $p$  units of water to the cups, placing at most 1 unit of water in each cup, and then the emptier selects  $p$  cups to remove up to 1 unit of water from. The emptier's goal is to minimize the backlog, which is the height of the fullest cup.

The  $p$ -processor cup game has been studied in many different settings, dating back to the late 1960's. All of the past work shares one common assumption: that  $p$  is fixed. This paper initiates the study of what happens when the number of available processors  $p$  varies over time, resulting in what we call the *variable-processor cup game*.

Remarkably, the optimal bounds for the variable-processor cup game differ dramatically from its classical counterpart. Whereas the  $p$ -processor cup has optimal backlog  $\Theta(\log n)$ , the variable-processor game has optimal backlog  $\Theta(n)$ . Moreover, there is an efficient filling strategy that yields backlog  $n^{1-\varepsilon}$  in quasi-polynomial time against any deterministic emptying strategy.

We additionally show that straightforward uses of randomization cannot be used to help the emptier. In particular, for any positive constant  $\Delta$ , and any  $\Delta$ -greedy randomized emptying algorithm  $\mathcal{A}$ , there is a filling strategy that achieves backlog  $n^{1-\varepsilon}$  against  $\mathcal{A}$  in quasi-polynomial time.

## 1 Introduction

A fundamental challenge in processor scheduling is how to perform load balancing, that is, how to share processors among tasks in order to keep any one task from getting too far behind. Consider  $n$  tasks executing in time slices on  $p < n$  processors. During each time slice, a scheduler must select  $p$  (distinct) tasks that will be executed during the slice, completing a total of up to  $p$  units of work. During the same time slice, however, up to  $p$  units of *new work* may be allocated to the tasks, with different tasks receiving different amounts of work. The goal of a load-balancing scheduler is to bound the backlog of the system, which is defined to be the maximum amount of uncompleted work for any task.

As a convention, the load balancing problem is often described as a game involving water and cups. The ***p*-processor cup game** is a multi-round game with two players, an *emptier* and a *filler*, that takes place on  $n$  initially empty cups. At the beginning of each round, the filler adds up to  $p$  units of water to the cups, subject to the constraint that each cup receives at most 1 unit of water. The emptier then selects up to  $p$  distinct cups and removes up to 1 unit of water from each of them. The emptier's goal is to minimize the amount of water in the fullest cup, also known as the ***backlog***. In terms of processor scheduling, the cups represent tasks, the water represents work assigned to each task, and the emptier represents a scheduling algorithm.

Starting with the seminal paper of Liu [30], work on the  $p$  processor cup game has spanned more than five decades [7, 20, 8, 29, 27, 33, 6, 23, 30, 31, 16, 10, 25, 1, 15, 28]. In addition to processor scheduling [7, 20, 8, 29, 27, 33, 6, 23, 30, 31, 1, 28, 16], applications include network-switch buffer management [21, 4, 35, 19], quality of service guarantees [7, 1, 28], and data structure deamortization [2, 16, 15, 3, 34, 22, 17, 24, 9].

The game has also been studied in many different forms. Researchers have studied the game with a fixed-filling-rate constraint [7, 20, 8, 29, 27, 33, 6, 23, 30, 31], with various forms of resource augmentation

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[10, 25, 28, 16], with both oblivious and adaptive adversaries [1, 7, 30, 10, 25], with smoothed analysis [25, 10], with a semi-clairvoyant emptier [28], with competitive analysis [5, 18, 14], etc.

For the plain form of the  $p$ -processor cup game, the greedy emptying algorithm (i.e., always empty from the fullest cups) is known to be asymptotically optimal [1, 10, 25], achieving backlog  $O(\log n)$ . The optimal backlog for randomized emptying algorithms remains an open question [16, 10, 25] and is known to be between  $\Omega(\log \log n)$  and  $O(\log \log n + \log p)$  [25].

**This paper: varying resources.** Although cup games have been studied in many forms, all of the prior work on cup games shares one common assumption: the number  $p$  of processors is fixed.

In modern computing, however, computers are often shared among multiple applications, users, and even virtual OS's. The result is that the amount of resources (e.g., memory, processors, cache, etc.) available to a given application may fluctuate over time. The problem of handling cache fluctuations has received extensive attention in recent years (see work on cache-adaptive analysis [32, 11, 12, 13, 26]), but the problem of handling a varying number of processors remains largely unstudied.

This paper introduces the *variable-processor cup game*, in which the filler is allowed to *change*  $p$  (the total amount of water that the filler adds, and the emptier removes, from the cups per round) at the beginning of each round. Note that we do not allow the resources of the filler and emptier to vary separately. That is, as in the standard game, we take the value of  $p$  for the filler and emptier to be identical in each round. This restriction is crucial since, if the filler is allowed more resources than the emptier, then the filler could trivially achieve unbounded backlog.

A priori having variable resources offers neither player a clear advantage. When the number  $p$  of processors is fixed, the greedy emptying algorithm (i.e., always empty from the fullest cups), is known to achieve backlog  $O(\log n)$  [1, 10, 25] regardless of the value of  $p$ . This seems to suggest that, when  $p$  varies, the correct backlog should remain  $O(\log n)$ . In fact, when we began this project, we hoped for a straightforward reduction between the two versions of the game.

**Results.** We show that the variable-processor cup game is *not* equivalent to the standard  $p$ -processor game. By strategically controlling the number  $p$  of processors, the filler can achieve substantially larger backlog than would otherwise be possible.

We begin by constructing filling strategies against deterministic emptying algorithms. We show that for any positive constant  $\varepsilon$ , there is a filling strategy that achieves backlog  $\Omega(n^{1-\varepsilon})$  within poly  $n$  rounds. Moreover, if we allow for  $n!$  rounds, then there is a filling strategy that achieves backlog  $\Omega(n)$ . In contrast, for the  $p$ -processor cup game with any fixed  $p$ , the backlog never exceeds  $O(\log n)$ .

Our lower-bound construction is asymptotically optimal. By introducing a novel set of invariants, we deduce that the greedy emptying algorithm achieves backlog  $O(n)$ .

A natural question of whether *randomized* emptying algorithms can do better. In particular, when the emptier is randomized, the filler is taken to be *oblivious*, meaning that the filler cannot see what the emptier does at each step. Thus the emptier can potentially use randomization to obfuscate their behavior from the filler, preventing the filler from being able to predict the heights of cups.

When studying randomized emptying strategies, we restrict ourselves to the class of *greedy-like emptying strategies*. This means that the emptier never chooses to empty from a cup  $c$  over another cup  $c'$  whose fill is more than  $\omega(1)$  greater than the fill of  $c$ . All of the known randomized emptying strategies for the classic  $p$ -processor cup game are greedy-like [10, 25].

Remarkably, the power of randomization does not help the emptier very much in the variable-processor cup game. For any constant  $\varepsilon > 0$ , we give an oblivious filling strategy that achieves backlog  $\Omega(n^{1-\varepsilon})$  in quazi-polynomial time (with probability  $1 - 2^{-\text{poly} \log n}$ ), no matter what (possibly randomized) greedy-like strategy the emptier follows.

Our results combine to tell a surprising story. They suggest that the problem of varying resources poses a serious theoretical challenge for the design and analysis of load-balancing scheduling algorithms. There are many possible avenues for future work. Can techniques from beyond worst-case analysis (e.g., smoothing, resource augmentation, etc.) be used to achieve better bounds on backlog? What about placing restrictions on the filler (e.g., bounds on how fast  $p$  can change), allowing the emptier to be able to be semi-clairvoyant, or making stochastic assumptions on the filler? We believe that all of these questions warrant further attention.

TODO: add bamboo citations

## 2 Preliminaries

The cup game consists of a sequence of rounds. On the  $t$ -th round, the state starts as  $S_t$ . To start, the filler chooses the number of processors  $p_t$  for the round. Next, the filler distributes  $p_t$  units of water among the cups (with at most 1 unit of water to any particular cup). Now the game is in an intermediate state on round  $t$ , which we call state  $I_t$ . Finally the emptier chooses  $p_t$  cups to empty at most 1 unit of water from, which marks the conclusion of round  $t$ . The state is then  $S_{t+1}$ .

Note that if the emptier empties from a cup  $c$  on round  $t$  with fill at  $I_t$  less than 1, then  $c$  now has 0 fill (not negative fill); we say that the emptier **zeroes out**  $c$  on round  $t$ . Note that on any round where the emptier zeroes out a cup the emptier has removed less total fill from the cups than the filler has added to the cups; hence the average fill of the cups has increased.

We denote the fill of a cup  $c$  at state  $S$  by  $\text{fill}_S(c)$ . Let the **mass** of a set of cups  $X$  at state  $S$  be  $m_S(X) = \sum_{c \in X} \text{fill}_S(c)$ . Denote the average fill of a set of cups  $X$  at state  $S$  by  $\mu_S(X)$ . Note that  $\mu_S(X)|X| = m_S(X)$ . Let the **backlog** at state  $S$  be  $\max_c \text{fill}_S(c)$ , let the **anti-backlog** at state  $S$  be  $\min_c \text{fill}_S(c)$ . Let the **rank** of a cup at a given state be its position in a list of the cups sorted by fill at the given state, breaking ties arbitrarily but consistently. For example, the fullest cup at a state has rank 1, and the least full cup has rank  $n$ . Let  $[n] = \{1, 2, \dots, n\}$ , let  $i + [n] = \{i + 1, i + 2, \dots, i + n\}$ . For a state  $S$ , let  $S(r)$  denote the rank  $r$  cup at state  $S$ , and let  $S(\{r_1, r_2, \dots, r_m\})$  denote the set of cups of ranks  $r_1, r_2, \dots, r_m$ .

As a tool in the analysis we define a new variant of the cup game: the **negative-fill** cup game. In the negative-fill cup game, when the emptier empties from a cup its fill always decreases by exactly 1, i.e. there is no zeroing out. We refer to the standard version of the cup game where cups can zero out as the **standard-fill** cup game when necessary for clarity. Negative fill can be interpreted as fill below average fill. Negative fill is especially useful in our recursive lower bound proofs in which we build on the average fill already achieved. Note that it is strictly easier for the filler to achieve high backlog in the standard-fill cup game than in the negative-fill cup game; hence a lower bound on backlog in the negative-fill cup game also serves as a lower bound on backlog in the standard-fill cup game. On the other hand, during the upper bound proof we use the standard-fill cup game: this makes it harder for the emptier to guarantee its upper bound.

## 3 Technical Overview

In this section we provide sketches of the proofs in the paper, omitting details.

### 3.1 Adaptive Lower Bound

In Section 4 we provide filling strategies that an adaptive filler can use to achieve backlog  $\text{poly}(n)$ ; in this subsection we sketch the proofs of these results.

First we note that there is a trivial algorithm, that we call **trivialg**, for achieving backlog at least  $1/2$  on at least 2 cups in time  $O(1)$ .

The essential ingredient in our polynomial lower bound proof is the **Amplification Lemma** which gives a way to improve a function for achieving a certain backlog.

**Lemma 1.** *Let  $\text{alg}(f)$  be a filling strategy that achieves backlog  $f(n)$  on  $n$  cups. There exists a filling strategy  $\text{alg}(f')$ , the **amplification** of  $\text{alg}(f)$ , that achieves backlog at least*

$$f'(n) \geq (1 - \delta)f(\lfloor (1 - \delta)n \rfloor) + f(\lceil \delta n \rceil).$$

*Amplification Lemma Proof Sketch.* The filler designates an **anchor set**  $A$  of size  $\lceil \delta n \rceil$  and a **non-anchor set**  $B$  of size  $\lfloor (1 - \delta)n \rfloor$ . The filler's strategy is as follows:

**Step 1:** Make  $\mu(A) \geq (1 - \delta)f(|B|)$  by using  $\text{alg}(f)$  repeatedly on  $B$  while placing 1 unit of fill into each anchor cup each round; if the emptier does not place extra resources into  $B$  this results in the filler achieving a cup with large fill in  $B$  which it can swap into  $A$  causing  $\mu(A)$  to increase, if the emptier does place extra resources into  $B$  to prevent a cup in  $B$  from gaining high fill, then the emptier is correspondingly placing fewer resources into  $A$  causing  $\mu(A)$  to increase.

**Step 2:** Use  $\text{alg}(f)$  once on  $A$  to obtain some cup with fill  $\mu(A) + f(|A|)$ .

Note that in order to use  $\text{alg}(f)$  on subsets of the cups the filler will need to vary  $p$ .

Consider Step 1. It can be shown that by using  $\text{alg}(f)$  at most  $|A|$  times on  $B$  the average fill of  $A$  will have increased to at least  $(1 - \delta)f(|B|)$  due either to the filler swapping many cups with high fill into

$A$ , or to the emptier repeatedly using more resources in  $B$  and less in  $A$  than the filler. Step 2 trivially succeeds. Thus the filler achieves the desired backlog:

$$(1 - \delta)f(|B|) + f(|A|).$$

□

We use the Amplification Lemma to give two lower bounds on backlog: one with reasonable running time, the other with slightly better backlog.

**Theorem 1.** *There is an adaptive filling strategy for achieving backlog  $\Omega(n^{1-\varepsilon})$  for constant  $\varepsilon \in (0, 1/2)$  in running time  $2^{O(\log^2 n)}$ .*

*Theorem 2 Proof Sketch.* We construct a sequence of filling strategies with  $\text{alg}(f_{i+1})$  the amplification of  $\text{alg}(f_i)$  using  $\delta = \Theta(1)$  determined as a function of  $\varepsilon$ , and  $\text{alg}(f_0) = \text{trivalg}$ . Choosing  $\delta$  appropriately, we show by induction on  $i$  that  $\text{alg}(f_{\Theta(\lg n)})$  achieves backlog  $\Omega(n^{1-\varepsilon})$  in running time  $2^{O(\log^2 n)}$ . □

**Theorem 2.** *There is an adaptive filling strategy for achieving backlog  $\Omega(n)$  in running time  $O(n!)$ .*

*Proposition 4 Proof Sketch.* We construct a sequence of filling strategies with  $\text{alg}(f_{i+1})$  the amplification of  $\text{alg}(f_i)$  using  $\delta = 1/(i+1)$ , and  $\text{alg}(f_0)$  a filling strategy for achieving backlog 1 on  $O(1)$  cups in  $O(1)$  time (this is a slight modification of  $\text{trivalg}$ ). We show by induction on  $i$  that  $\text{alg}(f_{\Theta(n)})$  achieves backlog  $\Omega(n)$  in running time  $O(n!)$ . □

## 3.2 Upper Bound

In Section 5 we prove that a greedy emptier, i.e. an emptier that always empties from the  $p$  fullest cups, never lets backlog exceed  $O(n)$ ; in this subsection we sketch the proof of this result.

The upper bound on backlog is derived by setting  $k = 1$  in ??.

**Theorem 3.** *The average fill of the  $k$  fullest cups never exceeds  $2n - k$ .*

*Theorem 3 Proof Sketch.* The proof is by induction on the round. Fix some round  $t$  and assume that all invariants hold on round  $t$ . Fix some  $k$ ; we aim to prove that the average fill of the  $k$  fullest cups is at most  $2n - k$  at the start of round  $t + 1$ .

Let  $A$  be the cups that are among the  $k$  fullest cups in  $I_t$ , are emptied from, and are among the  $k$  fullest cups in  $S_{t+1}$ . Let  $B$  be the cups that are among the  $k$  fullest cups in state  $I_t$ , are emptied from, and are not among the  $k$  fullest cups in  $S_{t+1}$ . Let  $C$  be the cups with ranks  $|A| + |B| + 1, \dots, k + |B|$  in state  $I_t$ . The set  $C$  is defined so that the  $k$  fullest cups in state  $S_{t+1}$  are  $AC$ , since once the cups in  $B$  are emptied from, the cups in  $B$  are not among the  $k$  fullest cups, so cups in  $C$  take their places among the  $k$  fullest cups.

It can be shown that we may assume without loss of generality that the rank  $r$  cup at state  $S_t$  is also the rank  $r$  cup at state  $I_t$  for all ranks  $r \in [n]$ , by changing the labels of the cups; intuitively this is true because if a cup  $c$  changes ranks from  $S_t$  to  $I_t$ , then some other cup must have fill very close to  $c$ 's fill.

We prove the invariant by considering several cases.

**Case 1:** Some cup in  $A$  zeroes out in round  $t$ .

**Analysis:** The fill of all cups in  $C$  must be at most 1 at state  $I_t$  to be less than the fill of the cup in  $A$  that zeroed out. Further,  $A$  has average fill at most  $2n - (a - 1)$  due to the cup with zero fill. Combined, with some algebra, these facts imply that the average fill in  $AC$  is not too large, in particular not larger than  $2n - k$ .

**Case 2:** No cups in  $A$  zero out in round  $t$  and  $b = 0$ .

**Analysis:** In this case the set of cups of ranks in  $[k]$  at state  $S_t$  is the same as the set of cups of ranks in  $[k]$  at state  $S_{t+1}$ , and these are both  $A$ . During round  $t$  the emptier removes  $a$  units of fill from the cups  $A$ . The filler cannot have added more than  $k$  fill to these cups, because it can add at most 1 fill to any given cup. Also, the filler cannot have added more than  $p_t$  fill to the cups because this is the total amount of fill that the filler is allowed to add. Hence the filler adds at most  $\min(p_t, k) = a + b = a + 0 = a$  fill to these cups. The emptier thus is removing at least as much water as the filler is adding to these cups, so the average fill has not increased, and is still at most  $2n - k$ .

**Case 3:** No cups in  $A$  zero out on round  $t$  and  $b > 0$ .

**Analysis:** Consider  $m_{S_{t+1}}(AC)$ , which is the mass of the  $k$  fullest cups at state  $S_{t+1}$ . Each cup in  $A$  was emptied from. The filler adds at most  $\min(k, p_t) = a + b$  fill to these cups. Hence,

$$m_{S_{t+1}}(AC) \leq m_{S_t}(AC) + b. \quad (1)$$

The key insight necessary to bound  $m_{S_t}(AC)$  is to notice that larger values for  $m_{S_t}(A)$  correspond to smaller values for  $m_{S_t}(C)$  because the invariants are satisfied at state  $S_t$ . In particular, because

$$m_{S_t}(C) \leq \frac{c}{b+c} m_{S_t}(BC) = \frac{c}{b+c} (m_{S_t}(ABC) - m_{S_t}(A)),$$

we have

$$m_{S_t}(AC) \leq \frac{c}{b+c} m_{S_t}(ABC) + \frac{b}{b+c} m_{S_t}(A). \quad (2)$$

As (1) is monotonically increasing in both  $m_{S_t}(A)$  and  $m_{S_t}(ABC)$  we can upper bound (1) by substituting the extremal values of  $m_{S_t}(A)$  and  $m_{S_t}(ABC)$  in, namely  $|A|(2n - |A|)$  and  $|ABC|(2n - |ABC|)$ . After some algebra (or via an elegant combinatorial argument) it can be shown that

$$\frac{c}{b+c} |ABC|(2n - |ABC|) + \frac{b}{b+c} |A|(2n - |A|) \leq k(2n - k) - cb. \quad (3)$$

Combined with (??), and the fact  $b > 0$ , (??) implies that the average fill of the  $k$  fullest cups in state  $S_{t+1}$  is at most  $2n - k$ , as desired.

We have shown the invariant holds for arbitrary  $k$ , so given that the invariants all hold at state  $S_t$  they also must all hold at state  $S_{t+1}$ . Thus, by induction we have the invariant for all rounds  $t \in \mathbb{N}$ .  $\square$

### 3.3 Oblivious Lower Bound

In Section 6 we provide filling strategies that an oblivious filler can use to achieve backlog  $n^{1-\varepsilon}$  for  $\varepsilon \in (0, 1/2)$  constant against “greedy-like” emptiers with probability at least  $1 - 2^{-\text{polylog}(n)}$  in running time  $2^{\text{polylog}(n)}$ ; in this subsection we sketch the proofs of these results. We remark that this proof is by far our most technically difficult result; however, interestingly, many of the ideas driving the oblivious lower bound are similar to those driving the adaptive lower bound.

First we make some definitions. The **fill-range** of a set of cups at state  $S$  is  $\max_c \text{fill}_S(c) - \min_c \text{fill}_S(c)$ . A cup configuration is  **$R$ -flat** if the fill-range is at most  $R$ . An emptier is called  **$\Delta$ -greedy-like** if whenever there are two cups  $c_1, c_2$  with  $\text{fill}_{I_t}(c_1) > \text{fill}_{I_t}(c_2) + \Delta$  the emptier doesn’t empty from  $c_2$  on round  $t$  unless it also empties from  $c_1$  on round  $t$ . For an oblivious filler we only prove lower bounds against  $O(1)$ -greedy-like emptiers; however this is a very interesting class of emptiers because all known randomized algorithms for the cup game are  $O(1)$ -greedy-like [10, 25]. We define a new variant of the cup game: In the  **$E$ -extra-emptyings  $S$ -skip-emptyings** cup game on  $n$  cups, the filler distributes  $p$  units of water amongst the cups, and then the emptier empties from  $p$  or more, or less cups. In particular the emptier is allowed to do  $E$  extra emptyings and is also allowed to skip  $S$  emptyings over the course of the game. Let the **regular** cup game be the 0-extra-emptyings  $\infty$ -skip-emptyings cup game: this is the regular cup game. Allowing for some extra emptyings, and bounding the number of skip emptyings is sometimes necessary when analyzing an algorithm that is a subroutine of a larger algorithm however, hence it sometimes makes sense to consider games with different values of  $E, S$ . Unless explicitly stated otherwise however we are considering the regular cup game.

Let  $R_\Delta = 2(2 + \Delta)$ . We now prove an important fact about  $\Delta$ -greedy-like emptiers.

**Lemma 2** (Sketch of proof of Lemma 5). *There is an oblivious filling strategy **fatalg** that, given an  $R$ -flat configuration of cups, achieves an  $R_\Delta$ -flat configuration of cups against a  $\Delta$ -greedy-like emptier in the  $p$ -processor,  $E$ -extra-emptyings,  $S$ -skip-emptyings negative-fill cup game on  $n = 2p$  cups in running time  $O(R + E + S)$ . Throughout the duration of **fatalg** the cups are always  $R$ -flat.*

*Proof.* The filler’s strategy is to place  $1/2$  units of fill into each cup on every round. Intuitively, if the fill-range of the cups is large then by greediness the emptier should be forced to empty from the fullest cups and not empty from the least full cups, thus decreasing the fill-range.  $\square$

Now we describe a well-known simple oblivious filling strategy that will be used as a subroutine later.

**Proposition 1.** *Consider an  $R$ -flat configuration of cups in the regular single-processor negative-fill cup game on  $n$  cups with initial average fill  $\mu_0$ . Let  $k \in [n]$ . Let  $d = \sum_{i=2}^k 1/i$ .*

*There is an oblivious filling strategy **randalg(k)** that achieves backlog  $\mu_0 - R + d$  with probability at least  $1/k!$  in time  $O(k)$ .*

*Furthermore, when applied against a  $\Delta$ -greedy-like emptier with  $R = R_\Delta$ , even if the emptier is allowed arbitrarily many extra emptyings (i.e. if the game occurs in the  $\infty$ -extra-emptyings  $\infty$ -skip-emptyings cup game), **randalg(k)** guarantees that the cup configuration is  $(R + d)$ -flat on every round.*

*Proof.* The filler maintains an **active set**, initialized to being an arbitrary subset of  $k$  of the cups. Every round the filler distributes 1 unit of fill equally among all cups in the active set. Next the emptier removes 1 unit of fill from some cup, or skips its emptying. Then the filler removes a random cup from the active set (chosen uniformly at random from the active set). This continues until a single cup  $c$  remains in the active set. If  $c$  has never been emptied from, then its fill has increased by at least  $1/k + 1/(k-1) + \dots + 1/2 = d$  from its starting value which was at least  $\mu_0 - R$ . Thus  $c$  has at least the desired fill if it has not been emptied from. By randomly removing cups from the active set the filler guarantees that, with probability at least  $1/(k-1)!$ ,  $c$  is not emptied from.

Now we consider a greedy-like emptier that is allowed extra-emptyings. Let  $\mathcal{A}_t$  be the event that the anti-backlog is smaller in  $S_{t+1}$  than in  $S_t$ , let  $\mathcal{B}_t$  be the event that some cup with fill equal to the backlog in  $S_{t+1}$  was emptied from on round  $t$ . If  $\mathcal{A}_t$  and  $\mathcal{B}_t$  are both true on round  $t$ , then by greediness the cups are quite flat, in particular  $R_\Delta$ -flat. Consider a round  $t_1$  where the cups are not  $R_\Delta$ -flat. Let  $t_0$  be the last round that the cups were  $R_\Delta$ -flat. On all rounds  $t \in (t_0, t_1)$  at least one of  $\mathcal{A}_t$  or  $\mathcal{B}_t$  must not hold. On a round where  $\mathcal{A}_t$  does not hold, anti-backlog does not decrease and backlog increases by at most  $1/(k-t+1)$ , so fill range increases by at most  $1/(k-t+1)$ . On a round where  $\mathcal{B}_t$  does not hold, anti-backlog decreases by at most 1 and backlog decreases by at least  $1 - 1/(k-t+1)$ , as all cups with fill equal to the backlog in state  $S_{t+1}$  were emptied from on round  $t$ , so fill-range increases by at most  $1/(k-t+1)$ . Hence in total fill-range increases by at most  $\sum_{i=2}^k 1/i$  from  $R$ , i.e. the cups are  $(R+d)$ -flat on round  $t_1$ .  $\square$

We now give a method for transforming a filling strategy for achieving large backlog into a filling strategy for achieving high fill in many cups.

**Definition 1.** Let  $\text{alg}_0$  be an oblivious filling strategy, that can get high fill (for some definition of high) in some cup against greedy-like emptiers with some probability. We construct a new filling strategy  $\text{rep}_\delta(\text{alg}_0)$  as follows:

Say we have some configuration of  $n$  cups. Let  $n_A = \lceil \delta n \rceil$ ,  $n_B = \lfloor (1-\delta)n \rfloor$ . Let  $N \gg n$  be large, let  $M = 2^{\text{polylog}(N)}$  be a chosen parameter. Initialize  $A$  to  $\emptyset$  and  $B$  to being all of the cups. We call  $A$  the **anchor set** and  $B$  the **non-anchor set**. The filler always places 1 unit of fill in each anchor cup on each round. The filling strategy consists of  $n_A$  **donation-processes**, which are procedures that result in a cup being **donated** from  $B$  to  $A$  (i.e. removed from  $B$  and added to  $A$ ). At the start of each donation-processes the filler chooses a value  $m_0$  uniformly at random from  $[M]$ . We say that the filler **applies** a filling strategy  $\text{alg}$  to  $B$  if the filler uses  $\text{alg}$  on  $B$  while placing 1 unit of fill in each anchor cup. During the donation-process the filler applies  $\text{alg}_0$  to  $B$   $m_0$  times, and flattens  $B$  by applying  $\text{flatalg}$  to  $B$  for  $\Theta(N^2)$  rounds before each application of  $\text{alg}_0$ . At the end of each donation process the filler takes the cup given by the final application of  $\text{alg}_0$  (i.e. the cup that  $\text{alg}_0$  guarantees with some probability against a certain class of emptiers to have a certain high fill), and donates this cup to  $A$ .

We say that the emptier **neglects** the anchor set on a round if it does not empty from each anchor cup. We say that an application of  $\text{alg}_0$  to  $B$  is **non-emptier-wasted** if the emptier does not neglect the anchor set during any round of the application of  $\text{alg}_0$ .

We use  $\text{rep}$  in two distinct places: first to get constant backlog, and second to prove the Oblivious counterpart of the Adaptive Amplification Lemma. For the rest of the section our goal is eventually to get backlog  $\text{poly}(N)$  in  $N$  cups for a value of  $N$  that we fix now; this value of  $N$  will be used throughout all of the proofs.

First we analyze  $\text{rep}(\text{randalg})$ .

**Lemma 3.** Let  $\Delta \leq O(1)$ , let  $h \leq O(1)$ , with  $h \geq 16(1+\Delta)$ , let  $k = \lceil e^{2h+1} \rceil$ , let  $\delta = \Theta(e^{-2h})$ , let  $n \ll N$  be sufficiently large. Consider an  $R_\Delta$ -flat cup configuration in the variable-processor cup game on  $n$  cups with initial average fill  $\mu_0$ .

Against a  $\Delta$ -greedy-like emptier,  $\text{rep}_\delta(\text{randalg}(k))$  using  $M = \Theta(N^2)$  either achieves mass  $N^2$  in the cups, or with probability at least  $1 - 2^{-\Omega(n)}$  makes an (unknown) set of  $\Theta(n)$  cups in  $A$  have fill at least  $h + \mu_0$  while also guaranteeing that  $\mu(B) \geq -h/2 + \mu_0$ , where  $A, B$  are the sets defined in Definition 1. The running time of  $\text{rep}_\delta(\text{randalg}(k))$  is  $\text{poly}(N)$ .

*Lemma 2 Proof Sketch.* We use the definitions given in Definition 1.

Note that if the emptier neglects the anchor set  $N^2$  times, or skips  $N^2$  emptyings, then the mass of the cups will be at least  $N^2$ , so the filler is done. For the rest of the proof we consider the case where the emptier chooses to neglect the anchor set fewer than  $N^2$  times, and choose to skip fewer than  $N^2$  emptyings.

First we show that  $\mu(B)$  never sinks too low, which is one of the guarantees of our algorithm, and necessary to ensure that we get large fill in many cups in  $A$ . Let  $d = \sum_{i=2}^k 1/i = \Theta(h)$ . Because extra-emptyings and skip-emptyings of  $B$  are limited, using Lemma 1 and Proposition 1, we can inductively show that  $B$  is always  $(R_\Delta + d)$ -flat, and that all applications of flatalg make  $B$  be  $R_\Delta$ -flat. Now we claim that  $\mu(B) \leq \mu(AB) + 2$ . There are two ways  $\mu(B) - \mu(AB)$  can increase:

**Case 1:** The emptier could empty from 0 cups in  $B$  while emptying from every cup in  $A$ .

By greediness this means that  $\mu(A) \geq \mu(B) - \Delta$ . Since  $|B| \gg |A|$ , this implies  $\mu(B) \leq \mu(AB) + 1$ .

**Case 2:** The filler could evict a cup with fill lower than  $\mu(B)$  from  $B$  at the end of a donation-process. Because  $B$  starts each application of randalg( $k$ ) being  $(R_\Delta + d)$ -flat, and the running time of the application is  $k - 1$  the cup donated from  $B$  cannot have fill lower than  $\mu(B) - R_\Delta - (k - 1)$ . But because  $n_B \gg n_A$  even if  $B$  donated  $n_A$  cups that were maximally empty the difference  $\mu(B) - \mu(AB)$  would only increase by at most 1.

Combining the analysis of Case 1 and Case 2 we have that  $\mu(B) \leq \mu(AB) + 2$ .

Combining the upper bound on  $\mu(B)$  with the fact that  $B$  is always flat and that the emptier is greedy-like, we have that no cup in  $A$  ever has its fill exceed  $u_A = \mu(AB) + 2 + R_\Delta + d + 1$ . Obviously  $\mu(A) \leq u_A$ . Hence we have an upper bound on  $\mu(A) - \mu(AB)$ ; plugging this upper bound into the relation  $m(A) + m(B) = m(AB)$ , and using the fact that  $|B| \gg |A|$  we get the desired bound on  $\mu(B)$ :

$$\mu(B) \geq -h/2 + \mu(AB) \geq -h/2 + \mu_0.$$

Now we show that we get a constant-fraction of the cups in  $A$  to have fill  $\mu_0 + h$ . If the emptier were not able to neglect the anchor set, then by a Chernoff bound a constant fraction of the applications of randalg( $k$ ) in a donation-process succeed with exponentially good probability in  $M$ . A successful application of randalg( $k$ ) yields a cup with fill at least  $\mu(B) - R_\Delta + d \geq h + \mu_0$  by our lower bound on  $\mu(B)$ . In order to mitigate the problem that the emptier can do extra-emptying we do many, in particular  $M = \Theta(N^2)$ , applications of randalg( $k$ ) and choose randomly how many to do before donating a cup; this guarantees that with constant probability each donation-process succeeds. Taking a Chernoff bound over the donation-processes gives that with exponentially good probability in  $n$  a constant fraction of the donation-processes succeed. Taking a union bound over all of our Chernoff bounds gives the desired probability of success.

The running time of the filling strategy is clearly  $n_A O(M)(O(N^2) + O(1)) = \text{poly}(N)$ , as each of the  $n_A$  donation-processes consists of  $O(M)$  applications of randalg( $k$ ) and  $O(M)$  applications of flatalg.  $\square$

Using Lemma 2 we show that an oblivious filler can achieve constant fill in a known cup.

**Proposition 2.** *Let  $H \leq O(1)$ , let  $\Delta \leq O(1)$ , let  $n \ll N$  be at least a sufficiently large constant determined by  $H$  and  $\Delta$ . Consider an  $R_\Delta$ -flat cup configuration in the variable-processor cup game on  $n$  cups with average fill  $\mu_0$ . There is an oblivious filling strategy that either achieves mass  $N^2$  among the cups, or achieves fill at least  $\mu_0 + H$  in a chosen cup in running time  $\text{poly}(N)$  against a  $\Delta$ -greedy-like emptier with probability at least  $1 - 2^{-\Omega(n)}$ .*

*Proof.* The filler starts by using  $\text{rep}_\delta(\text{randalg}(k))$  with parameter settings as in Lemma 6 where  $h = H \cdot 16(1 + \Delta)$ , i.e.  $k = \lceil e^{2h+1} \rceil$ ,  $\delta = \Theta(e^{-2h})$ . If this results in mass  $N^2$  among the cups we are done; we assume this is not the case for the rest of the proof. Let the number of cups which, with exponentially good probability in  $n$ , now exist by Lemma 6 with fill at least  $h + \mu_0$  be of size  $nc = \Theta(n)$ .

The filler sets  $p = 1$ , i.e. uses a single processor. Now the filler exploits the emptier's greedy-like nature to get fill  $H$  in a chosen cup  $c_0$ . Specifically, for  $(5/8)h$  rounds the filler places 1 unit of fill into  $c_0$ . Because the emptier is  $\Delta$ -greedy-like it must empty from the  $nc$  cups in  $A$  with fill at least  $h + \mu_0$  until  $c_0$  has large fill. Over  $(5/8)h$  rounds the cups in  $A$  cannot have their fill decrease below  $(3/8)h \geq h/8 + \Delta + \mu_0$ . Hence, any cups with fills less than  $h/8 + \mu_0$  must not be emptied from during these rounds. The fill of  $c_0$  started as at least  $-h/2 + \mu_0$  as  $\mu(B) \geq -h/2 + \mu_0$ . After  $(5/8)h$  rounds  $c_0$  has fill at least  $h/8 + \mu_0$ , because the emptier cannot have emptied  $c_0$  until it attained fill  $h/8 + \mu_0$ , and if  $c_0$  is never emptied from then it achieves fill  $h/8 + \mu_0$ . Thus the filling strategy achieves backlog  $h/8 + \mu_0 \geq H + \mu_0$  in  $c_0$ , a known cup, as desired.

The running time is of course still  $\text{poly}(N)$  by Lemma 2.  $\square$

Next we prove the Oblivious Amplification Lemma.

**Lemma 4.** *Let  $\delta \in (0, 1/2)$  be a constant parameter. Let  $\Delta \leq O(1)$ . Consider a cup configuration in the variable-processor cup game on  $n \leq N$ ,  $n > \Omega(1/\delta^2)$  cups with average fill  $\mu_0$  that is  $R_\Delta$ -flat. Let  $\text{alg}(f)$  be an oblivious filling strategy that either achieves mass  $N^2$  or, with failure probability at most*

$p \geq 2^{-\lg^8 N}$ , achieves backlog  $\mu_0 + f(n)$  on such cups in running time  $T(n)$  against a  $\Delta$ -greedy-like emptier. Let  $M = 2^{\text{polylog}(N)}$ .

Consider a cup configuration in the variable-processor cup game on  $n \leq N, n > \Omega(1/\delta^2)$  cups with average fill  $\mu_0$  that is  $R_\Delta$ -flat. There exists an oblivious filling strategy  $\text{alg}(f')$  that either achieves mass  $N^2$  or with failure probability at most

$$p' \leq np + 2^{-\lg^8 N}$$

achieves backlog  $f'(n)$  satisfying

$$f'(n) \geq (1 - \delta)^2 f(\lfloor (1 - \delta)n \rfloor) + f(\lceil \delta n \rceil) + \mu_0$$

and  $f'(n) \geq f(n)$ , in running time

$$T'(n) \leq Mn \cdot T(\lfloor (1 - \delta)n \rfloor) + T(\lceil \delta n \rceil)$$

against a  $\Delta$ -greedy-like emptier.

*Proof.* We use the definitions and notation given in Definition 2.

Note that if the emptier neglects the anchor set  $N^2$  times, or skips  $N^2$  emptyings, then the mass of the cups will be at least  $N^2$ , so the filler is done. For the rest of the proof we consider the case where the emptier chooses to neglect the anchor set fewer than  $N^2$  times, and choose to skip fewer than  $N^2$  emptyings.

The filler simply uses  $\text{alg}(f)$  on all the cups if this results in sufficient backlog, i.e. if

$$f(n) \geq (1 - \delta)^2 f(n_B) + f(n_A).$$

In this case our strategy trivially has the desired guarantees. In the rest of the proof we consider the case where  $\text{alg}(f)$  does not achieve sufficient backlog.

The filler's strategy is as follows:

**Step 1:** Make  $\mu(A) \geq (1 - \delta)^2 f(n_B)$  by using  $\text{rep}_\delta(\text{alg}(f))$  on all the cups, i.e. applying  $\text{alg}(f)$  repeatedly to  $B$ , flattening  $B$  before each application, and then donating a cup from  $B$  to  $A$ .

**Step 2:** Flatten  $A$  using  $\text{flatalg}$ , and then use  $\text{alg}(f)$  on  $A$ .

We now analyze Step 1. For this proof we need all donation-processes to succeed, as opposed to in the proof of Lemma 2 in which we only needed a constant fraction of the donation-processes to succeed. This necessitates choosing  $M$  very large. In particular we choose  $M = 2^{\lg^{24} N}$ —recall that  $[M]$  is the set from which we randomly choose how many times to apply  $\text{alg}(f)$  in a donation-process. By choosing  $M$  this large we cannot hope to guarantee that every application of  $\text{alg}(f)$  succeeds: there are far too many applications. On the other hand, having  $M$  so large allows us to have a very tight concentration bound on how many applications of  $\text{alg}(f)$  succeed. By a Chernoff bound with probability at least  $1 - e^{-2Mp^2}$  at least  $M(1 - 2p)$  of  $M$  applications of  $\text{alg}(f)$  would succeed if the emptier did not *interfere*, i.e. neglect the anchor set and do an extra emptying in the non-anchor set. The emptier can interfere with at most  $N^2$  of the  $M(1 - 2p)$  applications that would otherwise be successful. Let  $1 - q$  be the probability that a donation-process succeeds, i.e. the final application of  $\text{alg}(f)$  is not emptier-wasted and succeeds. We have

$$1 - q \geq (1 - e^{-2Mp^2}) \left( \frac{M \cdot (1 - 2p) - N^2}{M} \right).$$

Rearranging, simplifying by loosening the bound, and using the assumption  $p \geq 2^{-\lg^8 N}$ , we can show

$$q \leq 2p + 2^{-\lg^8 N}.$$

Taking a union bound, we have that with probability at least  $1 - q \cdot n_A$  all donation-process successfully achieve a cup with fill at least  $\mu_{S_0}(B) + f(n_B)$  where  $\mu_{S_0}(B)$  refers to the average fill of  $B$  measured at the start of the application of  $\text{alg}(f)$ ; now we assume all donation-processes are successful, and demonstrate that this translates into the desired average fill in  $A$ .

Let  $\text{skips}_t$  denote the number of times that the emptier has skipped the anchor set by round  $t$ . Consider how  $\mu(B) - \text{skips}/n_B$  changes over the course of the donation processes. As noted above, at the end of each donation-process  $\mu(B)$  decreases due to  $B$  donating a cup with fill at least  $\mu(B) + f(n_B)$ . In particular, if  $S$  denotes the cup state immediately before a cup is donated on the  $i$ -th donation-process,  $B_0$  denotes the set  $B$  before the donation and  $B_1$  denotes the set  $B$  after the donation, then  $\mu_S(B_1) = \mu_S(B_0) - f(n_B)/(n - i)$ . Now we claim that  $t \mapsto \mu_{S_t}(B) - \text{skips}_t/n_B$  is monotonically decreasing. Clearly donation decreases  $\mu(B) - \text{skips}/n_B$ . If the anchor set is neglected then  $\mu(B)$



decreases, causing  $\mu(B) - \text{skips}/n_B$  to decrease. If a skip occurs, then  $\text{skips}/n_B$  increases by more than  $\mu(B)$  increases, causing  $\mu(B) - \text{skips}/n_B$  to decrease. Let  $t_*$  be the cup state at the end of all the donation-processes. We have that

$$\mu_{S_{t_*}}(B) - \frac{\text{skips}_{t_*}}{n_B} \leq \mu_0 - \sum_{i=1}^{n_A} \frac{f(n_B)}{n-i}. \quad (4)$$

By conservation of mass we have

$$n_A \cdot \mu_{S_{t_*}}(A) + n_B \cdot \mu_{S_{t_*}}(B) = n\mu_0 + \text{skips}_{t_*}.$$

Rearranging,

$$\mu_{S_{t_*}}(A) = \mu_0 + \frac{n_B}{n_A} \left( \mu_0 + \frac{\text{skips}_{t_*}}{n_B} - \mu_{S_{t_*}}(B) \right). \quad (5)$$

Now we obtain a simpler form of Inequality (2). Recalling that harmonic numbers grow like  $\ln$  we have

$$\sum_{i=1}^{n_A} \frac{1}{n-i} \approx \ln n / (n - n_A) \approx \ln \frac{1}{1-\delta} > \delta.$$

Then using Inequality (2) in Equation 3 we essentially have

$$\mu_{S_{t_*}}(A) \geq \mu_0 + \frac{n_B}{n_A} \delta f(n_B) \approx \mu_0 + (1-\delta)f(n_B).$$

To handle the imprecisions indicated in the approximations above the bound becomes slightly worse:

$$\mu_{S_{t_*}}(A) \geq \mu_0 + (1-\delta)^2 f(n_B).$$

We have shown that in Step 1 the filler achieves average fill  $\mu_0 + (1-\delta)f(n_B)$  in  $A$  with failure probability at most  $q \cdot n_A$ . Now the filler flattens  $A$  and uses  $\text{alg}(f)$  on  $A$ . It is clear that this is possible, and succeeds with probability at least  $p$ . This gets a cup with fill

$$\mu_0 + (1-\delta)^2 f(n_B) + f(n_A)$$

in  $A$ , as desired.

Taking a union bound over the probabilities of Step 1 and Step 2 succeeding gives that the entire procedure fails with probability at most

$$p' \leq p + q \cdot n_A \leq np + 2^{-\lg^8 N}.$$

The running time of Step 1 is clearly  $M \cdot n \cdot T(\lfloor (1-\delta)n \rfloor)$  and the running time of Step 2 is clearly  $T(\lceil \delta n \rceil)$ ; summing these yields the desired upper bound on running time.  $\square$

Finally we prove that an oblivious filler can achieve backlog  $N^{1-\varepsilon}$ .

**Theorem 4.** *There is an oblivious filling strategy for the variable-processor cup game on  $N$  cups that achieves backlog at least  $\Omega(N^{1-\varepsilon})$  for any constant  $\varepsilon > 0$  in running time  $2^{\text{polylog}(n)}$  with probability at least  $1 - 2^{-\text{polylog}(n)}$  against a  $\Delta$ -greedy-like emptier with  $\Delta \leq O(1)$ .*

*Proof.* We show how to achieve backlog  $(N/n_b)^{1-\varepsilon} - 1$  for some  $n_b \leq \text{polylog}(N)$  on  $N$  cups; note that this implies that the filler can achieve backlog  $\Omega(N^{1-\varepsilon'})$  for any constant  $\varepsilon' \in (0, 1/2)$  on  $N$  cups. Let  $\delta$  be a constant, chosen as a function of  $\varepsilon$ .

By Proposition 6 there is an oblivious filling strategy that achieves backlog  $\Omega(1)$  on  $n$  cups with exponentially good probability in  $n$ ; we call this algorithm  $\text{alg } f_0$ . Let  $n_b = \log^8(N)$ . We can make  $\text{alg } f_0$  achieve backlog  $f_0(k) \geq H \geq \Omega(1)$  for all  $k \geq n_b$ , for constant  $H \geq \Omega(1)$  to be determined as a function of  $\delta$ . We construct  $f_{i+1}$  as the amplification of  $f_i$  using Lemma 7.

One can inductively show that  $f_{\Theta(\log N)}$  achieves backlog  $(N/n_b)^{1-\varepsilon} - 1$ , as desired. Analysis of the running time recurrence from the Oblivious Amplification Lemma gives that  $\text{alg}(f_{\Theta(\log N)})$  has running time  $2^{\text{polylog}(N)}$ , while analysis of the probability recurrence shows that  $\text{alg}(f_{\Theta(\log N)})$  succeeds with probability at least  $1 - 2^{-\text{polylog}(N)}$ .  $\square$

## 4 Adaptive Filler Lower Bound

In this section we give a  $2^{\text{polylog } n}$ -time filling strategy that achieves backlog  $n^{1-\varepsilon}$  for any positive constant  $\varepsilon$ . We also give a  $O(n!)$ -time filling strategy that achieves backlog  $\Omega(n)$ .

We begin with a trivial filling strategy that we call **trivalg** that gives backlog at least  $1/2$  when applied to at least 2 cups.

**Proposition 3.** *Consider an instance of the negative-fill 1-processor cup game on  $n$  cups, and let the cups start in any state with average fill is 0. If  $n \geq 2$ , there is an  $O(1)$ -step adaptive filling strategy **trivalg** that achieves backlog at least  $1/2$ . If  $n = 1$ , **trivalg** achieves backlog 0 in running time 0.*

*Proof.* If  $n = 1$ , **trivalg** does nothing and achieves backlog 0; for the rest of the proof we consider the case  $n \geq 2$ .

Let  $a$  and  $b$  be the fullest and second fullest cups in the in the starting configuration, and let their initial fills be  $\text{fill}(a) = \alpha, \text{fill}(b) = \beta$ . If  $\alpha \geq 1/2$  the filler need not do anything, the desired backlog is already achieved. Otherwise, if  $\alpha \in [0, 1/2]$ , the filler places  $1/2 - \alpha$  fill into  $a$  and  $1/2 + \alpha$  fill into  $b$  (which is possible as both fills are in  $[0, 1]$ , and they sum to 1). Since  $\alpha + \beta \geq 0$  we have  $\beta \geq -\alpha$ . Clearly  $a$  and  $b$  now both have fill at least  $1/2$ . The emptier cannot empty from both  $a$  and  $b$  as  $p = 1$ , so even after the emptier empties from a cup we still have backlog  $1/2$ , as desired.  $\square$

Next we prove the **Amplification Lemma**, which takes as input a filling strategy  $\text{alg}(f)$  and outputs a new filling strategy  $\text{alg}(f')$  that we call the **amplification** of  $\text{alg}(f)$ .  $\text{alg}(f')$  is able to achieve higher fill than  $\text{alg}(f)$ ; in particular, we will show that by starting with a filling strategy  $\text{alg}(f_0)$  for achieving constant backlog and then forming a sufficiently long sequence of filling strategies  $\text{alg}(f_0), \text{alg}(f_1), \dots, \text{alg}(f_{i_*})$  with  $\text{alg}(f_{i+1})$  the amplification of  $\text{alg}(f_i)$ , we eventually get a filling strategy for achieving  $\text{poly}(n)$  backlog.

**Lemma 5** (Adaptive Amplification Lemma). *Let  $\delta \in (0, 1/2]$  be a parameter. Let  $\text{alg}(f)$  be an adaptive filling strategy that achieves backlog  $f(n) < n$  in the negative-fill variable-processor cup game on  $n$  cups in running time  $T(n)$  starting from any initial cup state where the average fill is 0.*

*Then there exists an adaptive filling strategy  $\text{alg}(f')$  that achieves backlog  $f'(n)$  satisfying*

$$f'(n) \geq (1 - \delta)f(\lfloor (1 - \delta)n \rfloor) + f(\lceil \delta n \rceil)$$

*and  $f'(n) \geq f(n)$  in the negative-fill variable-processor cup game on  $n$  cups in running time*

$$T'(n) \leq n \lceil \delta n \rceil \cdot T(\lfloor (1 - \delta)n \rfloor) + T(\lceil \delta n \rceil)$$

*starting from any initial cup state where the average fill is 0.*

*Proof.* Let  $n_A = \lceil \delta n \rceil, n_B = n - n_A = \lfloor (1 - \delta)n \rfloor$ .

The filler defaults to using  $\text{alg}(f)$  if

$$f(n) \geq (1 - \delta)f(n_B) + f(n_A).$$

In this case using  $\text{alg}(f)$  achieves the desired backlog in the desired running time. In the rest of the proof, we describe our strategy in the case that we cannot simply use  $\text{alg}(f)$  to achieve the desired backlog.

Let  $A$ , the **anchor set**, be initialized to consist of the  $n_A$  fullest cups, and let  $B$  the **non-anchor set** be initialized to consist of the rest of the cups (so  $|B| = n_B$ ). Let  $h = (1 - \delta)f(n_B)$ .

The filler's strategy can be summarized as follows:

**Step 1:** Make  $\mu(A) \geq h$  by using  $\text{alg}(f)$  repeatedly on  $B$  to achieve cups with fill at least  $\mu(B) + f(n_B)$  in  $B$  and then swapping these into  $A$ . While doing this the filler always places 1 unit of fill in each anchor cup.

**Step 2:** Use  $\text{alg}(f)$  once on  $A$  to obtain some cup with fill  $\mu(A) + f(n_A)$ .

Note that in order to use  $\text{alg}(f)$  on subsets of the cups the filler will need to vary  $p$ .

We now describe how to achieve Step 1, which is complicated by the fact that the emptier may attempt to prevent the filler from achieving high fill in a cup in  $B$ .

The filling strategy always places 1 unit of water in each anchor cup. This ensures that no cups in the anchor set ever have their fill decrease. If the emptier wishes to keep the average fill of the anchor cups from increasing, then emptier must empty from every anchor cup on each step. If the emptier fails to do this on a given round, then we say that the emptier has **neglected** the anchor cups.

We say that the filler **applies**  $\text{alg}(f)$  to  $B$  if it follows the filling strategy  $\text{alg}(f)$  on  $B$  while placing 1 unit of water in each anchor cup. An application of  $\text{alg}(f)$  to  $B$  is said to be **successful** if  $A$  is never

neglected during the application of  $\text{alg}(f)$  to  $B$ . The filler uses a procedure that we call a *swapping-process* to achieve the desired average fill in  $A$ . In a swapping-process, the filler repeatedly applies  $\text{alg}(f)$  to  $B$  until a successful application occurs, and then takes the cup generated by  $\text{alg}(f)$  within  $B$  on this successful application with fill at least  $\mu(B) + f(|B|)$  and swaps it with the least full cup in  $A$  so long as doing so would increase  $\mu(A)$ . If the average fill in  $A$  ever reaches  $h$ , then the algorithm immediately halts (even if it is in the middle of a swapping-process) and is complete.

We give pseudocode for the filling strategy in Algorithm 1.

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**Algorithm 1** Adaptive Amplification (Step 1)

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**Input:**  $\text{alg}(f), \delta$ , set of  $n$  cups

**Output:** Guarantees that  $\mu(A) \geq h$

$A \leftarrow n_A$  fullest cups,  $B \leftarrow$  rest of the cups

Always place 1 fill in each cup in  $A$

**while**  $\mu(A) < h$  **do**

▷ Swapping-Processes

    Immediately **exit** this loop if ever  $\mu(A) \geq h$

    successful  $\leftarrow$  false

**while** not successful **do**

        Apply  $\text{alg}(f)$  to  $B$ ,  $\text{alg}(f)$  gives cup  $c$

**if** fill( $c$ )  $\geq h$  **then**

            successful  $\leftarrow$  true

    Swap  $c$  with least full cup in  $A$

---

Note that

$$\mu(A) \cdot |A| + \mu(B) \cdot |B| = \mu(AB) \geq 0,$$

as  $\mu(AB)$  starts as 0, but could become positive if the emptier skips emptyings. Thus we have

$$\mu(A) \geq -\mu(B) \cdot \frac{\lfloor (1-\delta)n \rfloor}{\lceil \delta n \rceil} \geq -\frac{1-\delta}{\delta} \mu(B).$$

Thus, if at any point  $B$  has average fill lower than  $-h \cdot \delta / (1-\delta)$ , then  $A$  has average fill at least  $h$ , so the algorithm is finished. Thus we can assume in our analysis that

$$\mu(B) \geq -h \cdot \delta / (1-\delta). \quad (6)$$

We will now show that during each swapping process, the filler applies  $\text{alg}(f)$  to  $B$  at most  $hn_A$  times. Each time the emptier neglects the anchor set, the mass of the anchor set increases by 1. If the emptier neglects the anchor set  $hn_A$  times, then the average fill in the anchor set increases by  $h$ . Since  $\mu(A)$  started as at least 0, and since  $\mu(A)$  never decreases (note in particular that cups are only swapped into  $A$  if doing so will increase  $\mu(A)$ ), an increase of  $h$  in  $\mu(A)$  implies that  $\mu(A) \geq h$ , as desired. Thus the swapping process consists of at most  $hn_A$  applications of  $\text{alg}(f)$ .

Consider the fill of a cup  $c$  swapped into  $A$  at the end of a swapping-process. Cup  $c$ 's fill is at least  $\mu(B) + f(n_B)$ , which by (4) is at least

$$-h \cdot \frac{\delta}{1-\delta} + f(n_B) = (1-\delta)f(n_B) = h.$$

Thus the algorithm for Step 1 succeeds within  $|A|$  swapping-processes, since at the end of the  $|A|$ -th swapping process either every cup in  $A$  has fill at least  $h$ , or the algorithm halted before  $|A|$  swapping-processes because it already achieved  $\mu(A) \geq h$ .

After achieving  $\mu(A) \geq h$ , the filler performs Step 2, i.e. the filler applies  $\text{alg}(f)$  to  $A$ , and hence achieves a cup with fill at least

$$\mu(A) + f(|A|) \geq (1-\delta)f(n_B) + f(n_A),$$

as desired.

Now we analyze the running time of the filling strategy  $\text{alg}(f')$ . First, recall that in Step 1  $\text{alg}(f')$  calls  $\text{alg}(f)$  on  $B$ , which has size  $n_B$ , as many as  $hn_A$  times. Because we mandate that  $h < n$ , Step 1

contributes no more than  $(n \cdot n_A) \cdot T(n_B)$  to the running time. Step 2 requires applying  $\text{alg}(f)$  to  $A$ , which has size  $n_A$ , once, and hence contributes  $T(n_A)$  to the running time. Summing these we have

$$T'(n) \leq n \cdot n_A \cdot T(n_B) + T(n_A).$$

□

We next show that by recursively using the Amplification Lemma we can achieve backlog  $n^{1-\varepsilon}$ .

**Theorem 5.** *There is an adaptive filling strategy for the variable-processor cup game on  $n$  cups that achieves backlog  $\Omega(n^{1-\varepsilon})$  for any constant  $\varepsilon > 0$  of our choice in running time  $2^{O(\log^2 n)}$ .*

*Proof.* Take constant  $\varepsilon \in (0, 1/2)$ . Let  $c, \delta$  be constants that will be chosen (later) as functions of  $\varepsilon$  satisfying  $c \in (0, 1), 0 < \delta \ll 1/2$ . We show how to achieve backlog at least  $cn^{1-\varepsilon} - 1$ .

Let  $\text{alg}(f_0) = \text{trivalg}$ , the algorithm given by Proposition 3; recall  $\text{trivalg}$  achieves backlog  $f_0(k) \geq 1/2$  for all  $k \geq 2$ , and  $f_0(1) = 0$ .

Next, using the Amplification Lemma we recursively construct  $\text{alg}(f_{i+1})$  as the amplification of  $\text{alg}(f_i)$  for  $i \geq 0$ .

Define a sequence  $g_i$  with

$$g_i = \begin{cases} \lceil 16/\delta \rceil, & i = 0, \\ \lfloor g_{i-1}/(1-\delta) \rfloor & i \geq 1 \end{cases}$$

We claim the following regarding this construction:

**Claim 1.** *For all  $i \geq 0$ ,*

$$f_i(k) \geq ck^{1-\varepsilon} - 1 \text{ for all } k \in [g_i]. \quad (7)$$

*Proof.* We prove Claim 1 by induction on  $i$ . For  $i = 0$ , the base case, (5) can be made true by taking  $c$  sufficiently small; in particular, taking  $c < 1$  makes (5) hold for  $k = 1$ , and, as  $g_0 > 2$ , taking  $c$  small enough to make  $cg_0^{1-\varepsilon} - 1 \leq f_0(g_0) = 1/2$  makes (5) hold for  $k \in [2, g_0]$  by monotonicity of  $k \mapsto ck^{1-\varepsilon} - 1$ .<sup>1</sup>

As our inductive hypothesis we assume (5) for  $f_i$ ; we aim to show that (5) holds for  $f_{i+1}$ . Note that, by design of  $g_i$ , if  $k \leq g_{i+1}$  then  $\lfloor k \cdot (1-\delta) \rfloor \leq g_i$ . Consider any  $k \in [g_{i+1}]$ . First we deal with the trivial case where  $k \leq g_0$ . In this case

$$f_{i+1}(k) \geq f_i(k) \geq \dots \geq f_0(k) \geq ck^{1-\varepsilon} - 1.$$

Now we consider the case where  $k \geq g_0$ . Since  $f_{i+1}$  is the amplification of  $f_i$  we have

$$f_{i+1}(k) \geq (1-\delta)f_i(\lfloor (1-\delta)k \rfloor) + f_i(\lceil \delta k \rceil).$$

By our inductive hypothesis, which applies as  $\lceil \delta k \rceil \leq g_i, \lfloor k \cdot (1-\delta) \rfloor \leq g_i$ , we have

$$f_{i+1}(k) \geq (1-\delta)(c \cdot \lfloor (1-\delta)k \rfloor^{1-\varepsilon} - 1) + c \lceil \delta k \rceil^{1-\varepsilon} - 1.$$

Dropping the floor and ceiling, incurring a  $-1$  for dropping the floor, we have

$$f_{i+1}(k) \geq (1-\delta)(c \cdot ((1-\delta)k - 1)^{1-\varepsilon} - 1) + c(\delta k)^{1-\varepsilon} - 1.$$

Because  $(x-1)^{1-\varepsilon} \geq x^{1-\varepsilon} - 1$ , due to the fact that  $x \mapsto x^{1-\varepsilon}$  is a sub-linear sub-additive function, we have

$$f_{i+1}(k) \geq (1-\delta)c \cdot (((1-\delta)k)^{1-\varepsilon} - 2) + c(\delta k)^{1-\varepsilon} - 1.$$

Moving the  $ck^{1-\varepsilon}$  to the front we have

$$f_{i+1}(k) \geq ck^{1-\varepsilon} \cdot \left( (1-\delta)^{2-\varepsilon} + \delta^{1-\varepsilon} - \frac{2(1-\delta)}{k^{1-\varepsilon}} \right) - 1.$$

Because  $(1-\delta)^{2-\varepsilon} \geq 1 - (2-\varepsilon)\delta$ , a fact called Bernoulli's Identity, we have

$$f_{i+1}(k) \geq ck^{1-\varepsilon} \cdot \left( 1 - (2-\varepsilon)\delta + \delta^{1-\varepsilon} - \frac{2(1-\delta)}{k^{1-\varepsilon}} \right) - 1.$$

<sup>1</sup>Note that it is important here that  $\varepsilon$  and  $\delta$  are constants, that way  $c$  is also a constant.

Of course  $-2(1 - \delta) \geq -2$ , so

$$f_{i+1}(k) \geq ck^{1-\varepsilon} \cdot \left(1 - (2 - \varepsilon)\delta + \delta^{1-\varepsilon} - \frac{2}{k^{1-\varepsilon}}\right) - 1.$$

Because

$$\frac{-2}{k^{1-\varepsilon}} \geq \frac{-2}{g_0^{1-\varepsilon}} \geq -2(\delta/16)^{1-\varepsilon} \geq -\delta^{1-\varepsilon}/2,$$

which follows from our choice of  $g_0 = \lceil 16/\delta \rceil$  and the restriction  $\varepsilon < 1/2$ , we have

$$f_{i+1}(k) \geq ck^{1-\varepsilon} \cdot (1 - (2 - \varepsilon)\delta + \delta^{1-\varepsilon} - \delta^{1-\varepsilon}/2) - 1.$$

Finally, combining terms we have

$$f_{i+1}(k) \geq ck^{1-\varepsilon} \cdot (1 - (2 - \varepsilon)\delta + \delta^{1-\varepsilon}/2) - 1.$$

Because  $\delta^{1-\varepsilon}$  dominates  $\delta$  for sufficiently small  $\delta$ , there is a choice of  $\delta = \Theta(1)$  such that

$$1 - (2 - \varepsilon)\delta + \delta^{1-\varepsilon}/2 \geq 1.$$

Taking  $\delta$  to be this small we have,

$$f_{i+1}(k) \geq ck^{1-\varepsilon} - 1,$$

completing the proof. We remark that the choices of  $c, \delta$  are the same for every  $i$  in the inductive proof, and depend only on  $\varepsilon$ .  $\square$

To complete the proof, we will show that  $g_i$  grows exponentially in  $i$ . Thus, after there exists  $i_* \leq O(\log n)$  such that  $g_{i_*} \geq n$ , and hence we have an algorithm  $\text{alg}(f_{i_*})$  that achieves backlog  $cn^{1-\varepsilon} - 1$  on  $n$  cups, as desired.

We lower bound the sequence  $g_i$  with another sequence  $g'_i$  defined as

$$g'_i = \begin{cases} 4/\delta, & i = 0 \\ g'_{i-1}/(1 - \delta) - 1, & i > 0. \end{cases}$$

Solving this recurrence, we find

$$g'_i = \frac{4 - (1 - \delta)^2}{\delta} \frac{1}{(1 - \delta)^i} \geq \frac{1}{(1 - \delta)^i},$$

which clearly exhibits exponential growth. In particular, let  $i_* = \lceil \log_{1/(1-\delta)} n \rceil$ . Then,

$$g_{i_*} \geq g'_{i_*} \geq n,$$

as desired.

Let the running time of  $f_i(n)$  be  $T_i(n)$ . From the Amplification Lemma we have following recurrence bounding  $T_i(n)$ :

$$\begin{aligned} T_i(n) &\leq n \lceil \delta n \rceil \cdot T_{i-1}(\lfloor (1 - \delta)n \rfloor) + T_{i-1}(\lceil \delta n \rceil) \\ &\leq 2n^2 T_{i-1}(\lfloor (1 - \delta)n \rfloor). \end{aligned}$$

It follows that  $\text{alg}(f_{i_*})$ , recalling that  $i_* \leq O(\log n)$ , has running time

$$T_{i_*}(n) \leq (2n^2)^{O(\log n)} \leq 2^{O(\log^2 n)}$$

as desired.  $\square$

Now we provide a very simple construction that can achieve backlog  $\Omega(n)$  in very long games. The construction can be interpreted as the same argument as in Theorem 2 but with an extremal setting of  $\delta$  to  $\Theta(1/n)$ .<sup>2</sup>

**Proposition 4.** *There is an adaptive filling strategy that achieves backlog  $\Omega(n)$  in time  $O(n!)$ .*

<sup>2</sup>Or more precisely, setting  $\delta$  in each level of recursion to be  $\Theta(1/n)$ , where  $n$  is the subproblem size; note in particular that  $\delta$  changes between levels of recursion, which was not the case in the proof of Theorem 2.

*Proof.* First we construct a slightly stronger version of  $\text{trivalg}$  that achieves backlog 1 on  $n \geq n_0 = 8$  cups, instead of just backlog  $1/2$ ; this simplifies the analysis.

**Claim 2.** *There is a filling algorithm  $\text{trivalg}_2$  that achieves backlog at least 1 on  $n_0 = 8$  cups.*

*Proof.* Let  $\text{trivalg}_1$  be the amplification of  $\text{trivalg}$  using  $\delta = 1/2$ . On 4 cups  $\text{trivalg}_1$  achieves backlog at least  $(1/2)(1/2) + 1/2 = 3/4$ . Let  $\text{trivalg}_2$  be the amplification of  $\text{trivalg}_1$  using  $\delta = 1/2$ . On 8 cups  $\text{trivalg}_2$  achieves backlog at least  $(1/2)(3/4) + 3/4 \geq 1$ .  $\square$

Let  $\text{alg}(f_0) = \text{trivalg}_2$ ; we have  $f_0(k) \geq 1$  for all  $k \geq n_0$ . For  $i > 0$  we construct  $\text{alg}(f_i)$  as the amplification of  $\text{alg}(f_{i-1})$  using the Amplification Lemma with parameter  $\delta = 1/(i+1)$ .

We claim the following regarding this construction:

**Claim 3.** *For all  $i \geq 0$ ,*

$$f_i((i+1)n_0) \geq \sum_{j=0}^i \left(1 - \frac{j}{i+1}\right). \quad (8)$$

*Proof.* We prove Claim 3 by induction on  $i$ . When  $i = 0$ , the base case, (6) becomes  $f_0(n_0) \geq 1$  which is true. Assuming (6) for  $f_{i-1}$ , we now show (6) holds for  $f_i$ . Because  $f_i$  is the amplification of  $f_{i-1}$  with  $\delta = 1/(i+1)$ , we have by the Amplification Lemma

$$f_i((i+1) \cdot n_0) \geq \left(1 - \frac{1}{i+1}\right) f_{i-1}(i \cdot n_0) + f_{i-1}(n_0).$$

Since  $f_{i-1}(n_0) \geq f_0(n_0) \geq 1$  we have

$$f_i((i+1) \cdot n_0) \geq \left(1 - \frac{1}{i+1}\right) f_{i-1}(i \cdot n_0) + 1.$$

Using the inductive hypothesis we have

$$f_i((i+1) \cdot n_0) \geq \left(1 - \frac{1}{i+1}\right) \sum_{j=0}^{i-1} \left(1 - \frac{j}{i}\right) + 1.$$

Note that

$$\begin{aligned} \left(1 - \frac{1}{i+1}\right) \cdot \left(1 - \frac{j}{i}\right) &= \frac{i}{i+1} \cdot \frac{i-j}{i} \\ &= \frac{i-j}{i+1} \\ &= 1 - \frac{j+1}{i+1}. \end{aligned}$$

Thus we have

$$f_i((i+1) \cdot n_0) \geq \sum_{j=1}^i \left(1 - \frac{j}{i+1}\right) + 1 = \sum_{j=0}^i \left(1 - \frac{j}{i+1}\right),$$

as desired.  $\square$

Let  $i_* = \lfloor n/n_0 \rfloor - 1$ , which by design satisfies  $(i_* + 1)n_0 \leq n$ . By Claim 3 we have

$$f_{i_*}((i_* + 1) \cdot n_0) \geq \sum_{j=0}^{i_*} \left(1 - \frac{j}{i_* + 1}\right) = i_*/2 + 1.$$

As  $i_* = \Theta(n)$ , we have thus shown that  $\text{alg}(f_{i_*})$  can achieve backlog  $\Omega(n)$  on  $n$  cups.

Let  $T_i$  be the running time of  $\text{alg}(f_i)$ . The recurrence for the running time of  $f_{i_*}$  is

$$T_i(n) \leq n \cdot n_0 T_{i-1}(n - n_0) + O(1).$$

Clearly  $T_{i_*}(n) \leq O(n!)$ .  $\square$

## 5 Upper Bound

In this section we analyze the *greedy emptier*, which always empties from the  $p$  fullest cups. We prove in Corollary 1 that the greedy emptier prevents backlog from exceeding  $O(n)$ .

In order to analyze the greedy emptier, we establish a system of invariants that hold at every step of the game.

Let  $\mu_S(X)$  and  $m_S(X)$  denote the average fill and the mass, respectively, of a set of cups  $X$  at state  $S$  (where  $S = S_t$  or  $S = I_t$ ).<sup>3</sup> We will use concatenation of sets to denote unions, i.e.  $AB = A \cup B$ .

The main result of the section is the following theorem.

**Theorem 6.** *In the variable-processor cup game on  $n$  cups, the greedy emptier maintains, at every step  $t$ , the invariants*

$$\mu_{S_t}(S_t([k])) \leq 2n - k \quad (9)$$

for all  $k \in [n]$ .

By applying Theorem 3 to the case of  $k = 1$ , we arrive at a bound on backlog:

**Corollary 1.** *In the variable-processor cup game on  $n$  cups, the greedy emptying strategy never lets backlog exceed  $O(n)$ .*

*Proof of Theorem 3.* We prove the invariants by induction on  $t$ . The invariants hold trivially for  $t = 1$  (the base case for the inductive proof): the cups start empty so  $\mu_{S_1}(S_1([k])) = 0 \leq 2n - k$  for all  $k \in [n]$ .

Fix a round  $t \geq 1$ , and any  $k \in [n]$ . We assume the invariants for all values of  $k' \in [n]$  for state  $S_t$  (we will only explicitly use two of the invariants for each  $k$ , but the invariants that we need depend on the choice of  $p_t$  by the filler) and show that the invariant on the  $k$  fullest cups holds on round  $t + 1$ , i.e. that

$$\mu_{S_{t+1}}(S_{t+1}([k])) \leq 2n - k.$$

Note that because the emptier is greedy it always empties from the cups  $I_t([p_t])$ . Let  $A$ , with  $a = |A|$ , be  $A = I_t([\min(k, p_t)]) \cap S_{t+1}([k])$ ;  $A$  consists of the cups that are among the  $k$  fullest cups in  $I_t$ , are emptied from, and are among the  $k$  fullest cups in  $S_{t+1}$ . Let  $B$ , with  $b = |B|$ , be  $B = I_t([\min(k, p_t)]) \setminus A$ ;  $B$  consists of the cups that are among the  $k$  fullest cups in state  $I_t$ , are emptied from, and are not among the  $k$  fullest cups in  $S_{t+1}$ . Let  $C = I_t(a + b + [k - a])$ , with  $c = k - a = |C|$ ;  $C$  consists of the cups with ranks  $a + b + 1, \dots, k + b$  in state  $I_t$ . The set  $C$  is defined so that  $S_{t+1}([k]) = AC$ , since once the cups in  $B$  are emptied from, the cups in  $B$  are not among the  $k$  fullest cups, so cups in  $C$  take their places among the  $k$  fullest cups.

Note that  $k - a \geq 0$  as  $a + b \leq k$ , and also  $|ABC| = k + b \leq n$ , because by definition the  $b$  cups in  $B$  must not be among the  $k$  fullest cups in state  $S_{t+1}$  so there are at least  $k + b$  cups. Note that  $a + b = \min(k, p_t)$ . We also have that  $A = I_t([a])$  and  $B = I_t(a + [b])$ , as every cup in  $A$  must have higher fill than all cups in  $B$  in order to remain above the cups in  $B$  after 1 unit of water is removed from all cups in  $AB$ .

We now establish the following claim, which we call the *interchangeability of cups*:

**Claim 4.** *There exists a cup state  $S'_t$  such that: (a)  $S'_t$  satisfies the invariants (7), (b)  $S'_t(r) = I_t(r)$  for all ranks  $r \in [n]$ , and (c) the filler can legally place water into cups in order to transform  $S'_t$  into  $I_t$ .*

*Proof.* Fix  $r \in [n]$ . We will show that  $S_t$  can be transformed into a state  $S'_t$  by relabelling only cups with ranks in  $[r]$  such that (a)  $S'_t$  satisfies the invariants (7), (b)  $S'_t([r]) = I_t([r])$  and (c) the filler can legally place water into cups in order to transform  $S'_t$  into  $I_t$ .

Say there are cups  $x, y$  with  $x \in S_t([r]) \setminus I_t([r])$ ,  $y \in I_t([r]) \setminus S_t([r])$ . Let the fills of cups  $x, y$  at state  $S_t$  be  $f_x, f_y$ ; note that

$$f_x > f_y. \quad (10)$$

Let the amount of fill that the filler adds to these cups be  $\Delta_x, \Delta_y \in [0, 1]$ ; note that

$$f_x + \Delta_x < f_y + \Delta_y. \quad (11)$$

Define a new state  $S'_t$  where cup  $x$  has fill  $f_y$  and cup  $y$  has fill  $f_x$ . Note that the filler can transform state  $S'_t$  into state  $I_t$  by placing water into cups as before, except changing the amount of water placed into cups  $x$  and  $y$  to be  $f_x - f_y + \Delta_x$  and  $f_y - f_x + \Delta_y$ , respectively.

<sup>3</sup>Note that in the lower bound proofs (i.e. Section 4 and Section 6) when we use the notation  $m$  (for mass) and  $\mu$  (for average fill), we omit the subscript indicating the state at which the properties are measured. In those proofs the state is implicitly clear. However, in this section it is necessary to make the state  $S$  explicit in the notation.

In order to verify that the transformation from  $S'_t$  to  $I_t$  is a valid step for the filler, one must check three conditions. First, the amount of water placed by the filler is unchanged: this is because  $(f_x - f_y + \Delta_x) + (f_y - f_x + \Delta_y) = \Delta_x + \Delta_y$ . Second, the fills placed in cups  $x$  and  $y$  are at most 1: this is because  $f_x - f_y + \Delta_x < \Delta_y \leq 1$  (by (9)) and  $f_y - f_x + \Delta_x < \Delta_x \leq 1$  (by (8)). Third, the fills placed in cups  $x$  and  $y$  are non-negative: this is because  $f_x - f_y + \Delta_x > \Delta_x \geq 0$  (by (8)) and  $f_y - f_x + \Delta_y > \Delta_x \geq 0$  (by (9)).

We can repeatedly apply this process to swap each cup in  $I_t([r]) \setminus S_t([r])$  into being in  $S'_t([r])$ . At the end of this process we will have some state  $S'_t$  for which  $S'_t([r]) = I_t([r])$ . Note that  $S'_t$  is simply a relabeling of  $S_t$ , hence it must satisfy the same invariants (7) satisfied by  $S_t$ . Further,  $S'_t$  can be transformed into  $I_t$  by a valid filling step.

Now we repeatedly apply this process, in descending order of ranks. In particular, we have the following process: create a sequence of states by starting with  $S_t^{n-1}$ , and to get to state  $S_t^r$  from state  $S_t^{r+1}$  apply the process described above. Note that  $S_t^{n-1}$  satisfies  $S_t^{n-1}([n-1]) = I_t([n-1])$  and thus also  $S_t^{n-1}(n) = I_t(n)$ . If  $S_t^{r+1}$  satisfies  $S_t^{r+1}(r') = I_t(r')$  for all  $r' > r+1$  then  $S_t^r$  satisfies  $S_t^r(r') = I_t(r')$  for all  $r' > r$ , because the transition from  $S_t^{r+1}$  to  $S_t^r$  has not changed the labels of any cups with ranks in  $(r+1, n]$ , but the transition does enforce  $S_t^r([r]) = I_t([r])$ , and consequently  $S_t^r(r+1) = I_t(r+1)$ . We continue with the sequential process until arriving at state  $S_t^1$  in which we have  $S_t^1(r) = I_t(r)$  for all  $r$ . Throughout the process each  $S_t^r$  has satisfied the invariants (7), so  $S_t^1$  satisfies the invariants (7). Further, throughout the process from each  $S_t^r$  it is possible to legally place water into cups in order to transform  $S_t^r$  into  $I_t$ .

Hence  $S_t^1$  satisfies all the properties desired, and the proof of Claim 4 is complete.  $\square$

Claim 4 tells us that we may assume without loss of generality that  $S_t(r) = I_t(r)$  for each rank  $r \in [n]$ . We will make this assumption for the rest of the proof.

In order to complete the proof of the theorem, we break it into three cases.

**Claim 5.** *If some cup in  $A$  zeroes out in round  $t$ , then the invariant  $\mu_{S_{t+1}}(S_{t+1}([k])) \leq 2n - k$  holds.*

*Proof.* Say a cup in  $A$  zeroes out in step  $t$ . Of course

$$m_{S_{t+1}}(I_t([a-1])) \leq (a-1)(2n - (a-1))$$

because the  $a-1$  fullest cups must have satisfied the invariant (with  $k = a-1$ ) on round  $t$ . Moreover, because  $\text{fill}_{S_{t+1}}(I_{t+1}(a)) = 0$

$$m_{S_{t+1}}(I_t([a])) = m_{S_{t+1}}(I_t([a-1])).$$

Combining the above equations, we get that

$$m_{S_{t+1}}(A) \leq (a-1)(2n - (a-1)).$$

Furthermore, the fill of all cups in  $C$  must be at most 1 at state  $I_t$  to be less than the fill of the cup in  $A$  that zeroed out. Thus,

$$\begin{aligned} m_{S_{t+1}}(S_{t+1}([k])) &= m_{S_{t+1}}(AC) \\ &\leq (a-1)(2n - (a-1)) + k - a \\ &= a(2n - a) + a - 2n + a - 1 + k - a \\ &= a(2n - a) + (k - n) + (a - n) - 1 \\ &< a(2n - a) \end{aligned}$$

as desired. As  $k$  increases from 1 to  $n$ ,  $k(2n - k)$  strictly increases (it is a quadratic in  $k$  that achieves its maximum value at  $k = n$ ). Thus  $a(2n - a) \leq k(2n - k)$  because  $a \leq k$ . Therefore,

$$m_{S_{t+1}}(S_{t+1}([k])) \leq k(2n - k).$$

$\square$

**Claim 6.** *If no cups in  $A$  zero out in round  $t$  and  $b = 0$ , then the invariant  $\mu_{S_{t+1}}(S_{t+1}([k])) \leq 2n - k$  holds.*



*Proof.* If  $b = 0$ , then  $S_{t+1}([k]) = S_t([k])$ . During round  $t$  the emptier removes  $a$  units of fill from the cups in  $S_t([k])$ , specifically the cups in  $A$ . The filler cannot have added more than  $k$  fill to these cups, because it can add at most 1 fill to any given cup. Also, the filler cannot have added more than  $p_t$  fill to the cups because this is the total amount of fill that the filler is allowed to add. Hence the filler adds at most  $\min(p_t, k) = a + b = a + 0 = a$  fill to these cups. Thus the invariant holds:

$$m_{S_{t+1}}(S_{t+1}([k])) \leq m_{S_t}(S_t([k])) + a - a \leq k(2n - k).$$

□

The remaining case, in which no cups in  $A$  zero out and  $b > 0$  is the most technically interesting.

**Claim 7.** *If no cups in  $A$  zero out on round  $t$  and  $b > 0$ , then the invariant  $\mu_{S_{t+1}}(S_{t+1}([k])) \leq 2n - k$  holds.*

*Proof.* Because  $b > 0$  and  $a + b \leq k$  we have that  $a < k$ , and  $c = k - a > 0$ . Recall that  $S_{t+1}([k]) = AC$ , so the mass of the  $k$  fullest cups at  $S_{t+1}$  is the mass of  $AC$  at  $S_t$  plus any water added to cups in  $AC$  by the filler, minus any water removed from cups in  $AC$  by the emptier. The emptier removes exactly  $a$  units of water from  $AC$ . The filler adds no more than  $p_t$  units of water to  $AC$  (because the filler adds at most  $p_t$  total units of water per round) and the filler also adds no more than  $k = |AC|$  units of water to  $AC$  (because the filler adds at most 1 unit of water to each of the  $k$  cups in  $AC$ ). Thus, the filler adds no more than  $a + b = \min(p_t, k)$  units of water to  $AC$ . Combining these observations we have:

$$m_{S_{t+1}}(S_{t+1}([k])) \leq m_{S_t}(AC) + b. \quad (12)$$

The key insight necessary to bound this is to notice that larger values for  $m_{S_t}(A)$  correspond to smaller values for  $m_{S_t}(C)$  because of the invariants; the higher fill in  $A$  *pushes down* the fill that  $C$  can have. By capturing the pushing-down relationship combinatorially we will achieve the desired inequality.

We can upper bound  $m_{S_t}(C)$  by

$$\begin{aligned} m_{S_t}(C) &\leq \frac{c}{b+c} m_{S_t}(BC) \\ &= \frac{c}{b+c} (m_{S_t}(ABC) - m_{S_t}(A)) \end{aligned}$$

because  $\mu_{S_t}(C) \leq \mu_{S_t}(B)$  without loss of generality by the interchangeability of cups. Thus we have

$$m_{S_t}(AC) \leq m_{S_t}(A) + \frac{c}{b+c} m_{S_t}(BC) \quad (13)$$

$$= \frac{c}{b+c} m_{S_t}(ABC) + \frac{b}{b+c} m_{S_t}(A). \quad (14)$$

Note that the expression in (12) is monotonically increasing in both  $\mu_{S_t}(ABC)$  and  $\mu_{S_t}(A)$ . Thus, by numerically replacing both average fills with their extremal values,  $2n - |ABC|$  and  $2n - |A|$ . At this point the claim can be verified by straightforward (but quite messy) algebra (and by combining (10) with (12)). We instead give a more intuitive argument, in which we examine the right side of (11) combinatorially.

Consider a new configuration of fills  $F$  achieved by starting with state  $S_t$ , and moving water from  $BC$  into  $A$  until  $\mu_F(A) = 2n - |A|$ .<sup>4</sup> This transformation increases (strictly increases if and only if we move a non-zero amount of water) the right side of (11). In particular, if mass  $\Delta \geq 0$  fill is moved from  $BC$  to  $A$ , then the right side of (11) increases by  $\frac{b}{b+c} \Delta \geq 0$ . Note that the fact that moving water from  $BC$  into  $A$  increases the right side of (11) formally captures the way the system of invariants being proven forces a tradeoff between the fill in  $A$  and the fill in  $BC$ —that is, higher fill in  $A$  pushes down the fill that  $BC$  (and consequently  $C$ ) can have.

Since  $\mu_F(A)$  is above  $\mu_F(ABC)$ , the greater than average fill of  $A$  must be counter-balanced by the lower than average fill of  $BC$ . In particular we must have

$$(\mu_F(A) - \mu_F(ABC))|A| = (\mu_F(ABC) - \mu_F(BC))|BC|.$$

<sup>4</sup>Note that whether or not  $F$  satisfies the invariants is irrelevant.

Note that

$$\begin{aligned}
& \mu_F(A) - \mu_F(ABC) \\
&= (2n - |A|) - \mu_F(ABC) \\
&\geq (2n - |A|) - (2n - |ABC|) \\
&= |BC|.
\end{aligned}$$

Hence we must have

$$\mu_F(ABC) - \mu_F(BC) \geq |A|.$$

Thus

$$\mu_F(BC) \leq \mu_F(ABC) - |A| \leq 2n - |ABC| - |A|. \quad (15)$$

Combining (11) with the fact that the transformation from  $S_t$  to  $F$  only increases the right side of (11), along with (13), we have the following bound:

$$\begin{aligned}
m_{S_t}(AC) &\leq m_F(A) + c\mu_F(BC) \\
&\leq a(2n - a) + c(2n - |ABC| - a) \\
&\leq (a + c)(2n - a) - c(a + c + b) \\
&\leq (a + c)(2n - a - c) - cb.
\end{aligned} \quad (16)$$

By (10) and (14), we have that

$$\begin{aligned}
m_{S_{t+1}}(S_{t+1}([k])) &\leq m_{S_t}(AC) + b \\
&\leq (a + c)(2n - a - c) - cb + b \\
&= k(2n - k) - cb + b \\
&\leq k(2n - k),
\end{aligned}$$

where the final inequality uses the fact that  $c \geq 1$ . This completes the proof of the claim.  $\square$

We have shown the invariant holds for arbitrary  $k$ , so given that the invariants all hold at state  $S_t$  they also must all hold at state  $S_{t+1}$ . Thus, by induction we have the invariant for all rounds  $t \in \mathbb{N}$ .  $\square$

## 6 Oblivious Filler Lower Bound

In this section we prove that, surprisingly, an oblivious filler can achieve backlog  $n^{1-\varepsilon}$ , although only against a certain class of “greedy-like” emptiers.

The **fill-range** of a set of cups at a state  $S$  is  $\max_c \text{fill}_S(c) - \min_c \text{fill}_S(c)$ . We call a cup configuration ***R-flat*** if the fill-range of the cups less than or equal to  $R$ ; note that in an  $R$ -flat cup configuration with average fill 0 all cups have fills in  $[-R, R]$ . We say an emptier is  ***$\Delta$ -greedy-like*** if, whenever there are two cups with fills that differ by at least  $\Delta$ , the emptier never empties from the less full cup without also emptying from the more full cup. That is, if on some round  $t$ , there are cups  $c_1, c_2$  with  $\text{fill}_{I_t}(c_1) > \text{fill}_{I_t}(c_2) + \Delta$ , then a  $\Delta$ -greedy-like emptier doesn’t empty from  $c_2$  on round  $t$  unless it also empties from  $c_1$  on round  $t$ . Note that a perfectly greedy emptier is 0-greedy-like. We call an emptier ***greedy-like*** if it is  $\Delta$ -greedy-like for  $\Delta \leq O(1)$ .

With an oblivious filler we are only able to prove lower bounds on backlog against greedy-like emptiers; whether or not our results can be extended to a more general class of emptiers is an interesting open question. Nonetheless, greedy-like emptiers are of great interest because all the known randomized algorithms for the cup game are greedy-like [10, 25].

As a tool in our analysis we define a new variant of the cup game: In the  $p$ -processor ***E-extra-emptyings S-skip-emptyings*** negative-fill cup game on  $n$  cups, the filler distributes  $p$  units of water amongst the cups, and then the emptier empties from  $p$  or more, or less cups. In particular the emptier is allowed to do  $E$  extra emptyings and is also allowed to skip  $S$  emptyings over the course of the game. Note that the emptier still cannot empty from the same cup twice on a single round, and also that note that a  $\Delta$ -greedy-like emptier must take into account extra emptyings and skip emptyings to determine valid moves. Further, note that the emptier is allowed to skip extra emptyings, although skipping extra emptyings looks the same as if the extra-emptyings had simply not been performed. Let the ***regular*** cup game be the 0-extra-emptyings  $\infty$ -skip-emptyings cup game: this is the regular cup game. Allowing

for some extra emptyings, and bounding the number of skip emptyings is sometimes necessary when analyzing an algorithm that is a subroutine of a larger algorithm however, hence it sometimes makes sense to consider games with different values of  $E, S$ . Unless explicitly stated otherwise however we are considering the regular cup game.

For a  $\Delta$ -greedy-like emptier let  $R_\Delta = 2(2 + \Delta)$ ; we now prove a key property of these emptiers: there is an oblivious filling strategy, which we term **flatalg**, that attains an  $R_\Delta$ -flat cup configuration against a  $\Delta$ -greedy-like emptier, given cups of a known starting fill-range.

**Lemma 6.** *Consider an  $R$ -flat cup configuration in the  $p$ -processor  $E$ -extra-emptyings  $S$ -skip-emptyings negative-fill cup game on  $n = 2p$  cups. There is an oblivious filling strategy **flatalg** that achieves an  $R_\Delta$ -flat configuration of cups against a  $\Delta$ -greedy-like emptier in running time  $2(R + \lceil(1 + 1/n)(E + S)\rceil)$ . Furthermore, flatalg guarantees that the cup configuration is  $R$ -flat on every round.*

*Proof.* If  $R \leq R_\Delta$  the algorithm does nothing, since the desired fill-range is already achieved; for the rest of the proof we consider  $R > R_\Delta$ .

The filler's strategy is to distribute fill equally amongst all cups at every round, placing  $p/n = 1/2$  fill in each cup. Let  $\ell_t = \min_{c \in S_t} \text{fill}_{S_t}(c)$ ,  $u_t = \max_{c \in S_t} \text{fill}_{S_t}(c)$ .

First we show that the fill-range of the cups can only increase if the fill-range is very small.

**Claim 8.** *If  $u_{t+1} - \ell_{t+1} > u_t - \ell_t$  then*

$$u_{t+1} - \ell_{t+1} \leq R_\Delta.$$

*Proof.* First we remark that the fill of any cup changes by at most  $1/2$  from round to round, and in particular  $|u_{t+1} - u_t| \leq 1/2$ ,  $|\ell_{t+1} - \ell_t| \leq 1/2$ . In order for the fill-range to increase, the emptier must have emptied from some cup with fill in  $[\ell_t, \ell_t + 1]$  without emptying from some cup with fill in  $[u_t - 1, u_t]$ ; if the emptier had not emptied from every cup with fill in  $[\ell_t, \ell_t + 1]$  then we would have  $\ell_{t+1} = \ell_t + 1/2$  so the fill-range could not have increased, and similarly if the emptier had emptied from every cup with fill in  $[u_t - 1, u_t]$  then we would have  $u_{t+1} = u_t - 1/2$  so again the fill-range could not have increased. Because the emptier is  $\Delta$ -greedy-like emptying from a cup with fill at most  $\ell_t + 1$  and not emptying from a cup with fill at least  $u_t - 1$  implies that  $u_t - 1$  and  $\ell_t + 1$  differ by at most  $\Delta$ . Thus,

$$u_{t+1} - \ell_{t+1} \leq u_t + 1/2 - (\ell_t - 1/2) \leq \Delta + 3 \leq R_\Delta.$$

□

Because by Claim 8 whenever the fill-range of the cups increases it increases to a value bounded above by  $R_\Delta \leq R$ , we have by induction that the fill-range of the cups never exceeds  $R$ , i.e. the cups are always  $R$ -flat. While Claim 8 does imply that the fill-range must decrease until the fill-range is at most  $R_\Delta$ , and once the fill-range is at most  $R_\Delta$  it is always at most  $R_\Delta$ , Claim 8 does not preclude the possibility that the fill-range doesn't change for many rounds, or decreases by a very small amount. For this reason we actually do not use Claim 8 in the remainder of the proof; we proved this result because the fact that fill-range does not increase during flatalg is an important property of flatalg. In the rest of the proof we establish that the fill-range indeed must eventually be at most  $R_\Delta$ .

Let  $L_t$  be the set of cups  $c$  with  $\text{fill}_{S_t}(c) \leq \ell_t + 2 + \Delta$ , and let  $U_t$  be the set of cups  $c$  with  $\text{fill}_{S_t}(c) \geq u_t - 2 - \Delta$ .

Now we prove a key property of the sets  $U_t$  and  $L_t$ : if a cup is in  $U_t$  or  $L_t$  it is also in  $U_{t'}, L_{t'}$  for all  $t' > t$ . This follows immediately from Claim 9.

**Claim 9.**

$$U_t \subseteq U_{t+1}, \quad L_t \subseteq L_{t+1}.$$

*Proof.* Consider a cup  $c \in U_t$ .

If  $c$  is not emptied from, i.e.  $\text{fill}(c)$  has increased by  $1/2$  from the previous round, then clearly  $c \in U_{t+1}$ , because backlog has increased by at most  $1/2$ , so  $\text{fill}(c)$  must still be within  $2 + \Delta$  of the backlog on round  $t + 1$ .

On the other hand, if  $c$  is emptied from, i.e.  $\text{fill}(c)$  has decreased by  $1/2$ , we consider two cases.

**Case 1:** If  $\text{fill}_{S_t}(c) \geq u_t - \Delta - 1$ , then  $\text{fill}_{S_t}(c)$  is at least 1 above the bottom of the interval defining which cups belong to  $U_t$ . The backlog increases by at most  $1/2$  and the fill of  $c$  decreases by  $1/2$ , so  $\text{fill}_{S_{t+1}}(c)$  is at least  $1 - 1/2 - 1/2 = 0$  above the bottom of the interval, i.e. still in the interval.

**Case 2:** On the other hand, if  $\text{fill}_{S_t}(c) < u_t - \Delta - 1$ , then every cup with fill in  $[u_t - 1, u_t]$  must have been emptied from because the emptier is  $\Delta$ -greedy-like. Therefore the fullest cup on round  $t + 1$  is the

same as the fullest cup on round  $t$ , because every cup with fill in  $[u_t - 1, u_t]$  has had its fill decrease by  $1/2$ , and no cup with fill less than  $u_t - 1$  had its fill increase by more than  $1/2$ . Hence  $u_{t+1} = u_t - 1/2$ . Because both  $\text{fill}(c)$  and the backlog have decreased by  $1/2$ , the distance between them is still at most  $\Delta + 2$ , hence  $c \in U_{t+1}$ .

The argument for why  $L_t \subseteq L_{t+1}$  is symmetric.  $\square$

Now we show that under certain conditions  $u_t$  decreases and  $\ell_t$  increases.

**Claim 10.** *On any round  $t$  where the emptier empties from at least  $n/2$  cups, if  $|U_t| \leq n/2$  then  $u_{t+1} = u_t - 1/2$ . On any round  $t$  where the emptier empties from at most  $n/2$  cups, if  $|L_t| \leq n/2$  then  $\ell_{t+1} = \ell_t + 1/2$ .*

*Proof.* Consider a round  $t$  where the emptier empties from at least  $n/2$  cups. If there are at least  $n/2$  cups outside of  $U_t$ , i.e. cups with fills in  $[\ell_t, u_t - 2 - \Delta]$ , then all cups with fills in  $[u_t - 2, u_t]$  must be emptied from; if one such cup was not emptied from then by the pigeon-hole principle some cup outside of  $U_t$  was emptied from, which is impossible as the emptier is  $\Delta$ -greedy-like. This clearly implies that  $u_{t+1} = u_t - 1/2$ : no cup with fill less than  $u_t - 2$  has gained enough fill to become the fullest cup, and the fullest cup from the previous round has lost  $1/2$  unit of fill.

By a symmetric argument  $\ell_{t+1} = \ell_t + 1/2$  if the emptier empties at most  $n/2$  cups on a round  $t$  where  $|L_t| \leq n/2$ .  $\square$

Now we show that eventually  $L_t \cap U_t \neq \emptyset$ .

**Claim 11.** *There is a round  $t_0 \leq 2(R + \lceil(1 + 1/n)(E + S)\rceil)$  such that  $U_t \cap L_t \neq \emptyset$  for all  $t \geq t_0$ .*

*Proof.* We call a round where the emptier doesn't use  $p = n/2$  resources, i.e. a round where the number of skipped emptyings and the number of extra emptyings are not equal, an **unbalanced round**; we call a round that is not unbalanced a **balanced round**.

Note that there are clearly at most  $E + S$  unbalanced rounds. We now associate some unbalanced rounds with balanced rounds; in particular we define what it means for a balanced round to **cancel** an unbalanced round. We define cancellation by a sequential process. For  $i = 1, 2, \dots, 2(R + \lceil(1 + 1/n)(E + S)\rceil)$  (iterating in ascending order of  $i$ ), if round  $i$  is unbalanced then we say that the first balanced round  $j > i$  that hasn't already been assigned (earlier in the sequential process) to cancel another unbalanced round  $i' < i$ , if any such round  $j$  exists, **cancels** round  $i$ . Note that cancellation is a one-to-one relation: each unbalanced round is cancelled by at most one balanced round and each balanced round cancels at most one unbalanced round.

Consider rounds of the form  $2(R + \lceil(E + S)/n\rceil) + (E + S) + i$  for  $i \in [E + S + 1] - 1$ . We claim that there is some such  $i$  such that among rounds  $[2(R + \lceil(E + S)/n\rceil) + (E + S) + i]$  every unbalanced round has been cancelled, and such that there are  $2(R + \lceil(E + S)/n\rceil)$  balanced rounds not cancelling other rounds. Assume for contradiction that such an  $i$  does not exist. Note that there are at least  $2(R + \lceil(E + S)/n\rceil)$  balanced rounds in the first  $2(R + \lceil(E + S)/n\rceil) + (S + E)$  rounds. Thus every balanced round  $2R + (E + S) + \lceil(E + S)/n\rceil + i - 1$  for  $i \in [E + S + 1]$  is necessarily a cancelling round, or else there would be a round by which there are no uncanceled unbalanced rounds. Hence by round  $2(R + \lceil(E + S)/n\rceil) + 2(E + S)$ , there must have been  $E + S$  cancelled rounds, so on round  $2(R + \lceil(E + S)/n\rceil) + 2(E + S)$  all unbalanced rounds are cancelled, which leaves  $2(R + \lceil(E + S)/n\rceil)$  balanced rounds that are not cancelling any rounds, as desired.

Let  $t_e$  be the first round by which there are  $2(R + \lceil(E + S)/n\rceil)$  balanced non-cancelling rounds. Note that the average fill of the cups cannot have decreased by more than  $E/n$  from its starting value; similarly the average fill of the cups cannot have increased by more than  $S/n$ . Because the cups start  $R$ -flat, we have that  $u_t$  cannot have decreased by more than  $R + E/n$  or else  $u_t$  would necessarily be below the average fill, and identically  $\ell_t$  cannot have increased by more than  $R + S/n$  or else it would be above the average fill. Now, by Claim 10 we have that eventually  $|L_t| > n/2$ : if  $|L_t| \leq n/2$  were always true, then on every balanced round  $\ell_t$  would have increased by  $1/2$ , and since  $\ell_t$  increases by at most  $1/2$  on unbalanced rounds, this implies that in total  $\ell_t$  would have increased by at least  $(1/2)2(R + \lceil(E + S)/n\rceil)$ , which is impossible. By a symmetric argument it is impossible that  $|U_t| \leq n/2$  for all rounds.

Since  $|U_{t+1}| \geq |U_t|$  and  $|L_{t+1}| \geq |L_t|$  by Claim 9, we have that there is some round  $t_0 \in [2(R + \lceil(1 + 1/n)(E + S)\rceil)]$  such that for all  $t \geq t_0$  we have  $|U_t| > n/2$  and  $|L_t| > n/2$ . But then we have  $U_t \cap L_t \neq \emptyset$ , as desired.  $\square$

If there exists a cup  $c \in L_t \cap U_t$ , then

$$\text{fill}(c) \in [u_t - 2 - \Delta, u_t] \cap [\ell_t, \ell_t + 2 + \Delta].$$

Hence we have that

$$\ell_t + 2 + \Delta \geq u_t - 2 - \Delta.$$

Rearranging,

$$u_t - \ell_t \leq 2(2 + \Delta) = R_\Delta.$$

Thus the cup configuration is  $R_\Delta$ -flat by the end of this flattening process.  $\square$

Next we describe a simple oblivious filling strategy, that we call **randalg**, that will be used as a subroutine in Lemma 6; variants of this strategy are well-known, and similar versions of it can be found in [10, 16, 25].

**Proposition 5.** *Consider an  $R$ -flat cup configuration in the regular single-processor  $\infty$ -extra-emptyings  $\infty$ -skip-emptyings negative-fill cup game on  $n$  cups with initial average fill  $\mu_0$ . Let  $k \in [n]$  be a parameter. Let  $d = \sum_{i=2}^k 1/i$ .*

*There is an oblivious filling strategy **randalg**( $k$ ) with running time  $k - 1$  that achieves fill at least  $\mu_0 - R + d$  in a known cup  $c$  with probability at least  $1/k!$  if we condition on the emptier not performing extra emptyings. **randalg**( $k$ ) achieves fill at most  $\mu_0 + R + d$  in this cup (unconditionally).*

*Furthermore, when applied against a  $\Delta$ -greedy-like emptier with  $R = R_\Delta$ , **randalg**( $k$ ) guarantees that the cup configuration is  $(R + d)$ -flat on every round (unconditionally).*

*Proof.* First we condition on the emptier does not using extra emptying and show that in this case the filler has probability at least  $1/(k - 1)!$  (which we lower bound by  $1/k!$  for sake of simplicity) of attaining a cup with fill at least  $\mu_0 - R + d$ . The filler maintains an **active set**, initialized to being an arbitrary subset of  $k$  of the cups. Every round the filler distributes 1 unit of fill equally among all cups in the active set. Next the emptier removes 1 unit of fill from some cup, or skips its emptying. Then the filler removes a random cup from the active set (chosen uniformly at random from the active set). This continues until a single cup  $c$  remains in the active set.

We now bound the probability that  $c$  has never been emptied from. Assume that on the  $i$ -th step of this process, i.e. when the size of the active set is  $n - i + 1$ , no cups in the active set have ever been emptied from; consider the probability that after the filler removes a cup randomly from the active set there are still no cups in the active set that the emptier has emptied from. If the emptier skips its emptying on this round, or empties from a cup not in the active set then it is trivially still true that no cups in the active set have been emptied from. If the cup that the emptier empties from is in the active set then with probability  $1/(k - i + 1)$  it is evicted from the active set, in which case we still have that no cup in the active set has ever been emptied from. Hence with probability at least  $1/(k - 1)!$  the final cup in the active set,  $c$ , has never been emptied from. In this case,  $c$  will have gained fill  $d = \sum_{i=2}^k 1/i$  as claimed. Because  $c$  started with fill at least  $-R + \mu_0$ ,  $c$  now has fill at least  $-R + d + \mu_0$ .

Now note that regardless of if the emptier uses extra emptyings  $c$  has fill at most  $\mu_0 + R + d$ , as  $c$  starts with fill at most  $R$ , and  $c$  gains at most  $1/(k - i + 1)$  fill on the  $i$ -th round of this process.

Now we analyze this algorithm specifically for a  $\Delta$ -greedy-like emptier. Let  $\mathcal{A}_t$  be the event that the anti-backlog is smaller in  $S_{t+1}$  than in  $S_t$ , let  $\mathcal{B}_t$  be the event that some cup with fill equal to the backlog in  $S_{t+1}$  was emptied from on round  $t$ . If  $\mathcal{A}_t$  and  $\mathcal{B}_t$  are both true on round  $t$ , then by greediness the cups are quite flat. In particular, let  $a$  be a cup with fill equal to the anti-backlog in state  $S_{t+1}$  that was emptied from on round  $t$ , and let  $b$  be a cup with fill equal to the backlog in state  $S_{t+1}$  that was not emptied from on round  $t$ . By greediness  $\text{fill}_{I_t}(a) + \Delta > \text{fill}_{I_t}(b)$ . Of course  $\text{fill}_{I_t}(b) = \text{fill}_{S_{t+1}}(b)$ ; for  $b$  to have fill equal to the backlog on round  $t + 1$ ,  $b$  must have fill less than 1 below backlog on round  $t$ . Of course  $\text{fill}_{I_t}(a) \leq \text{fill}_{S_t}(a) + 1$ ; for  $a$  to have fill equal to the anti-backlog on round  $t + 1$ ,  $a$  must have fill less than 1 above the anti-backlog on round  $t$ . Thus we have that the backlog and anti-backlog differ by at most  $\Delta + 3 \leq R_\Delta$  on round  $t$ , i.e. the cups are  $R_\Delta$ -flat.

Consider a round  $t_1$  where the cups are not  $R_\Delta$ -flat. Let  $t_0$  be the last round that the cups were  $R_\Delta$ -flat. On all rounds  $t \in (t_0, t_1)$  at least one of  $\mathcal{A}_t$  or  $\mathcal{B}_t$  must not hold. On a round where  $\mathcal{A}_t$  does not hold, anti-backlog does not decrease and backlog increases by at most  $1/(k - t + 1)$ , so fill range increases by at most  $1/(k - t + 1)$ . On a round where  $\mathcal{B}_t$  does not hold, anti-backlog decreases by at most 1 and backlog decreases by at least  $1 - 1/(k - t + 1)$ , as all cups with fill equal to the backlog in state  $S_{t+1}$  were emptied from on round  $t$ , so fill-range increases by at most  $1/(k - t + 1)$ . Hence in total fill-range increases by at most  $\sum_{i=2}^k 1/i$  from  $R$ , i.e. the cups are  $(R + d)$ -flat on round  $t_1$ .  $\square$

We now give a method for transforming a filling strategy for achieving large backlog into a filling strategy for achieving high fill in many cups, or high average fill in a set of cups (which of these we guarantee depends on the original filling strategy). The idea of repeating an algorithm many times is also used in the proof of the Adaptive Amplification Lemma; the construction is slightly more complicated in the randomized case however, and is much harder to analyze.

**Definition 2.** Let  $\text{alg}_0$  be an oblivious filling strategy, that can get high fill (for some definition of high) in some cup against greedy-like emptiers with some probability. We construct a new filling strategy  $\text{rep}_\delta(\text{alg}_0)$  (rep stands for “repetition”) as follows:

Say we have some configuration of  $n$  cups. Let  $n_A = \lceil \delta n \rceil, n_B = \lfloor (1 - \delta)n \rfloor$ . Let  $N \gg n$  be large, let  $M = 2^{\text{polylog}(N)}$  be a chosen parameter. Initialize  $A$  to  $\emptyset$  and  $B$  to being all of the cups. We call  $A$  the **anchor set** and  $B$  the **non-anchor set**. The filler always places 1 unit of fill in each anchor cup on each round. The filling strategy consists of  $n_A$  **donation-processes**, which are procedures that result in a cup being **donated** from  $B$  to  $A$  (i.e. removed from  $B$  and added to  $A$ ). At the start of each donation-process the filler chooses a value  $m_0$  uniformly at random from  $[M]$ . We say that the filler **applies** a filling strategy  $\text{alg}$  to  $B$  if the filler uses  $\text{alg}$  on  $B$  while placing 1 unit of fill in each anchor cup. During the donation-process the filler applies  $\text{alg}_0$  to  $B$   $m_0$  times, and flattens  $B$  by applying  $\text{flatalg}$  to  $B$  for  $\Theta(N^2)$  rounds before each application of  $\text{alg}_0$ . At the end of each donation process the filler takes the cup given by the final application of  $\text{alg}_0$  (i.e. the cup that  $\text{alg}_0$  guarantees with some probability against a certain class of emptiers to have a certain high fill), and donates this cup to  $A$ .

We give pseudocode for this algorithm in Algorithm 2.

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**Algorithm 2**  $\text{rep}_\delta(\text{alg}_0)$

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**Input:**  $\text{alg}_0, \delta, N, M$ , set of  $n$  cups

**Output:** Guarantees on the sets  $A, B$  (will vary based on  $\text{alg}_0$ )

---

$n_A \leftarrow \lceil \delta n \rceil, n_B \leftarrow \lfloor (1 - \delta)n \rfloor$

$A \leftarrow \emptyset, B \leftarrow$  all the cups

Always place 1 fill in each cup in  $A$

**for**  $i \in [n_A]$  **do**

▷ Donation-Processes

$m_0 \leftarrow \text{random}([M])$

**for**  $j \in [m_0]$  **do**

Apply  $\text{flatalg}$  to  $B$  for  $\Theta(N^2)$  rounds

Apply  $\text{alg}_0$  to  $B$

Donate the cup given by  $\text{alg}_0$  from  $B$  to  $A$

---

We say that the emptier **neglects** the anchor set on a round if it does not empty from each anchor cup. We say that an application of  $\text{alg}_0$  to  $B$  is **non-emptier-wasted** if the emptier does not neglect the anchor set during any round of the application of  $\text{alg}_0$ .

We use the idea of repeating an algorithm in two different contexts. First in Proposition 6 we prove a result analogous to that of Proposition 3: in particular, we show that we can achieve constant fill in a known cup by using  $\text{rep}_{\Theta(1)}(\text{randalg}(\Theta(1)))$  which achieves, by a Chernoff bound,  $\Theta(n)$  unknown cups with constant fill, and then exploiting the emptier’s greedy-like nature to achieve constant fill in a known cup. After doing this, we prove the **Oblivious Amplification Lemma**, a result analogous to the Adaptive Amplification Lemma: in particular, we show how to take an algorithm for achieving some backlog, and then achieve higher backlog by repeating the algorithm many times. Although these results have deterministic analogues, their proofs are different and significantly more complex than the proofs for the deterministic cases.

In the rest of the section our aim is to achieve backlog  $N^{1-\varepsilon}$  in  $N$  cups. We will use this value  $N$  within all of the following proofs. Many values implicitly depend on  $N$ . Note that we implicitly consider the cups to be part of a larger game in these results. Also note that we are happy if mass  $N^2$  is achieved in the cups, because then backlog is always at least  $N$ .

Before proving Proposition 6 we analyze  $\text{rep}_{\Theta(1)}(\text{randalg}(\Theta(1)))$  in Lemma 6.

**Lemma 7.** Let  $\Delta \leq O(1)$ , let  $h \leq O(1)$  with  $h \geq 16 + 16\Delta$ , let  $k = \lceil e^{2h+1} \rceil$ , let  $\delta = \Theta(e^{-2h})$ , let  $n$  be at least a sufficiently large constant determined by  $h$  and  $\Delta$ . Consider an  $R_\Delta$ -flat cup configuration in the variable-processor cup game on  $n$  cups with initial average fill  $\mu_0$ .

Against a  $\Delta$ -greedy-like emptier,  $\text{rep}_\delta(\text{randalg}(k))$  using  $M = \Theta(N^2)$  either achieves mass at least  $N^2$  in the cups, or with probability at least  $1 - 2^{-\Omega(n)}$  makes an (unknown) set of  $\Theta(n)$  cups in  $A$  have fill at least  $h + \mu_0$  while also guaranteeing that  $\mu(B) \geq -h/2 + \mu_0$ , where  $A, B$  are the sets defined in Definition 2. Furthermore,  $\text{rep}_\delta(\text{randalg}(k))$  has running time  $\text{poly}(N)$ .

*Proof.* We use the definitions given in Definition 2.

Without loss of generality we assume that the emptier does not neglect the anchor set more than  $N^2$  in any particular donation-process; if the emptier chooses to neglect the anchor set this much then the anchor cups will have achieved mass  $N^2$  so Lemma 6 is already fulfilled. Similarly we assume that the emptier does not choose to skip more than  $N^2$  emptyings; doing so clearly would result in mass at least  $N^2$  in the cups.

As in Proposition 5, we define  $d = \sum_{i=2}^k 1/i$ ; we remark that, because harmonic numbers grow like  $x \mapsto \ln x$ , it is clear that  $d = \Theta(h)$ . We say that an application of  $\text{randalg}(k)$  to  $D$  is **lucky** if it achieves backlog at least  $\mu_S(B) - R_\Delta + d$  where  $S$  denotes the state of the cups at the start of the application of  $\text{randalg}(k)$ ; note that by Proposition 5 if we condition on an application of  $\text{randalg}(k)$  where  $B$  started  $R_\Delta$ -flat being non-emptier-wasted then the application has at least a  $1/k!$  chance of being lucky.

Now we prove several important bounds satisfied by  $A$  and  $B$ .

**Claim 12.** *All applications of  $\text{flatlg}$  make  $B$  be  $R_\Delta$ -flat and  $B$  is always  $(R_\Delta + d)$ -flat.*

*Proof.* Given that the application of  $\text{flatlg}$  immediately prior to an application of  $\text{randalg}(k)$  made  $B$  be  $R_\Delta$ -flat, by Proposition 5 we have that  $B$  will stay  $(R_\Delta + d)$ -flat during the application of  $\text{randalg}(k)$ . Given that the application of  $\text{randalg}(k)$  immediately prior to an application of  $\text{flatlg}$  resulted in  $B$  being  $(R_\Delta + d)$ -flat, we have that  $B$  remains  $(R_\Delta + d)$ -flat throughout the duration of the application of  $\text{flatlg}$  by Lemma 5. Given that  $B$  is  $(R_\Delta + d)$ -flat before a donation occurs  $B$  is clearly still  $(R_\Delta + d)$ -flat after the donation, because the only change to  $B$  during a donation is that a cup is removed from  $B$  which cannot increase the fill-range of  $B$ . Note that  $B$  started  $R_\Delta$ -flat at the beginning of the first donation-process. Note that if an application of  $\text{flatlg}$  begins with  $B$  being  $(R_\Delta + d)$ -flat, then by considering the flattening to happen in the  $(|B|/2)$ -processor  $N^2$ -extra-emptyings  $N^2$ -skip-emptyings cup game we ensure that it makes  $B$  be  $R_\Delta$ -flat. Hence we have by induction that  $B$  has always been  $(R_\Delta + d)$ -flat and that all flattening processes have made  $B$  be  $R_\Delta$ -flat.  $\square$

Now we aim to show that  $\mu(B)$  is never very low, which we need in order to establish that every non-emptier-wasted lucky application of  $\text{randalg}(k)$  gets a cup with high fill. Interestingly, in order to lower bound  $\mu(B)$  we find it convenient to first upper bound  $\mu(B)$ , which by greediness and flatness of  $B$  gives an upper bound on  $\mu(A)$  which we then use to get a lower bound on  $\mu(B)$ .

**Claim 13.** *We have always had*

$$\mu(B) \leq \mu(AB) + 2.$$

*Proof.* There are two ways that  $\mu(B) - \mu(AB)$  can increase:

**Case 1:** The emptier could empty from 0 cups in  $B$  while emptying from every cup in  $A$ .

**Case 2:** The filler could evict a cup with fill lower than  $\mu(B)$  from  $B$  at the end of a donation-process.

Note that cases are exhaustive, in particular note that if the emptier skips more than 1 emptying then  $\mu(B) - \mu(AB)$  must decrease because  $|B| > |AB|/2$ , as opposed to in Case 1 where  $\mu(B) - \mu(AB)$  increases.

In Case 1, because the emptier is  $\Delta$ -greedy-like,

$$\min_{a \in A} \text{fill}(a) > \max_{b \in B} \text{fill}(b) - \Delta.$$

Thus  $\mu(B) \leq \mu(A) + \Delta$ . We can use this to get an upper bound on  $\mu(B) - \mu(AB)$ . We have,

$$\begin{aligned} \mu(B) &= \frac{\mu(AB)|AB| - \mu(A)|A|}{|B|} \\ &\leq \frac{\mu(AB)|AB| - (\mu(B) - \Delta)|A|}{|B|}. \end{aligned}$$

Rearranging terms:

$$\mu(B) \left( 1 + \frac{|A|}{|B|} \right) \leq \frac{\mu(AB)|AB| + \Delta|A|}{|B|}.$$

Now, because  $|A| \cdot \Delta \leq n_A \cdot \Delta < n$  (by our choice of  $\delta$  to be a very small constant), we have

$$\mu(B) \frac{|AB|}{|B|} \leq \frac{\mu(AB)|AB| + n}{|B|}.$$

Isolating  $\mu(B)$  we have

$$\mu(B) \leq \mu(AB) + 1.$$

Consider the final round on which  $B$  is skipped while  $A$  is not skipped (or consider the first round if there is no such round).

From this round onwards the only increase to  $\mu(B) - \mu(AB)$  is due to  $B$  evicting cups with fill well below  $\mu(B)$ . We can upper bound the increase of  $\mu(B) - \mu(AB)$  by the increase of  $\mu(B)$  as  $\mu(AB)$  is strictly increasing.

The cup that  $B$  evicts at the end of a donation-process has fill at least  $\mu(B) - R_\Delta - (k - 1)$ , as the running time of  $\text{randalg}(k)$  is  $k - 1$ , and because  $B$  starts  $R_\Delta$ -flat by Claim 12. Evicting a cup with fill  $\mu(B) - R_\Delta - (k - 1)$  from  $B$  changes  $\mu(B)$  by  $(R_\Delta + k - 1)/(|B| - 1)$  where  $|B|$  is the size of  $B$  before the cup is evicted from  $B$ . Even if this happens on each of the  $n_A$  donation-processes  $\mu(B)$  cannot rise higher than  $n_A(R_\Delta + k - 1)/(n - n_A)$  which by design in choosing  $n_B \gg n_A$ , as was done in choosing  $\delta = \Theta(e^{-2h})$ , is at most 1.

Thus  $\mu(B) \leq \mu(AB) + 2$  is always true. □

Now, the upper bound on  $\mu(B) - \mu(AB)$  along with the guarantee that  $B$  is flat allows us to bound the highest that a cup in  $A$  could rise by greediness, which in turn upper bounds  $\mu(A)$  which in turn lower bounds  $\mu(B)$ .

**Claim 14.** *We always have*

$$\mu(B) \geq -h/2 + \mu_0.$$

*Proof.* By Claim 13 and Claim 12 we have that no cup in  $B$  ever has fill greater than  $u_B = \mu(AB) + 2 + R_\Delta + d$ . Let  $u_A = u_B + \Delta + 1$ . We claim that the backlog in  $A$  never exceeds  $u_A$ . Note that  $\mu(AB)$ ,  $u_A$ ,  $u_B$  are implicitly functions of the round;  $\mu(AB)$  can increase from  $\mu_0$  if the emptier skips emptyings.

Consider how high the fill of a cup  $c \in A$  could be. If  $c$  came from  $B$  then when it is donated to  $A$  its fill is at most  $u_B$ ; otherwise,  $c$  started with fill at most  $R_\Delta$ . Both of these expressions are less than  $u_A - 1$ . Now consider how much the fill of  $c$  could increase while being in  $A$ . Because the emptier is  $\Delta$ -greedy-like, if a cup  $c \in A$  has fill more than  $\Delta$  higher than the backlog in  $B$  then  $c$  must be emptied from, so any cup with fill at least  $u_B + \Delta = u_A - 1$  must be emptied from, and hence  $u_A$  upper bounds the backlog in  $A$ .

Of course an upper bound on backlog in  $A$  also serves as an upper bound on the average fill of  $A$  as well, i.e.  $\mu(A) \leq u_A$ . Now we have

$$\begin{aligned} \mu(B) &= -\frac{|A|}{|B|}\mu(A) + \frac{|AB|}{|B|}\mu(AB) \\ &\geq -(\mu(AB) + 3 + R_\Delta + d + \Delta)\frac{|A|}{|B|} + \frac{|AB|}{|B|}\mu(AB) \\ &= -(3 + R_\Delta + d + \Delta)\frac{|A|}{|B|} + \mu(AB) \\ &\geq -h/2 + \mu(AB) \end{aligned}$$

where the final inequality follows because  $\mu(AB) \geq 0$ , and  $|B| \gg |A|$ , in particular by our choice of  $\delta = \Theta(e^{-2h})$ . Of course  $\mu(AB) \geq \mu_0$  so we have

$$\mu(B) \geq -h/2 + \mu_0. \quad \square$$

Now we show that at least a constant fraction of the donation-processes succeed with exponentially good probability.



**Claim 15.** *By choosing  $M = \Theta(N^2)$  the filler can guarantee that with probability at least  $1 - 2^{-\Omega(n)}$ , the filler achieves fill at least  $h + \mu_0$  in  $\Theta(n)$  of the cups in  $A$ .*

*Proof.* If the emptier was not allowed to neglect the anchor set ever then the claim would clearly be true as each application of  $\text{randalg}(k)$  would simply succeed with constant probability, so a Chernoff bound would give that  $\Theta(n)$  of the donation-processes donate a cup with fill at least  $\mu(B) - R_\Delta + d \geq h + \mu_0$ , where the inequality follows from Claim 14 which asserts that  $\mu(B) \geq -h/2 + \mu_0$ , and from the facts  $d \geq 2h$  and  $h \geq 16(1 + \Delta)$ .

However, the emptier is allowed to neglect the anchor set, and worse, the emptier can choose to neglect the anchor set conditional on the filler's progress during  $\text{randalg}(k)$ ! However, by applying  $\text{randalg}(k)$  a random number of times, chosen from  $[M]$  (where  $M = \Theta(N^2)$ ), we guarantee that with exponentially good probability in  $M$  the filler succeeds many times, in particular  $\Theta(N^2)$  times. But since the emptier cannot neglect the anchor set more than  $N^2$  times, by appropriately large choice of  $M$  we can make it so that the filler succeeds at least  $2N^2$  times with exponentially good probability. Then the emptier would have at best a  $1/2$  chance of preventing the donation-process from giving away a cup with fill  $h + \mu_0$  whenever one such cup is achieved. We now formalize this reasoning.

We can lower bound the probability of getting  $\Theta(n)$  cups with fills all at least  $h + \mu_0$  by considering an augmented emptier that is allowed to *interfere* with  $N^2$  applications of  $\text{randalg}(k)$  per donation-process that only interferes with applications of  $\text{randalg}(k)$  that would otherwise donate a cup with fill at least  $h + \mu_0$  into  $A$ ; if this (augmented) emptier interferes with an application of  $\text{randalg}(k)$  then the application is *emptier-wasted*, i.e. we assume no guarantees on the fill it achieved. The optimal strategy for such an emptier, for the goal of maximizing the probability that the final round in a donation-process is interfered with, given our filler's strategy of randomly choosing how many times to apply  $\text{randalg}(k)$  before donating a cup, is obviously to interfere with the first  $N^2$  applications of  $\text{randalg}(k)$  that would have achieved a cup with fill  $h + \mu_0$  without interference.

Let  $M = 4N^2k!$ ; note that as stated previously we choose  $M = \Theta(N^2)$ . Recall that conditional on the emptier not interfering, each of these applications of  $\text{randalg}(k)$  has at least a  $1/k!$  chance of getting a cup with fill  $h$ . Hence, by a Chernoff bound with exponentially good probability in  $M$  at least  $2N^2$  of the  $M$  applications of  $\text{randalg}(k)$  have the potential to donate a cup with fill  $h + \mu_0$  to  $A$ , if the emptier does not interfere. The filler chooses an application uniformly at random from  $[M]$  on which to donate a cup. With probability at least  $1/k!$  this is on an application where the filler could get a cup with fill  $h + \mu_0$  in  $A$  if the emptier does not interfere, and with probability at least  $1/2$  the emptier does not interfere on this application of  $\text{randalg}(k)$ , because the emptier can interfere on at most  $N^2$  of the applications of  $\text{randalg}(k)$ .

Against this augmented emptier whether or not donation-processes achieve a cup with fill  $h + \mu_0$  in  $A$  are independent events. As each happens with at least constant probability, by a Chernoff bound there is exponentially high probability that at least a constant fraction of them succeed.

Note that we used a Chernoff bound in two distinct places: (a) in guaranteeing that each donation-process consists of at least  $2N^2$  applications of  $\text{randalg}(k)$  that would donate a cup with fill  $\mu_0 + h$  if the emptier did not interfere, and (b) in guaranteeing that a constant fraction of the donation-processes succeed given that their successes are independent and all happen with constant probability. The Chernoff bound in (a) is actually with exponentially good probability in  $M \gg n$ , but of course also holds with exponentially good probability in  $n$ . Then we can take a union bound over  $\text{poly}(n)$  events that all occur with exponentially good probability in  $n$ , which gives still gives exponentially good probability in  $n$  that all of the desired events occur.

The described augmented emptier is clearly strictly more powerful than the real emptier, so the result transfers over.  $\square$

We now analyze the running time of the filling strategy. There are  $n_A$  donation-processes. Each donation-process consists of  $O(M)$  applications of  $\text{randalg}(k)$ , which each take time  $O(1)$ , and  $O(M)$  applications of  $\text{flatalg}$ , which each take  $\Theta(N^2)$  time. Thus overall the algorithm takes time

$$n_A \cdot O(M)(O(1) + O(N^2)) = \text{poly}(N),$$

as desired.  $\square$

Now, using Lemma 6 we show in Proposition 6 that an oblivious filler can achieve constant fill in a known cup.

**Proposition 6.** *Let  $H \leq O(1)$ , let  $\Delta \leq O(1)$ , let  $n \ll N$  be at least a sufficiently large constant determined by  $H$  and  $\Delta$ . Consider an  $R_\Delta$ -flat cup configuration in the variable-processor cup game on  $n$  cups with average fill  $\mu_0$ . There is an oblivious filling strategy that either achieves mass  $N^2$  among the cups, or achieves fill at least  $\mu_0 + H$  in a chosen cup in running time  $\text{poly}(N)$  against a  $\Delta$ -greedy-like emptier with probability at least  $1 - 2^{-\Omega(n)}$ .*

*Proof.* The filler starts by using  $\text{rep}_\delta(\text{randalg}(k))$  with parameter settings as in Lemma 6 where  $h = H \cdot 16(1 + \Delta)$ , i.e.  $k = \lceil e^{2h+1} \rceil$ ,  $\delta = \Theta(e^{-2h})$ . If this results in mass  $N^2$  among the cups we are done; we assume this is not the case for the rest of the proof. Let the number of cups which, with exponentially good probability in  $n$ , now exist by Lemma 6 with fill at least  $h + \mu_0$  be of size  $nc = \Theta(n)$ .

The filler sets  $p = 1$ , i.e. uses a single processor. Now the filler exploits the emptier's greedy-like nature to get fill  $H$  in a chosen cup  $c_0$ . Specifically, for  $(5/8)h$  rounds the filler places 1 unit of fill into  $c_0$ . Because the emptier is  $\Delta$ -greedy-like it must empty from the  $nc$  cups in  $A$  with fill at least  $h + \mu_0$  until  $c_0$  has large fill. Over  $(5/8)h$  rounds the cups in  $A$  cannot have their fill decrease below  $(3/8)h \geq h/8 + \Delta + \mu_0$ . Hence, any cups with fills less than  $h/8 + \mu_0$  must not be emptied from during these rounds. The fill of  $c_0$  started as at least  $-h/2 + \mu_0$  as  $\mu(B) \geq -h/2 + \mu_0$ . After  $(5/8)h$  rounds  $c_0$  has fill at least  $h/8 + \mu_0$ , because the emptier cannot have emptied  $c_0$  until it attained fill  $h/8 + \mu_0$ , and if  $c_0$  is never emptied from then it achieves fill  $h/8 + \mu_0$ . Thus the filling strategy achieves backlog  $h/8 + \mu_0 \geq H + \mu_0$  in  $c_0$ , a known cup, as desired.

The running time is of course still  $\text{poly}(N)$  by Lemma 6. □

Next we prove the **Oblivious Amplification Lemma**.

**Lemma 8** (Oblivious Amplification Lemma). *Let  $\delta \in (0, 1/2)$  be a constant parameter. Let  $\Delta \leq O(1)$ . Consider a cup configuration in the variable-processor cup game on  $n \leq N, n > \Omega(1/\delta^2)$  cups with average fill  $\mu_0$  that is  $R_\Delta$ -flat. Let  $\text{alg}(f)$  be an oblivious filling strategy that either achieves mass  $N^2$  or, with failure probability at most  $p \geq 2^{-\lg^8 N}$ , achieves backlog  $\mu_0 + f(n)$  on such cups in running time  $T(n)$  against a  $\Delta$ -greedy-like emptier. Let  $M = 2^{\text{polylog}(N)}$ .*

*Consider a cup configuration in the variable-processor cup game on  $n \leq N, n > \Omega(1/\delta^2)$  cups with average fill  $\mu_0$  that is  $R_\Delta$ -flat. There exists an oblivious filling strategy  $\text{alg}(f')$  that either achieves mass  $N^2$  or with failure probability at most*

$$p' \leq np + 2^{-\lg^8 N}$$

*achieves backlog  $f'(n)$  satisfying*

$$f'(n) \geq (1 - \delta)^2 f(\lfloor (1 - \delta)n \rfloor) + f(\lceil \delta n \rceil) + \mu_0$$

*and  $f'(n) \geq f(n)$ , in running time*

$$T'(n) \leq Mn \cdot T(\lfloor (1 - \delta)n \rfloor) + T(\lceil \delta n \rceil)$$

*against a  $\Delta$ -greedy-like emptier.*

*Proof.* We use the definitions and notation given in Definition 2.

Note that the emptier cannot neglect the anchor set more than  $N^2$  times per donation-process, and the emptier cannot skip more than  $N^2$  emptyings, without causing the mass of the cups to be at least  $N^2$ ; we assume for the rest of the proof that the emptier chooses not to do this.

The filler defaults to using  $\text{alg}(f)$  on all the cups if

$$f(n) \geq (1 - \delta)^2 f(n_B) + f(n_A).$$

In this case our strategy trivially has the desired guarantees. In the rest of the proof we consider the case where we cannot simply fall back on  $\text{alg}(f)$  to achieve the desired backlog.

The filler's strategy is roughly as follows:

**Step 1:** Make  $\mu(A) \geq (1 - \delta)^2 f(n_B)$  by using  $\text{rep}_\delta(\text{alg}(f))$  on all the cups, i.e. applying  $\text{alg}(f)$  repeatedly to  $B$ , flattening  $B$  before each application, and then donating a cup from  $B$  to  $A$ .

**Step 2:** Flatten  $A$  using  $\text{flatalg}$ , and then use  $\text{alg}(f)$  on  $A$ .

Now we analyze Step 1, and show that by appropriately choosing parameters it can be made to succeed.

For this proof we need all donation-processes to succeed, as opposed to in the proof of Lemma 6 in which we only needed a constant fraction of the donation-processes to succeed. This necessitates choosing

$M$  very large. In particular we choose  $M = 2^{\lg^{24} N}$ —recall that  $[M]$  is the set from which we randomly choose how many times to apply  $\text{alg}(f)$  in a donation-process. By choosing  $M$  this large we cannot hope to guarantee that every application of  $\text{alg}(f)$  succeeds: there are far too many applications. On the other hand, having  $M$  so large allows us to have a very tight concentration bound on how many applications of  $\text{alg}(f)$  succeed. Ignoring for a moment the fact that the emptier can choose to neglect the anchor set, i.e. assuming that no applications of  $\text{alg}(f)$  are emptier-wasted, the probability that fewer than  $M \cdot (1 - 2p)$  applications of  $\text{alg}(f)$  succeed is at most

$$e^{-2Mp^2}$$

by a Chernoff bound. The emptier is allowed to interfere, i.e. neglect the anchor set and do extra emptying in the non-anchor set, with at most  $N^2$  of the applications of  $\text{alg}(f)$ , thus if we condition on there being at least  $M(1 - 2p)$  applications that would succeed if the emptier does not interfere, there are at least  $M(1 - 2p) - N^2$  applications of  $\text{alg}(f)$  that succeed. Let  $\mathcal{W}$  be the event that the donation-process succeeds, i.e. the final application of  $\text{alg}(f)$  is not emptier-wasted and succeeds, and let  $\mathcal{D}$  be the event that the event that at least  $M(1 - 2p)$  of the  $M$  applications of  $\text{alg}(f)$  would succeed without interference by the emptier. Let  $1 - q = \Pr[\mathcal{W}]$ . Obviously

$$\Pr[\mathcal{W}] \geq \Pr[\mathcal{W} \wedge \mathcal{D}] = \Pr[\mathcal{D}] \cdot \Pr[\mathcal{W}|\mathcal{D}].$$

Because the filler chooses which application of  $\text{alg}(f)$  is the final application uniformly at random from  $[M]$  we thus have

$$1 - q \geq (1 - e^{-2Mp^2}) \left( \frac{M \cdot (1 - 2p) - N^2}{M} \right).$$

Rearranging, and over-estimating (i.e. dropping unnecessary terms to simplify the expression, while maintaining the truth of the expression), we have

$$q \leq e^{-2Mp^2} + 2p + \frac{N^2}{M}.$$

By assumption  $p \geq 2^{-\lg^8 N}$ , so  $Mp^2 \geq 2^{\lg^8 N}$ , and we have the bound

$$q \leq 2p + 2^{-2 \cdot 2^{\lg^8 N}} + \frac{N^2}{2^{\lg^{24} N}}.$$

We choose to loosen this to

$$q \leq 2p + 2^{-\lg^8 N}.$$

Taking a union bound we have that with failure probability at most  $q \cdot n_A$  all donation-process successfully achieve a cup with fill at least  $\mu_{S_0}(B) + f(n_B)$  where  $\mu_{S_0}(B)$  refers to the average fill of  $B$  measured at the start of the application of  $\text{alg}(f)$ ; now we assume all donation-processes are successful, and demonstrate that this translates into the desired average fill in  $A$ .

Let  $\text{skips}_t$  denote the number of times that the emptier has skipped the anchor set by round  $t$ . Consider how  $\mu(B) - \text{skips}/n_B$  changes over the course of the donation processes. As noted above, at the end of each donation-process  $\mu(B)$  decreases due to  $B$  donating a cup with fill at least  $\mu(B) + f(n_B)$ . In particular, if  $S$  denotes the cup state immediately before a cup is donated on the  $i$ -th donation-process,  $B_0$  denotes the set  $B$  before the donation and  $B_1$  denotes the set  $B$  after the donation, then  $\mu_S(B_1) = \mu_S(B_0) - f(n_B)/(n - i)$ . Now we claim that  $t \mapsto \mu_{S_t}(B) - \text{skips}_t/n_B$  is monotonically decreasing. Clearly donation decreases  $\mu(B) - \text{skips}/n_B$ . If the anchor set is neglected then  $\mu(B)$  decreases, causing  $\mu(B) - \text{skips}/n_B$  to decrease. If a skip occurs, then  $\text{skips}/n_B$  increases by more than  $\mu(B)$  increases, causing  $\mu(B) - \text{skips}/n_B$  to decrease. Let  $t_*$  be the cup state at the end of all the donation-processes. We have that

$$\mu_{S_{t_*}}(B) - \frac{\text{skips}_{t_*}}{n_B} \leq \mu_0 - \sum_{i=1}^{n_A} \frac{f(n_B)}{n - i}. \quad (17)$$

By conservation of mass we have

$$n_A \cdot \mu_{S_{t_*}}(A) + n_B \cdot \mu_{S_{t_*}}(B) = n\mu_0 + \text{skips}_{t_*}.$$

Rearranging,

$$\mu_{S_{t_*}}(A) = \mu_0 + \frac{n_B}{n_A} \left( \mu_0 + \frac{\text{skips}_{t_*}}{n_B} - \mu_{S_{t_*}}(B) \right). \quad (18)$$

Now we obtain a simpler form of Inequality (15). Let  $H_n$  denote the  $n$ -th harmonic number. We desire a simpler lower bound for

$$\sum_{i=1}^{n_A} \frac{1}{n-i} = H_{n-1} - H_{n_B-1}.$$

We use the well known fact that

$$\frac{1}{2(n+1)} < H_n - \ln n - \gamma < \frac{1}{2n} \quad (19)$$

where  $\gamma = \Theta(1)$  denotes the Euler-Mascheroni constant. Of course  $H_{n-1} - H_{n_B-1} \geq H_n - H_{n_B}$ . Now using Inequality (17) we have

$$\begin{aligned} H_n - H_{n_B} &> \left( \ln n + \gamma + \frac{1}{2(n+1)} \right) - \left( \ln n_B + \gamma + \frac{1}{2n_B} \right) \\ &> \ln \frac{1}{1-\delta} + \frac{1}{2} \left( \frac{n_B - n - 1}{(n+1)n_B} \right) \\ &> \delta - \Theta \left( \frac{\delta}{(1-\delta)n} \right). \end{aligned}$$

Now using this lower bound on  $H_n - H_{n_B}$  in Inequality (16) we have:

$$\begin{aligned} \mu_{t_*}(A) &> \mu_0 + \frac{n_B}{n_A} \left( \delta - \Theta \left( \frac{\delta}{(1-\delta)n} \right) \right) f(n_B) \\ &= \mu_0 + \frac{\lfloor (1-\delta)n \rfloor}{\lceil \delta n \rceil} \left( \delta - \Theta \left( \frac{\delta}{(1-\delta)n} \right) \right) f(n_B) \\ &> \mu_0 + \left( \frac{1-\delta}{\delta} - \frac{1}{\delta^2 n} \right) \left( \delta - \Theta \left( \frac{\delta}{(1-\delta)n} \right) \right) f(n_B) \\ &> \mu_0 + ((1-\delta) - \Theta(1/(\delta n))) f(n_B). \end{aligned}$$

Thus, by choosing  $n > \Omega(1/\delta^2)$  we have

$$\mu_{t_*}(A) > \mu_0 + (1-\delta)^2 f(n_B).$$

We have shown that in Step 1 the filler achieves average fill  $\mu_0 + (1-\delta)f(n_B)$  in  $A$  with failure probability at most  $q \cdot n_A$ . Now the filler flattens  $A$  and uses  $\text{alg}(f)$  on  $A$ . It is clear that this is possible, and succeeds with probability at least  $p$ . This gets a cup with fill

$$\mu_0 + (1-\delta)^2 f(n_B) + f(n_A)$$

in  $A$ , as desired.

Taking a union bound over the probabilities of Step 1 and Step 2 succeeding gives that the entire procedure fails with probability at most

$$p' \leq p + q \cdot n_A \leq np + 2^{-\lg^8 N}.$$

The running time of Step 1 is clearly  $M \cdot n \cdot T(\lfloor (1-\delta)n \rfloor)$  and the running time of Step 2 is clearly  $T(\lceil \delta n \rceil)$ ; summing these yields the desired upper bound on running time.  $\square$

Finally we prove that an oblivious filler can achieve backlog  $N^{1-\varepsilon}$ , just like an adaptive filler despite the oblivious filler's disadvantage. The proof is very similar to the proof of Theorem 2, but more complicated because in the oblivious case we must guarantee that the result holds with good probability, and also more complicated because the Oblivious Amplification Lemma is more complicated than the Adaptive Amplification Lemma.

**Theorem 7.** *There is an oblivious filling strategy for the variable-processor cup game on  $N$  cups that achieves backlog at least  $\Omega(N^{1-\varepsilon})$  for any constant  $\varepsilon > 0$  in running time  $2^{\text{polylog}(n)}$  with probability at least  $1 - 2^{-\text{polylog}(n)}$  against a  $\Delta$ -greedy-like emptier with  $\Delta \leq O(1)$ .*

*Proof.* We aim to achieve backlog  $(N/n_b)^{1-\varepsilon} - 1$  for some  $n_b \leq \text{polylog}(N)$  on  $N$  cups. Let  $\delta$  be a constant, chosen as a function of  $\varepsilon$ .

By Proposition 6 there is an oblivious filling strategy that achieves backlog  $\Omega(1)$  on  $n$  cups with exponentially good probability in  $n$ ; we call this algorithm  $\text{alg } f_0$ . However, unlike in the proof of Theorem 2, we obviously cannot use the base case with a constant number of cups: doing so would completely destroy our probability of success. Because the running time of our algorithm will be  $2^{\text{polylog}(N)}$ , we will be required to take a union bound over  $2^{\text{polylog}(N)}$  events. By making the size of our base case  $n_b = \log^8(N)$  we get that the probability of the algorithm failing in the base case is at most  $2^{-\log^8(N)}$ . By Proposition 6  $\text{alg } f_0$  achieves backlog  $f_0(k) \geq H \geq \Omega(1)$  for all  $k \geq n_b$ , for some constant  $H \geq \Omega(1)$  to be determined ( $H$  is a function of  $\delta$ ).

We construct  $f_{i+1}$  as the amplification of  $f_i$  using Lemma 7.

Define a sequence  $g_i$  as

$$g_i = \begin{cases} n_b \lceil 16/\delta \rceil, & i = 0 \\ \lfloor g_{i-1}/(1-\delta) \rfloor, & i \geq 1 \end{cases}.$$

We claim the following regarding our construction:

**Claim 16.**

$$f_i(k) \geq (k/n_b)^{1-\varepsilon} - 1 \text{ for all } k \leq g_i. \quad (20)$$

*Proof.* We prove Claim 16 by induction on  $i$ .

When  $i = 0$ , the base case of our induction, (18) is trivially true as  $(k/n_b)^{1-\varepsilon} - 1 \leq H$  by definition of  $H$  for  $k \leq g_0$ .

Assume (18) for  $f_i$ , consider  $f_{i+1}$ .

Note that, by design of  $g_i$ , if  $k \leq g_{i+1}$  then  $\lfloor k \cdot (1-\delta) \rfloor \leq g_i$ . Consider any  $k \in [g_{i+1}]$ .

First we deal with the trivial case where  $k \leq g_0$ . In this case

$$f_{i+1}(k) \geq f_i(k) \geq \dots \geq f_0(k) \geq (k/n_b)^{1-\varepsilon} - 1.$$

Now we consider  $k \geq g_0$ . Note that in this case  $\lfloor (1-\delta)k \rfloor \geq n_b$ . Since  $f_{i+1}$  is the amplification of  $f_i$ , and  $k$  is sufficiently large, we have by Lemma 7 that

$$f_{i+1}(k) \geq (1-\delta)^2 f_i(\lfloor (1-\delta)k \rfloor) + f_i(\lceil \delta k \rceil).$$

By our inductive hypothesis, which applies as  $\lceil \delta k \rceil \leq g_i$ ,  $\lfloor k \cdot (1-\delta) \rfloor \leq g_i$ , we have

$$f_{i+1}(k) \geq (1-\delta)^2 (\lfloor (1-\delta)k/n_b \rfloor^{1-\varepsilon} - 1) + \lceil \delta k/n_b \rceil^{1-\varepsilon} - 1.$$

Dropping the floor and ceiling, incurring a  $-1$  for dropping the floor, we have

$$f_{i+1}(k) \geq (1-\delta)^2 (((1-\delta)k/n_b - 1)^{1-\varepsilon} - 1) + (\delta k/n_b)^{1-\varepsilon} - 1.$$

Because  $(x-1)^{1-\varepsilon} \geq x^{1-\varepsilon} - 1$ , due to the fact that  $x \mapsto x^{1-\varepsilon}$  is a sub-linear sub-additive function, we have

$$f_{i+1}(k) \geq (1-\delta)^2 (((1-\delta)k/n_b)^{1-\varepsilon} - 2) + (\delta k/n_b)^{1-\varepsilon} - 1.$$

Moving the  $(k/n_b)^{1-\varepsilon}$  to the front we have

$$f_{i+1}(k) \geq (k/n_b)^{1-\varepsilon} \cdot \left( (1-\delta)^{3-\varepsilon} + \delta^{1-\varepsilon} - \frac{2(1-\delta)^2}{(k/n_b)^{1-\varepsilon}} \right) - 1.$$

Because  $(1-\delta)^{3-\varepsilon} \geq 1 - (3-\varepsilon)\delta$ , a fact called Bernoulli's Identity, we have

$$f_{i+1}(k) \geq (k/n_b)^{1-\varepsilon} \cdot \left( 1 - (3-\varepsilon)\delta + \delta^{1-\varepsilon} - \frac{2(1-\delta)^2}{(k/n_b)^{1-\varepsilon}} \right) - 1.$$

Of course  $-2(1-\delta)^2 > -2$ , so

$$f_{i+1}(k) \geq (k/n_b)^{1-\varepsilon} \cdot (1 - (3-\varepsilon)\delta + \delta^{1-\varepsilon} - 2/(k/n_b)^{1-\varepsilon}) - 1.$$

Because

$$\frac{-2}{(k/n_b)^{1-\varepsilon}} \geq \frac{-2}{(g_0/n_b)^{1-\varepsilon}} \geq -2(\delta/16)^{1-\varepsilon} \geq -\delta^{1-\varepsilon}/2,$$

which follows from our choice of  $g_0 = \lceil 8/\delta \rceil n_b$  and the restriction  $\varepsilon < 1/2$ , we have

$$f_{i+1}(k) \geq (k/n_b)^{1-\varepsilon} \cdot (1 - (3-\varepsilon)\delta + \delta^{1-\varepsilon} - \delta^{1-\varepsilon}/2) - 1.$$

Finally, combining terms we have

$$f_{i+1}(k) \geq (k/n_b)^{1-\varepsilon} \cdot (1 - (3-\varepsilon)\delta + \delta^{1-\varepsilon}/2) - 1.$$

Because  $\delta^{1-\varepsilon}$  dominates  $\delta$  for sufficiently small  $\delta$ , there is a choice of  $\delta = \Theta(1)$  such that

$$1 - (3-\varepsilon)\delta + \delta^{1-\varepsilon}/2 \geq 1.$$

Taking  $\delta$  to be this small we have,

$$f_{i+1}(k) \geq (k/n_b)^{1-\varepsilon} - 1,$$

completing the proof.  $\square$

The sequence  $g_i$  is  $n_b$  times the sequence  $g_i$  from the proof of Theorem 2; we thus have that  $g_{i_*} \geq N$  for some  $i_* \leq O(\log N)$ . Hence  $\text{alg } f_{i_*}$  achieves backlog

$$f_{i_*}(N) \geq (N/n_b)^{1-\varepsilon} - 1.$$

Let  $\varepsilon' = 2\varepsilon$ . Of course  $\Omega(N^\varepsilon) \geq \text{polylog}(N)$ , so

$$(N/n_b)^{1-\varepsilon} - 1 \geq \Omega(N^{1-\varepsilon'}).$$

Let the running time of  $f_i(N)$  be  $T_i(N)$ . From the Amplification Lemma we have following recurrence bounding  $T_i(N)$ :

$$\begin{aligned} T_i(n) &\leq 2^{\text{polylog}(N)} \cdot T_{i-1}(\lfloor (1-\delta)n \rfloor) + T_{i-1}(\lceil \delta n \rceil) \\ &\leq 2^{\text{polylog}(N)} T_{i-1}(\lfloor (1-\delta)n \rfloor). \end{aligned}$$

It follows that  $\text{alg } f_{i_*}$ , recalling that  $i_* \leq O(\log N)$ , has running time

$$T_{i_*}(n) \leq (2^{\text{polylog}(N)})^{O(\log N)} \leq 2^{\text{polylog}(N)}$$

as desired.

Now we analyze the probability that the construction fails. Consider the recurrence  $a_{i+1} = \alpha a_i + \beta$ ,  $a_0 = \gamma$ ; the recurrence bounding failure probability is a special case of this. Expanding, we see that the recurrence solves to  $a_k = \Theta(\alpha^{k-1})\beta + \alpha^k \gamma$ . In our case we have

$$\alpha \leq N, \beta = 2^{-\lg^8 N}, \gamma = 2^{-\lg^8 N}.$$

Hence the recurrence solves to

$$p_{i_*} \leq 2^{-\text{polylog}(N)},$$

as desired.  $\square$

## 7 Conclusion

We asked a natural question to extend understanding of the cup game: what if the resources of the players are variable? We found several shocking results, which combined demonstrate that having variable resources makes the cup game fundamentally changes the cup game.

More work remains to be done on the variable-processor cup game. Extending our oblivious lower bound on backlog to apply to a broader class of emptiers, rather than just greedy-like emptiers, is an interesting open question. Analyzing versions of the cup game with variable resources and resources augmentation is also an interesting open problem.

Our work suggests that looking at other scheduling problems in the context of variable resources is, surprisingly, a very interesting question.

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