7 Appendix: Proofs

Proof of Lemma 1.

Proof. Define

$$f_i(w_i) = \frac{du_i}{dw_i} = -T_i\psi'(T_i(1-w_i))\phi(S_{-i}) + \alpha_i q_i T_i \sum_{j\neq i} \frac{S_{-ij}}{(S_{-ij}+q_iT_iw_i)^2} T_j r_j$$

It's easy to see that $\frac{df_i(w_i)}{dw_i} < 0$. We need to examine the incentive constraints of the three groups in equilibrium.

1) content consumers: I_c

For user $i \in I_c$, the necessary and sufficient condition for her to choose $w_i = 0$ is

$$f_i(0) = -T_i\psi'(T_i)\phi(S_{-i}) + \alpha_i q_i T_i \sum_{j\neq i} \frac{T_j r_j}{S_{-ij}} \leq 0 \tag{15}$$

Since $\frac{r_j}{S_{-ij}} = 0$ if $j \in I_p$ and $\frac{r_j}{S_{-ij}} = \frac{1}{S_{-i}}$ if $j \in I_c$, $\sum_{j\neq i} \frac{T_j r_j}{S_{-ij}} = \frac{1}{S_{-i}} \sum_{j \in I_C, j\neq i} T_j + \sum_{j\in I_m, j\neq i} \frac{T_j r_j}{S_{-ij}}$. Inequality 15 becomes to

$$\alpha_i q_i \leq \frac{S_{-i}}{T^C_{-i} + S_{-i}\sum_{j\in I_m, j\neq i} \frac{T_j r_j}{S_{-ij}}} \psi'(T_i)\phi(S_{-i}) = h_C(i)$$

2) content producers: I_p

For user $i \in I_p$, the necessary and sufficient condition for him to choose $w_i = 1$ is

$$f_i(1) = -T_i\psi'(0)\phi(S_{-i}) + \alpha_i q_i T_i \sum_{j\neq i} \frac{S_{-ij}}{(S_{-ij}+q_iT_i)^2} T_j r_j \geq 0 \tag{16}$$

$$\begin{aligned}
\sum_{j\neq i} \frac{S_{-ij}}{(S_{-ij}+q_iT_i)^2} T_j r_j &= \sum_{j\in I_C, j\neq i} \frac{S_{-ij}}{(S_{-ij}+q_iT_i)^2} T_j + \sum_{j\in I_M, j\neq i} \frac{S_{-ij}}{(S_{-ij}+q_iT_i)^2} T_j r_j \\
&= \frac{S_{-i}}{(S_{-i}+q_iT_i)^2} \sum_{j\in I_C, j\neq i} T_j + \sum_{j\in I_M, j\neq i} \frac{S_{-ij}}{(S_{-ij}+q_iT_i)^2} T_j r_j \\
&= \frac{S_{-i}}{(S_{-i}+q_iT_i)^2} T^C_{-i} + \sum_{j\in I_M, j\neq i} \frac{S_{-ij}}{(S_{-ij}+q_iT_i)^2} T_j r_j
\end{aligned}$$

Inequality 16 becomes

$$\alpha_i q_i \geq \frac{(S_{-i}+q_iT_i)^2}{S_{-i}T^C_{-i} + (S_{-i}+q_iT_i)^2 \sum_{j\in I_M, j\neq i} \frac{S_{-ij}}{(S_{-ij}+q_iT_i)^2} T_j r_j} \psi'(0)\phi(S_{-i}) = h_P(i)$$

Apparently, user with $h_C(i) < \alpha_i q_i < h_P(i)$ will choose $0 < w_i < 1$. □

Proof of Lemma 2.

Proof. (1)

If $n_M/n \nrightarrow 0$ as $n \to \infty$, then we immediately have $n_M \to \infty$ as $n \to \infty$. Pick $1 > \delta > 0, \underline{w} > 0$ such that $\forall n$, at least $n_M\delta$ of those $i \in I_M$ choose $w_i > \underline{w}$. [8].

$$S_{-i} = \sum_{j \neq i} q_j T_j w_j \geq \sum_{j \in I_M, j \neq i} q_j T_j w_j \geq (n_M\delta - 1)\underline{qwT}$$

$$\frac{T^C_{-i}}{S^\beta_{-i}} < \frac{\overline{T}n}{\underline{q}^\beta \underline{w}^\beta \underline{T}^\beta (n_M\delta - 1)^\beta} \to 0 \text{ as } n \to 0$$

If $n_M/n \to 0$ as $n \to \infty$, then we must have $T^C_{-i} \to \infty$ and $S_{-i} \to \infty$ since otherwise either $h_C(i) \to \infty$ or $h_P(i) \to 0$ both of which can't be true in equilibrium. Furthermore, $\frac{T^C_{-i}}{S_{-i}} \nrightarrow \infty$ as $n \to \infty$ since otherwise $h_P(i) \to 0$ too. Therefore, $\lim_{n\to\infty} \frac{T^C_{-i}}{S^\beta_{-i}} = 0, \forall \beta > 1$.

(2)

If $n_M/n \nrightarrow 0$, then

$$\sum_{j \in I_M, j \neq i} \frac{T_j r_j}{S^\beta_{-ij}} < \frac{n_M \overline{T}}{(n_M\delta - 2)^\beta \underline{w}^\beta \underline{q}^\beta \underline{T}^\beta} \to 0 \text{ as } n \to 0$$

where $\delta, \underline{w}$ are defined in the first part of the proof.

If $n_M/n \to 0$, then $n_C/n \nrightarrow 0$ since otherwise $\frac{T^C_{-i}}{S_{-i}} \to 0$, $h_C(i) \to \infty$ which can not be true in equilibrium. So we must have $\sum_{j \in I_M, j \neq i} T_j r_j < T^C_{-i}$. Now

$$\sum_{j \in I_M, j \neq i} \frac{T_j r_j}{S^\beta_{-ij}} < \frac{S^\beta_{-i}}{(S_{-i} - \overline{q}\overline{T})^\beta} \frac{T^C_{-i}}{S^\beta_{-i}} \to 0 \text{ as } n \to 0$$

□

Proof of Proposition 1.

Proof. We will prove the proposition in four steps. Throughout the proof, we will constantly use the boundedness of $\phi(\cdot)$ but we won't refer to it each time.

1) First we will show

$$\lim_{n\to\infty} \frac{h_C(i)}{h_P(i)} = \frac{\psi'(T_i)}{\psi'(0)}$$

Define $h(i) = h_C(i)/h_P(i)$, which could be written as

$$h(i) = \frac{\frac{S_{-i}T^C_{-i}}{(S_{-i}+q_iT_i)^2} + \sum_{j \in I_M, j \neq i} \frac{S_{-ij}}{(S_{-ij}+q_iT_i)^2} T_j r_j}{\frac{T^C_{-i}}{S_{-i}} + \sum_{j \in I_M, j \neq i} \frac{T_j r_j}{S_{-ij}}} \frac{\psi'(T_i)}{\psi'(0)}$$

[8] Technically, it is possible that such $(\delta, \underline{w})$ does not exist. In such case, $\frac{n_M}{n} \nrightarrow 0$, but $w_i \to 0, \forall i \in I_M$. We don't discuss this pathological limit equilibrium in the current paper.

$$\frac{T^C_{-i}}{S_{-i}} - \frac{S_{-i}T^C_{-i}}{(S_{-i}+q_iT_i)^2} = T^C_{-i}\frac{2S_{-i}+q_iT_i}{S_{-i}(S_{-i}+q_iT_i)^2}q_iT_i < 2q_iT_i\frac{T^C_{-i}}{S^2_{-i}} \to 0 \text{ as } n \to 0$$

$$\begin{aligned}\sum_{j\in I_M, j\neq i}\frac{T_jr_j}{S_{-ij}} - \sum_{j\in I_M, j\neq i}\frac{S_{-ij}}{(S_{-i}+q_iT_i)^2}T_jr_j &= \sum_{j\in I_M, j\neq i}T_jr_j\frac{q_iT_i(2S_{-ij}+q_iT_i)}{S_{-ij}(S_{-ij}+q_iT_i)^2} \\ &< 2q_iT_i\sum_{j\in I_M, j\neq i}\frac{T_jr_j}{S_{-ij}(S_{-ij}+q_iT_i)} \\ &< 2q_iT_i\sum_{j\in I_M, j\neq i}\frac{T_jr_j}{S^2_{-ij}} \to 0 \text{ as } n\to\infty\end{aligned}$$

Since $h_C(i) \nrightarrow \infty$ in equilibrium and $\phi(\cdot)$ is bounded, $\frac{T^C_{-i}}{S_{-i}} + \sum_{j\in I_M, j\neq i}\frac{T_jr_j}{S_{-ij}} \nrightarrow 0$ as $n\to\infty$. So $\lim_{n\to\infty} h(i) = \frac{\psi'(T_i)}{\psi'(0)}$.

2) Second, we will show

$$\lim_{n\to\infty}\frac{h_C(i)}{h_C(k)} = \frac{\psi'(T_i)}{\psi'(T_k)}, \forall i,k$$

$$\begin{aligned}\left|\sum_{j\in I_m, j\neq i}\frac{T_jr_j}{S_{-ij}} - \sum_{j\in I_m, j\neq k}\frac{T_jr_j}{S_{-kj}}\right| &= \sum_{j\in I_M, j\neq i,k}\left|\frac{q_kT_kw_k - q_iT_iw_i}{S_{-ij}S_{-kj}}\right|T_jr_j + \frac{T_kr_k - T_ir_i}{S_{-ik}} \\ &\leq |q_kT_kw_k - q_iT_iw_i|\sum_{j\in I_M, j\neq i}\frac{T_jr_j}{S^2_{-ij}} + \frac{T_kr_k - T_ir_i}{S_{-ik}} \\ &\to 0 \text{ as } n\to\infty \qquad (17)\end{aligned}$$

Since $h_C(i) \nrightarrow \infty$, $\frac{T^C_{-i}}{S_{-i}} + \sum_{j\in I_m, j\neq i}\frac{T_jr_j}{S_{-ij}} \nrightarrow 0$, hence

$$\frac{h_C(i)}{h_C(k)} = \frac{\frac{T^C_{-k}}{S_{-k}} + \sum_{j\in I_m, j\neq k}\frac{T_jr_j}{S_{-kj}}}{\frac{T^C_{-i}}{S_{-i}} + \sum_{j\in I_m, j\neq i}\frac{T_jr_j}{S_{-ij}}}\frac{\psi'(T_i)\phi(S_{-i})}{\psi'(T_k)\phi(S_{-k})} \to \frac{\psi'(T_i)}{\psi'(T_k)}$$

3) From 1) and 2), we immediately have

$$\lim_{n\to\infty}\frac{h_P(i)}{h_P(k)} = \frac{h_C(i)}{h_C(k)}\frac{h_C(k)/h_P(k)}{h_C(i)/h_P(i)} = \frac{\psi'(T_i)}{\psi'(T_k)}\frac{\psi'(T_k)/\psi'(0)}{\psi'(T_i)/\psi'(0)} = 1, \forall i,k$$

Since $h_P(k) \nrightarrow 0, \forall k$, $h_P(i) - h_P(k) \to 0, \forall i,k$. Denote $\lim_{n\to\infty} h_P(i) = h_P$, then $\lim_{n\to\infty} h_C(i) = \frac{\psi'(T_i)}{\psi'(0)}h_P$. □

Proof of Corollary 1.

Proof. By Proposition (1), we only need to examine the case when w_i and w_k are the interior solutions of the first-order conditions of user i and user k's utility maximization problem. From the proof of Lemma (1), we have

$$\psi'(T_i(1-w_i))\phi(S_{-i}) = \alpha_i q_i \sum_{j\neq i} \frac{S_{-ij}}{(S_{-ij}+q_iT_iw_i)^2} T_j r_j$$

$$\psi'(T_k(1-w_k))\phi(S_{-k}) = \alpha_k q_k \sum_{j\neq k} \frac{S_{-kj}}{(S_{-kj}+q_kT_iw_k)^2} T_j r_j$$

$$\frac{\psi'(T_i(1-w_i))}{\psi'(T_k(1-w_k))} = \frac{\phi(S_{-k})}{\phi(S_{-i})} \frac{\alpha_i}{\alpha_k} \frac{\sum_{j\neq i} \frac{S_{-ij}q_i}{(S_{-ij}+q_iT_iw_i)^2} T_j r_j}{\sum_{j\neq k} \frac{S_{-kj}q_k}{(S_{-kj}+q_kT_iw_k)^2} T_j r_j}$$

(1) If $T_i = T_k, q_i = q_k, \alpha_i \geq \alpha_k$, then, using Lemma(2), one can easily show that

$$\lim_{n\to\infty} \frac{\sum_{j\neq i} \frac{S_{-ij}q_i}{(S_{-ij}+q_iT_iw_i)^2} T_j r_j}{\sum_{j\neq k} \frac{S_{-kj}q_k}{(S_{-kj}+q_kT_iw_k)^2} T_j r_j} = 1$$

Hence, $\lim_{n\to\infty} \frac{\psi'(T_i(1-w_i))}{\psi'(T_k(1-w_k))} = \frac{\alpha_i}{\alpha_k} \geq 1$, which implies that $w_i \geq w_k$

(2) If $T_i = T_k, \alpha_i = \alpha_k, q_i \geq q_k$, then using Lemma(2), one can easily show that

$$\lim_{n\to\infty} \frac{\sum_{j\neq i} \frac{S_{-ij}q_i}{(S_{-ij}+q_iT_iw_i)^2} T_j r_j}{\sum_{j\neq k} \frac{S_{-kj}q_k}{(S_{-kj}+q_kT_iw_k)^2} T_j r_j} = \frac{q_i}{q_k}$$

Hence, $\lim_{n\to\infty} \frac{\psi'(T_i(1-w_i))}{\psi'(T_k(1-w_k))} = \frac{q_i}{q_k} \geq 1$, which implies that $w_i \geq w_k$ □

Proof of Proposition 2.

Proof. The "if" part is obvious from Proposition 1 and is explained in the paper. The "only if" part could be similarly proved. Suppose $\lim_{n\to\infty} \frac{n_M}{n} = 0$, then

$$\lim_{n\to\infty} \sum_{j\in I_m} \frac{T_j r_j}{S_{-ij}} = 0, \quad \lim_{n\to\infty} \sum_{j\in I_M, j\neq i} \frac{S_{-ij}}{(S_{-ij}+q_iT_i)^2} T_j r_j = 0$$

since $S \to \infty$ as $n \to \infty$. Hence

$$\lim_{n\to\infty} h_C(i) = \frac{S}{T^C}\psi'(T_i) \lim_{n\to\infty} \phi(S), \quad \lim_{n\to\infty} h_P(i) = \frac{S}{T^C}\psi'(0) \lim_{n\to\infty} \phi(S)$$

With continuous distribution of (α, q, T), if $\psi''(\cdot) < 0$, then there is a always positive proportion of user who have $h_C(i) < \alpha_i q_i < h_P(i)$ as $n \to \infty$ and those user choose $r_i > 0, w_i > 0$. Hence $\frac{n_M}{n} \nrightarrow 0$, contradiction. □

Proof of Corollary 2.

Proof. In a partition equilibrium, the utility function simplifies to

$$u_i = \psi(T_i(1-w_i))\phi(S_{-i}) + \alpha_i q_i T_i w_i \frac{T_C}{S}$$

Since $r_j = 0$ if $j \in I_C$ and $r_j = 0$ if $j \in I_P$.

If $i \in I_C$, then $w_i = 0$ and $S_{-i} = S$. So $u_i^C = \psi(T_i)\phi(S)$.

If $i \in I_P$, then $w_i = 1$. So $u_i^P = \alpha_i q_i T_i \frac{T_C}{S}$.

From Proposition 1, we know in a partition equilibrium

$$\lim_{n\to\infty} h_C(i) = \lim_{n\to\infty} h_P(i) = \frac{S}{T^C}\psi'(0)\lim_{S\to\infty}\phi(S) = \frac{S}{T^C} = h$$

and $S = \sum_{\alpha_i q_i > h} q_i T_i$, $T^C = \sum_{\alpha_i q_i < h} T_i$, so, h is determined by

$$h = \frac{\sum_{\alpha_i q_i > h} q_i T_i}{\sum_{\alpha_i q_i < h} T_i} \tag{18}$$

which always has a solution in $(0, \overline{\alpha q})$. □

Proof of Corollary 3.

Proof. The original threshold h is determined by

$$h = \frac{\sum_{\alpha_i q_i > h} q_i T_i}{\sum_{\alpha_i q_i < h} T_i} \tag{19}$$

Denote h' the threshold after the shift and $\hat{h}$ the threshold that keeps the same group of people content consumers/producers, i.e., $\sum_{\alpha_i' q_i < \hat{h}} T_i = \sum_{\alpha_i q_i < h} T_i$ or $\sum_{\alpha_i q_i' < \hat{h}} T_i = \sum_{\alpha_i q_i < h} T_i$.

If the population shifts up in α, then

$$h' = \frac{\sum_{\alpha_i' q_i > h'} q_i T_i}{\sum_{\alpha_i' q_i < h'} T_i} \tag{20}$$

and

$$h = \frac{\sum_{\alpha_i' q_i > \hat{h}} q_i T_i}{\sum_{\alpha_i' q_i < \hat{h}} T_i} \tag{21}$$

We must have $h' \geq h$ since otherwise the RHS of (20) will be greater than (19) which leads to contradiction. From this, we must have $h' < \hat{h}$ since otherwise the RHS of (20) will be smaller than (21). which also leads to contradiction. This implies that more user will become content producers and that more content will be generated.

If the population shifts up in q, then similarly we would have $h' \geq h$. Now suppose $S' = \sum_{\alpha_i q_i' > h'} < S = \sum_{\alpha_i q_i > h}$, i.e., $h' \sum_{\alpha_i q_i' < h'} T_i < h \sum_{\alpha_i q_i < h} T_i$, then $\sum_{\alpha_i q_i' < h'} T_i < \sum_{\alpha_i q_i < h} T_i$ which implies $h' < h$, contradiction. Hence we must have $S' > S$, i.e., more content will be generated after the shift up of q. □

Proof of Proposition 3.

Proof. Suppose that user i chooses T_i in the first stage, and that in the second stage, the partition equilibrium is played. Denote user i's utility by u_i^C if he is a content consumer and u_i^P if he is a content producer. From Corollary (2) and our assumption of quadratic cost function, we have

$$u_i^C = T_i\phi(S)\tau - \frac{1}{2\theta_i}T_i^2,\ u_i^P = \frac{T_C}{S}\alpha_i q_i T_i - \frac{1}{2\theta_i}T_i^2$$

where $S = \sum_{i\in I_P} q_i T_i$.

In the first stage, each user chooses T_i to maximize utility. We have

$$\begin{cases} T_i^C = \phi(S)\tau\theta_i, & i \in I_C \\ T_i^P = \frac{\sum_{j\in I_C} T_j}{S}\alpha_i q_i \theta_i, & i \in I_P \end{cases} \tag{22}$$

Summing up over $i \in I_C$ for the first equation, we get $T^C = \sum_{i\in I_P} \phi(S)\tau\theta_i$. Multiplying by q_i on both sides of the second equation, and summing up over $i \in I_P$, we get $S = \sum_{i\in I_C} \frac{T^C}{S}\alpha_i q_i^2\theta_i$. By Proposition (1), $i \in I_C$ if $\alpha_i q_i < \frac{S}{T^C}$ and $i \in I_P$ if $\alpha_i q_i > \frac{S}{T^C}$. So (S, T_C) is the solution to Equation (6). □

Proof of Lemma 3.

Proof. Denote $f(S) = \beta\phi(S) - \phi'(S)S$, $f'(S) = \beta\phi'(S) - \phi'(S) - S\phi''(S) = (\beta-1)\phi'(S) - S\phi''(S) > 0, \forall S > 0, \beta \geq 1$. $f(0) = 0$, Hence $f(S) > 0, \forall S > 0$ □

Proof of Proposition 4.

Proof. From the proof of Proposition (3) we know

$$\begin{cases} T^C = \sum_{i\in I_P} \phi(S)\tau\theta_i \\ S = \sum_{i\in I_C} \frac{T^C}{S}\alpha_i q_i^2\theta_i \end{cases} \tag{23}$$

Denote

$$\begin{cases} k_1 = \sum_{i\in I_C} \theta_i \\ k_2 = \sqrt{\sum_{j\in I_P} \alpha_i q_i^2 \theta_i} \end{cases}$$

Then we obtain Equations(8) which characterizes the content consumption and production at the macro-level. From Equations(8), we have $S^{*2} = k_1 k_2 \phi(S^*)$. Obviously, $(S^*, T^{C*}) = (0, 0)$ is always a solution. But there is at least one solution $(S^*, T^{C*}) \neq (0, 0)$ since $\phi'(0) > 0$.

The proof of asymptotic stability of this equilibrium point is a simple application of Liapunov's indirect method.

$$\mathbf{G} = \begin{pmatrix} \frac{\partial g_1}{\partial T^C} & \frac{\partial g_1}{\partial S} \\ \frac{\partial g_1}{\partial T^C} & \frac{\partial g_1}{\partial S} \end{pmatrix} = \begin{pmatrix} 0 & k_1\phi'(S) \\ \frac{k_2}{2\sqrt{T^C}} & 0 \end{pmatrix} \tag{24}$$

The eigenvalues of $\mathbf{G}$ satisfy $|\lambda|^2 = \frac{k_1 k_2 \phi'(S)\tau}{2\sqrt{T^C}}$. We need to check whether or not $|\lambda| < 1$ at the equilibrium point (T^{C*}, S^*).

$$|\lambda| < 1 \iff k_1 k_2 \phi'(S^*)\tau < 2\frac{S^*}{k_2} \tag{25}$$

$$\iff k_1 k_2^2 \phi'(S^*) S^* \tau < 2S^{*2} = 2k_1 k_2^2 \phi(S^*)\tau \tag{26}$$

$$\iff \phi'(S^*) S^* < 2\phi(S^*) \tag{27}$$

The last inequality is ensured by Lemma (3) □

Proof of Corollary 4.

Proof. By checking $\frac{dT^{C*}}{dk_1} > 0$ and $\frac{dS^*}{dk_2} > 0$, the corollary follows. □

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