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## 9. APPENDIX

### 9.1 Proof of Theorem 1

We first show that each of the 2 factors in the denominator of  $\phi(a_1, a_2)$  can be replaced by the corresponding truncated sum while affecting its value by at most  $1 + 1/C^2$ . Since the numerator is decreased by truncation, this establishes the upper bound on  $\phi'(a_1, a_2)$ . We then show that for the numerator of  $\phi(a_1, a_2)$ , the difference between the infinite sum and its truncated version is at most  $1/C$  times the first term in this sum. Since the denominator is decreased by truncation, this establishes the lower bound on  $\phi'$ .

To obtain the upper bound, we first consider the factor  $\sum_{k=a_1}^{\infty} \frac{\lambda^k}{k!} \binom{k}{a_1} (1-p_1)^{k-a_1}$  in the denominator. Expanding the binomial coefficient and pulling common terms outside the summation, this factor can be written as:

$$\frac{\lambda^{a_1}}{a_1!} \sum_{k \geq a_1} \frac{\lambda^{k-a_1} (1-p_1)^{k-a_1}}{(k-a_1)!} = \frac{\lambda^{a_1}}{a_1!} \sum_{k \geq 0} \frac{\lambda^k (1-p_1)^k}{k!}$$

Note that first term in this revised sum evaluates to 1, the term of index  $\ln C$  evaluates to  $\lambda^{\ln C} (1-p_1)^{\ln C} / (\ln C)! \ll \frac{1}{C^2}$ , and the sum of all terms from  $\ln C$  onward are at most  $\frac{\lambda^{\ln C} (1-p_1)^{\ln C} / (\ln C)!}{(1-\lambda)}$  (upper bounding the infinite sum with a geometric series). Since  $\lambda < 1/2$ , we conclude that the sum of all terms from index  $\ln C$  onward are less than  $1/C^2$  times the first term.

The truncated sum for the second factor in the denominator can be bounded identically, giving us the desired upper bound on  $\phi'(a_1, a_2)$ .

It remains only to establish the lower bound by bounding the truncated numerator. We assume without loss of generality that  $a_1 \geq a_2$ . Expanding the binomial coefficients in the definition of the numerator of  $\phi(a_1, a_2)$  and pulling common terms outside the summation, we can rewrite the numerator as:

$$\frac{\lambda_1^{a_1} (1-p_2)^{(a_1-a_2)}}{a_1! a_2!} \sum_{k \geq a_1} \frac{\lambda^{k-a_1} ((1-p_1)(1-p_2))^{k-a_1} \cdot k!}{(k-a_1)! (k-a_2)!}$$

The first term inside the revised sum is simply  $a_1! / (a_1 - a_2)! > 1$ . Let  $i$  denote the final index in the truncated sum,  $a_1 + \max\{\ln C, 2a_1\}$ . The  $i$ th term is upper bounded by  $\lambda^{i-a_1} \cdot \frac{i!}{(i-a_1)! (i-a_2)!}$ . If  $a_1 \geq 4$ , then since  $i \geq 3a_1$ , it is easy to see that  $\frac{i!}{(i-a_1)!^2} < 1/2$ . If  $a_1 \leq 4$ , then since  $i - a_1 \geq \ln C \geq 7$ , we can note that  $\frac{i!}{(i-a_1)!^2} < 1/2$ . As  $\lambda < 1/2$  and  $i > a_1 + \ln C$ , the  $i$ th term is less than  $1/C \cdot 1/2$ . Again upper bounding the infinite sum with a geometric series, the sum of all terms from index  $i$  onward is less than the  $i$ th term divided by  $(1-\lambda)$ , and hence  $< 1/C$ . Therefore, the sum of all terms from the  $i$ th term onward is less than  $1/C$  times the first term, completing the proof.

### 9.2 Proof of Lemma 2

Recall that in Lemma 2, we proved that  $E[\text{Score}(u, v, \ell, t)] \leq 0$  for any pair of users  $u, v$  such that  $v \neq \sigma_I(u)$ . For  $v = \sigma_I(u)$ , we showed that the expected score is lower bounded by:

$$\begin{aligned} & X(0, 0) \ln \frac{X(0, 0)}{Y(0, 0)} + (1 - X(0, 0)) \ln \frac{(1 - X(0, 0))}{(1 - Y(0, 0))} \\ &= X(0, 0) \ln \frac{X(0, 0)}{Y(0, 0)} - (1 - X(0, 0)) \ln \frac{(1 - Y(0, 0))}{(1 - X(0, 0))} \\ &\geq (1 - \lambda(p_1 + p_2 - p_1 p_2)) \lambda p_1 p_2 - \\ &\quad \lambda(p_1 + p_2 - p_1 p_2) \ln \frac{(1 - e^{-\lambda(p_1 + p_2)})}{(1 - e^{-\lambda(p_1 + p_2 - p_1 p_2)})} \end{aligned}$$

To prove that this expression is lower bounded by  $(\lambda p_1 p_2)^2 K$ , it suffices to prove that:

$$\begin{aligned} & (1 - \lambda(p_1 + p_2 - p_1 p_2)) \lambda p_1 p_2 - \\ & \lambda(p_1 + p_2 - p_1 p_2) \ln \frac{(1 - e^{-\lambda(p_1 + p_2)})}{(1 - e^{-\lambda(p_1 + p_2 - p_1 p_2)})} \\ & \geq (\lambda p_1 p_2)^2 K \end{aligned}$$

or equivalently:

$$\begin{aligned} & (1 - \lambda(p_1 + p_2 - p_1 p_2)) p_1 p_2 - \lambda(p_1 p_2)^2 K \\ & - (p_1 + p_2 - p_1 p_2) \ln \frac{(1 - e^{-\lambda(p_1 + p_2)})}{(1 - e^{-\lambda(p_1 + p_2 - p_1 p_2)})} \geq 0 \quad (2) \end{aligned}$$

We can simplify the final factor in this inequality as follows:

$$\begin{aligned} & \ln \frac{(1 - e^{-\lambda(p_1 + p_2)})}{(1 - e^{-\lambda(p_1 + p_2 - p_1 p_2)})} = \ln e^{-\lambda(p_1 p_2)} \frac{(e^{\lambda(p_1 + p_2)} - 1)}{(e^{\lambda(p_1 + p_2 - p_1 p_2)} - 1)} \\ &= \left( \ln \frac{(e^{\lambda(p_1 + p_2)} - 1)}{(e^{\lambda(p_1 + p_2 - p_1 p_2)} - 1)} \right) - \lambda p_1 p_2 \end{aligned}$$

where the first equality came from multiplying the numerator and denominator by  $e^{\lambda(p_1 + p_2 - p_1 p_2)}$ .

Substituting into Inequality (2), our lemma reduces to:

$$\begin{aligned} & (1 - \lambda(p_1 + p_2 - p_1 p_2)) p_1 p_2 - \lambda(p_1 p_2)^2 K \\ & (p_1 + p_2 - p_1 p_2) \left( \ln \frac{(e^{\lambda(p_1 + p_2)} - 1)}{(e^{\lambda(p_1 + p_2 - p_1 p_2)} - 1)} - \lambda p_1 p_2 \right) \geq 0 \end{aligned}$$

or, equivalently:

$$\begin{aligned} & p_1 p_2 (1 - \lambda(p_1 p_2) K) - \\ & (p_1 + p_2 - p_1 p_2) \ln \frac{(e^{\lambda(p_1 + p_2)} - 1)}{(e^{\lambda(p_1 + p_2 - p_1 p_2)} - 1)} \geq 0 \quad (3) \end{aligned}$$

This is hard to simplify directly, so we introduce the following upper bound:

$$\lambda p_1 p_2 = \ln \frac{1}{e^{-\lambda p_1 p_2}} = \ln \frac{e^{\lambda(p_1 + p_2)}}{e^{\lambda(p_1 + p_2 - p_1 p_2)}} \leq \ln \frac{e^{\lambda(p_1 + p_2)} - 1}{e^{\lambda(p_1 + p_2 - p_1 p_2)} - 1}$$

Using  $Z$  to represent the quantity  $\ln \frac{e^{\lambda(p_1 + p_2)} - 1}{e^{\lambda(p_1 + p_2 - p_1 p_2)} - 1}$  and substituting the new inequality in Inequality (3), we are try-

ing to prove:

$$\begin{aligned}
& p_1 p_2 (1 - ZK) - (p_1 + p_2 - p_1 p_2) Z \geq 0 \\
& \Leftrightarrow p_1 p_2 \geq (p_1 + p_2 - p_1 p_2 (1 - K)) Z \\
& \Leftrightarrow \frac{p_1 p_2}{p_1 + p_2 - p_1 p_2 (1 - K)} \geq Z \\
& \Leftrightarrow e^{\frac{p_1 p_2}{p_1 + p_2 - p_1 p_2 (1 - K)}} \geq \frac{e^{\lambda(p_1 + p_2)} - 1}{e^{\lambda(p_1 + p_2 - p_1 p_2)} - 1}
\end{aligned}$$

Now to conclude the proof we use two inequalities that follows from the Taylor expansions. In particular we have:

$$e^x \geq 1 + x + \frac{1}{2}x^2$$

and for  $x \in o(1)$ :

$$e^x \leq 1 + x + x^2$$

Now by assuming that  $\lambda \in o(1)$  and by fixing  $K = \frac{1}{2}\lambda(p_1 + p_2 - p_1 p_2)^2$  we get:

$$\begin{aligned}
& e^{\frac{p_1 p_2}{p_1 + p_2 - p_1 p_2 (1 - K)}} \geq \frac{e^{\lambda(p_1 + p_2)} - 1}{e^{\lambda(p_1 + p_2 - p_1 p_2)} - 1} \\
\Leftrightarrow & 1 + \frac{p_1 p_2}{p_1 + p_2 - p_1 p_2 + \frac{1}{2}\lambda(p_1 + p_2 - p_1 p_2)^2} + \\
& \frac{p_1^2 p_2^2}{2(p_1 + p_2 - p_1 p_2 + \frac{1}{2}\lambda(p_1 + p_2 - p_1 p_2)^2)^2} \geq \\
& \frac{\lambda(p_1 + p_2) + \lambda^2(p_1 + p_2)^2}{\lambda(p_1 + p_2 - p_1 p_2 + \frac{1}{2}\lambda(p_1 + p_2 - p_1 p_2)^2)} \\
\Leftrightarrow & 1 + \frac{p_1 p_2}{p_1 + p_2 - p_1 p_2 + \frac{1}{2}\lambda(p_1 + p_2 - p_1 p_2)^2} + \\
& \frac{p_1^2 p_2^2}{2(p_1 + p_2 - p_1 p_2 + \frac{1}{2}\lambda(p_1 + p_2 - p_1 p_2)^2)^2} \geq \\
& 1 + \frac{p_1 p_2 + \lambda(p_1 + p_2)^2}{p_1 + p_2 - p_1 p_2 + \frac{1}{2}\lambda(p_1 + p_2 - p_1 p_2)^2} \\
\Leftrightarrow & \frac{\frac{1}{2}p_1^2 p_2^2}{p_1 + p_2 - p_1 p_2 + \frac{1}{2}\lambda(p_1 + p_2 - p_1 p_2)^2} \geq \lambda(p_1 + p_2)^2
\end{aligned}$$

Now by fixing  $\lambda < \frac{1}{8} \frac{p_1^2 p_2^2}{(p_1 + p_2)^2}$  we get:

$$\begin{aligned}
& \frac{\frac{1}{2}p_1^2 p_2^2}{p_1 + p_2 - p_1 p_2 + \frac{1}{2}\lambda(p_1 + p_2 - p_1 p_2)^2} \geq \lambda(p_1 + p_2)^2 \\
\Leftrightarrow & \frac{\frac{1}{2}p_1^2 p_2^2}{p_1 + p_2 - p_1 p_2 + \frac{1}{16}p_1^2 p_2^2} \geq \frac{1}{8}p_1^2 p_2^2 \\
\Leftrightarrow & \frac{1}{4}p_1^2 p_2^2 \geq \frac{1}{8}p_1^2 p_2^2
\end{aligned}$$

So the claim follows.