Antibiotic Resistance, Drug Prices, and Entry

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Abstract

Antibiotic resistance is modeled by future drug-cost increase through current consumption. Price competition leads to free-riding inefficiency. Competitive rationing drug plans partially mitigate resistance. A monopoly fully internalizes free-riding resistance effect, but price may still be high despite lower cost. Demand and cost configurations determine if consumer surplus becomes higher under monopoly. A firm may enter with a superior drug; incumbent and entrant compete under Cournot. The incumbent may deter entry by lowering sales and future cost. Entry deterrence reduces resistance, but the new drug is lost. Entry accommodation may exacerbate resistance because the incumbent does not internalize resistance effects.

Keywords: antibiotic resistance, drug prices, pharmaceuticals, competition, monopoly, entry, Cournot

JEL: I1, I11, L1

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1 Introduction

Antibiotics are medicines that kill bacteria, protozoa, and fungi. From the beginning of antibiotic use less than 100 years ago, the problem of microbial resistance has been noted. Sir Alexander Fleming warned in 1945 that "it is not difficult to make microbes resistant to penicillin in the laboratory..."[1] Fleming's worry was the resistance brought about by under dosage, which would allow survivors to adapt. Fleming said towards the end of his Nobel lecture: "Moral: If you use penicillin, use enough."

Today's problem is markedly different. According to the World Health Organization (WHO), antibiotic resistance has been "accelerated by human activities, mainly the overuse and misuse of antibiotics against infections..."[2] The US Center for Disease Control in 2021 estimated that more than 35,000 people died because of antimicrobial-resistant infections, with more than 2.8 million infections occurring in the United States.[3] Such antibiotic resistance threats are estimated to cost more than $4.6 billion annually (Nelson et al. 2021). The increased costs due to antibiotic resistance come from an extended length of stay, additional treatments, and more intensive care required for patients. Also, the Food and Agriculture Organization of the United Nations claims that antibiotic resistance "would cost the world $412 billion a year in additional healthcare costs and $443 billion per year in lost workforce productivity."[4] Based on reports from WHO, pharmaceutical companies are reluctant to invest in antibiotic development due to the high cost of research and development as well as the low return compared to other drugs (Klug et al. 2021).[5]

[1] https://www.nobelprize.org/uploads/2018/06/fleming-lecture.pdf, p93

[2] https://www.who.int/news-room/fact-sheets/detail/antimicrobial-resistance, Overview section

[3] https://www.cdc.gov/antimicrobial-resistance/stories/partner-estimates.html

[4] https://www.fao.org/antimicrobial-resistance/news-and-events/news/news-details/en/c/1680317/

[5] https://www.pewtrusts.org/en/research-and-analysis/articles/2024/07/15/world-health-organization-

The economic issue of antibiotic resistance is a form of the "tragedy of the commons," wherein self-interested individuals free ride and deplete a shared resource, which, in this case, is antibiotics' power to kill microbes. Other examples of the failure of the sort are over-fishing, over-grazing, and environmental pollution.[6]

In this paper, we define antibiotic resistance by the antibiotic becoming more costly, or equivalently lower quality, in the future because of higher current consumption; antibiotics' powers are being depleted by use. Current users do not internalize the depletion damage, so there is an antibiotic-resistance market failure.

We analyze basic economic issues of antibiotic resistance in various market structures and dynamics in a two-period model. We consider competitive and monopoly, as well as Cournot competition between an incumbent and a potential entrant. Our basic questions concern market allocations and how antibiotic resistance is being manifested in different markets. We study various market outcomes.

In a conventional competitive market, firms sell antibiotics at marginal costs. This leads to the highest consumption, and antibiotic resistance becomes most serious. The resistance market failure leads to an inefficient allocation under competition. Then we study an alternative form of competition in which drug plans sell contracts to consumers. Consumers pay a premium, and receive medicines under a rationing rule, but at zero monetary cost. We characterize the competitive drug plan equilibrium. Even in a competitive environment, drug plans internalize some of the cost-increase (or quality-reduction) consequence of antibiotic use. This results in a higher consumer surplus from a more efficient allocation. Tragedy of the commons can be avoided to some extent,

warns-that-antibiotic-innovation-still-insufficient

[6]We focus only on human use of antibiotics. The evidence that animal use of antibiotics leading to resistance is insignificant; see Adda (2020).

under an alternative form of competition.

We next consider a monopoly market. A single firm produces antibiotics, so the monopolist does fully internalize the antimicrobial resistance adverse effect. As a result the monopolist does reduce resistance from the competitive level, but it reaps the benefit by maximizing its profit optimally. There are two effects: first, the drug cost is lower due to the monopolist internalizes resistance; second, the monopolist exploits the lower cost and obtains higher profits. We characterize (necessary and sufficient) conditions for the monopoly allocation yielding higher consumer surplus than the competitive allocation.

Possible entrants may provide a relief to antibiotic resistance, so we consider a market with an incumbent monopolist facing a potential entrant. In the first period, the incumbent monopolist chooses to sell a quantity of antibiotics, which then determines its cost in the second period. Then in the second period, the entrant, having a higher quality antibiotic, can enter if its post-entry profit can cover its fixed and variable costs. We model the post-entry competition by a Cournot game with firms having drugs with different qualities.

The incumbent can deter entry by making its own future cost low, which makes the entrant variable profit low. The entry deterrence strategy is favorable for preventing antibiotic resistance: current consumption is reduced. But of course the loss is the lack of a superior drug, as well as reduced consumer surplus.

The incumbent can accommodate entry. Under this strategy, the incumbent chooses its quantity in the first period with the expectation that the entrant will enter in the second period. There are two effects in play. First, as in standard Cournot interactions, the incumbent's future profit is decreasing in its future costs. If the incumbent manages to lower its future cost, the future profit will increase. This is an incentive to reduce antibiotic resistance. Second, and this is a counter

effect, because of entry and a reduced market share, the incumbent has less of a concern about internalizing the cost increase due to resistance. The total effect is the sum of these two, so it is ambiguous if entry accommodation will actually enhance or reduce antibiotic resistance.

The antibiotic market structure has surprising effects. Whereas it is clear that conventional perfect competition may lead to antibiotic resistance in the most serious way, drug plan competition entails some remedies. The monopoly situation is even more subtle. The monopolist may internalize the antibiotic resistance effect, but its interest is in using the internalization to raise profit, not to enhance consumer surplus. However, even the monopolist's pure profit motive may benefit consumers. Finally, in the potential entry scenario, the effect on antibiotic resistance is nuanced. Entry deterrence and accommodation yield different incentives for reducing antibiotic resistance.

Our purpose here is to show that conventional policies such as taxes and subsidies simply may miss the overall market picture. So to speak, throwing money at firms that strive to invent antibiotics, penalizing antibiotic use, or subsidizing new antibiotic use should be more firmly grounded in economic analyses of the basic industry structure. Firms are not stand alone entities; a firm exists in a market and interacts with other firms. Moreover, when drug-plan competition, rather than price competition, is available, subsidizing plans may raise overall welfare because it encourages more consumers to subscribe to drug-plan rationing. One might liken the drug-plan competition as a form of antibiotic stewardship, and our result provides some foundation for how stewardship may be structured.

One cannot dismiss the various industry structures here as theoretical curiosities. These market structures are readily shown empirically. National Sales Perspectives (NSP) aggregates dollar and unit sales at actual transaction prices from wholesalers, distributors, and pharmaceutical manufac-

turers that cover 90% of the U.S. pharmaceutical market.[7] As an illustration, we consider three classes of common antibiotics: broad-spectrum penicillins, medium/narrow-spectrum penicillins, and tetracyclines & combinations. For years between 2017 and 2022, we identify the top four pharmaceutical companies according to the total dollar sales for each of these three classes. Market shares are computed as sales divided by the total sales in each quarter of each year.

In each of the following three figures, the horizontal axis lists quarters over the years wheres the vertical axis measures market shares. Figure 1 plots broad-spectrum penicillin market shares; they appear to be quite evenly distributed among the top four firms. The broad-spectrum market is competitive. Figure 2 plots medium/narrow-spectrum penicillin market shares. Pfizer maintained a very high market share throughout the data period. The medium/narrow spectrum market is concentrated. Finally, Figure 3 plots the tetracyclines and combinations market shares. There, market entry and exit are apparent. Almirall S.A. initially held more than 30% market share but exited the market in Q4 2019, while Paratek Pharmaceuticals entered the market in Q4 2018, increased its share gradually to take the lead in 2020, and eventually reached over 25% of the market by 2022. In brief, the NSP data show that competition, monopoly, and imperfect competition do exist.

[7] https://www.iqvia.com/insights/the-iqvia-institute/available-iqvia-data

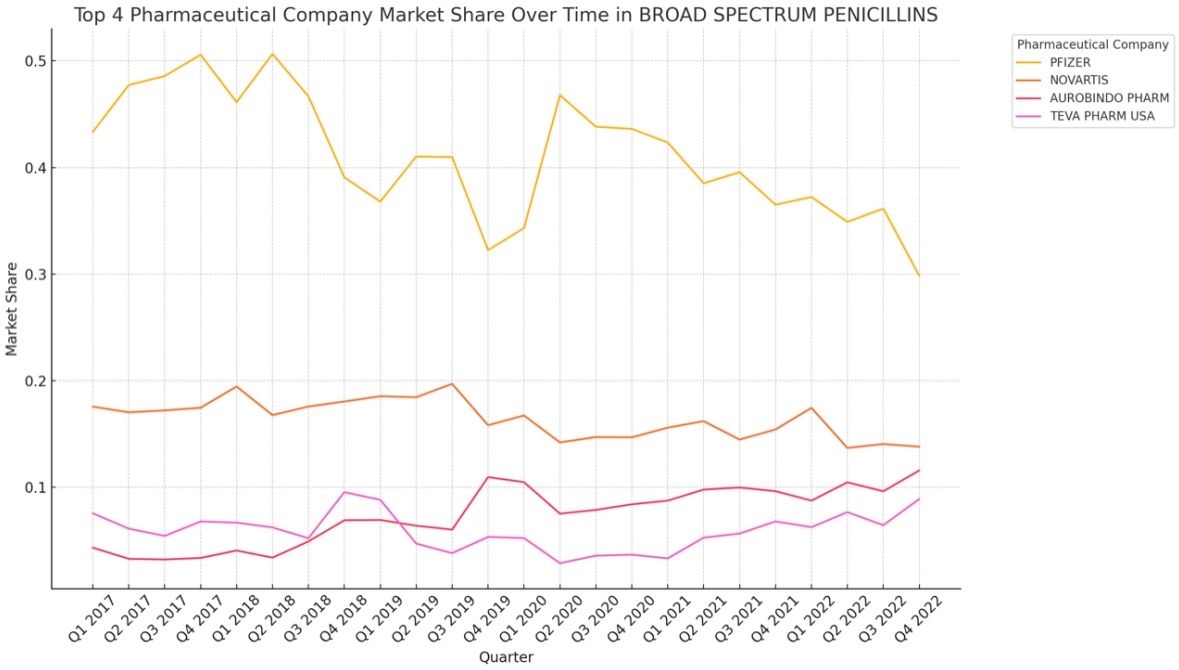

Figure 1: Broad Spectrum Penicillins Market Shares

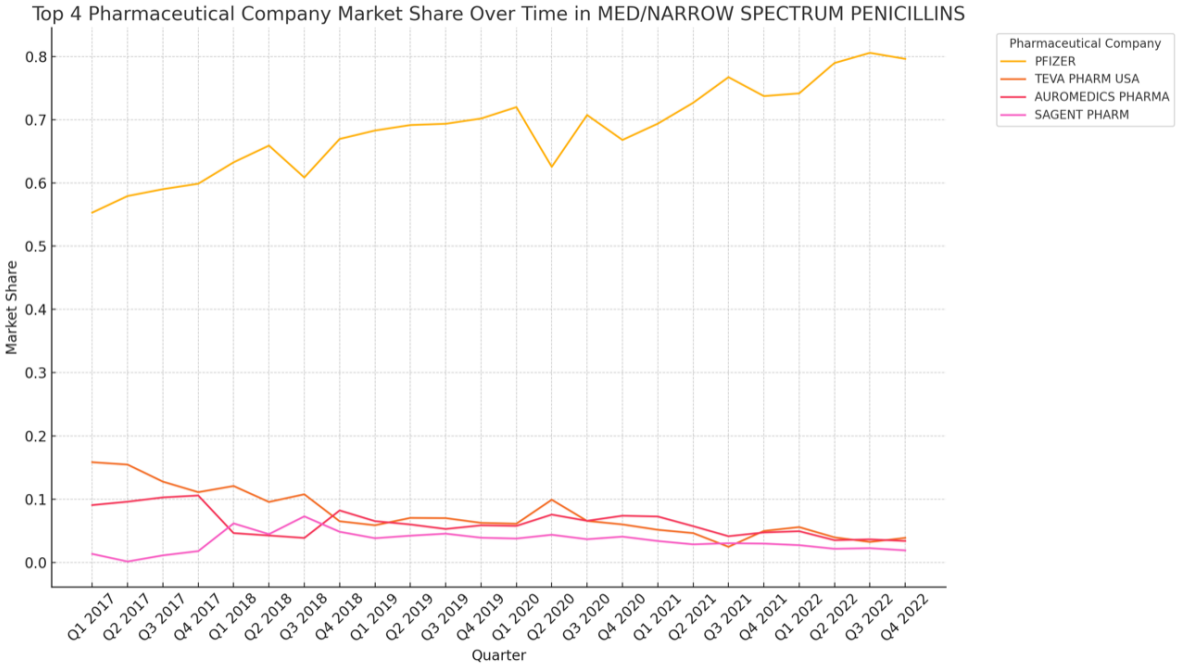

Figure 2: Medium/Narrow Spectrum Penicillins Market Shares

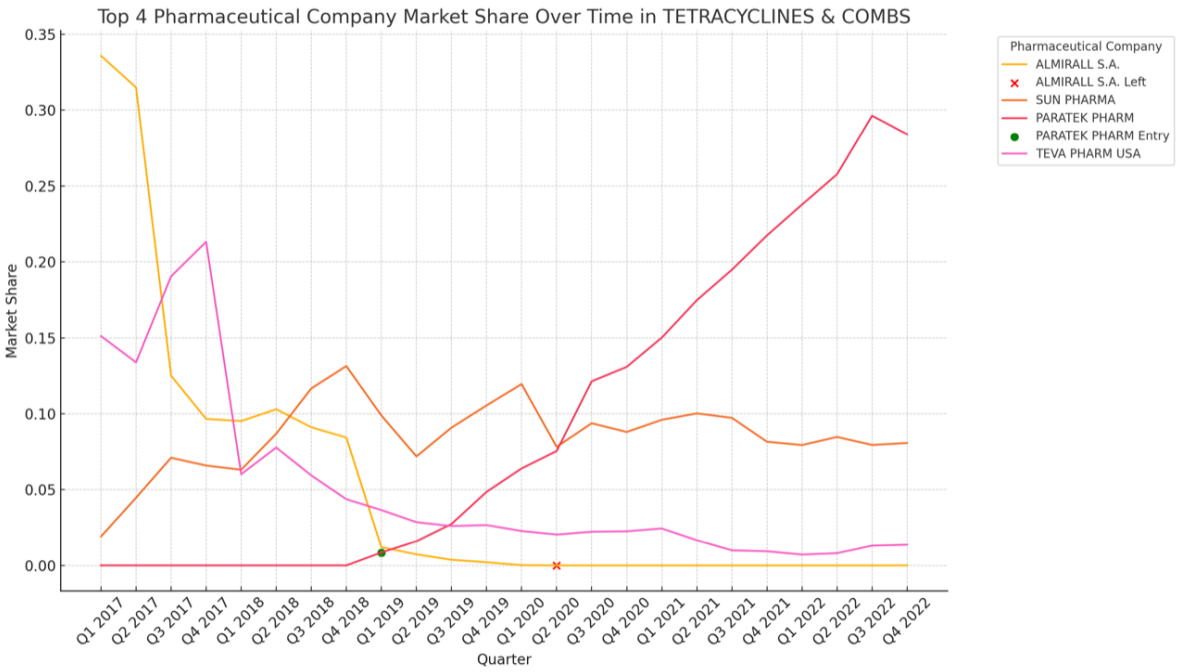

Figure 3: Tetracyclines and Combinations Market Shares

The paper is organized as follows. Section 2 is a literature review. Section 3 presents the demand and cost structures, and derives the first best. In Section 4, we show internalization failures under conventional pricing in a competitive market. We then show that managed-care, drug plan competition can alleviate some internalization failure. Section 5 analyzes how a monopolist will internalize cost increase, and compares welfare between competitive and monopolist markets. Section 6 considers the potential entry by a firm with a drug of higher quality. Cournot competition with differentiated products formalizes post-entry interactions between firms. Finally, Section 7 draws some conclusions. Where proofs of results are not presented in the main sections, they are collected in the Appendix.

2 Literature Reviews

The extant literature has widely recognized antibiotic resistance. Outterson (2009) and Outterson et al. (2015) frame antibiotic effectiveness as a common pool resource that is steadily depleted

through use. An individual consumer, making a short-run antibiotic use decision, fails to consider the long-run depletion effect of this resource. Outterson et al. (2015) argue that the current rate of innovation is insufficient to meet the growing challenge of antibiotic resistance, a concern echoed by the U.S. Center for Disease Control and Prevention in 2024.

The tragedy of the commons problem naturally calls for a Pigouvian remedy. Thus, Giubilini (2019) advocates for a tax on antibiotic uses because humans should have a moral obligation to protect the common good. While such taxes may create inequities and unequal access to healthcare, Giubilini (2019) argues that the antibiotic emergency may justify such drastic measures. Similarly, Kuhn et al. (2011) extend this approach by incorporating a life-cycle framework for evaluating healthcare distribution. They highlight the spillover effects of antibiotic use across the life cycle, necessitating a tax-transfer system to align individual behaviors with social objectives.

Laxminarayan and Brown (2001) use a Susceptible-Infected-Suspectible (SIS) model, adapted from the standard Susceptible-Infected-Recovery (SIR) framework in epidemiology, to describe multiple antibiotics use by consumers. Their model shows that using one antibiotic continuously depletes its effectiveness, and they derive conditions under which consumers should switch between antibiotics based on cost and drug efficacy. Laxminarayan and Weitzman (2002) contribute to this by showing that resistance is compounded by uniform treatment strategies and thus favor a mixed strategy of treatment. Later works by Herrmann and Nkuiya (2009) and Herrmann and Gaudet (2017) explore the dynamic efficacy of antibiotics under open-access conditions, showing how taxes and subsidies can be employed to restore efficiency in antibiotic usage.

For monopolies, Hermann (2010) explores pricing policy under patent protection (so entries are absent) with an SIS model, whereas Hermann et al. (2013) study innovation under incentives provided by dynamic tax-subsidy policies. In Albert (2021), the SIS model is combined with

economic components to study the evolution of resistance under imperfect competition, with perfect competition and monopoly as special cases. The SIS model involves a set of differential equations and closed form solutions are usually unavailable. Simulations and calibrations are often required to draw some conclusions. The paper here uses exclusively an economic modeling method, the primitives being demand and cost functions. The patient-physician interaction in Albert (2021) is simplified as an overall demand. We are able to model imperfect competition explicitly by Cournot, and analyze the fundamental market failure in a tractable way.

Currie et al., (2011, 2014) conduct field experiments on antibiotic prescription practices in China, manipulating physician incentives to observe how they influence prescribing behavior. Their findings suggest that physicians are more likely to prescribe when patients' purchase may potentially benefit physicians financially. In most countries, physicians do not directly benefit from medicine sales, and these experiments warn against a relaxation of such a regime.

Antibiotic consumption exhibits a behavioral perspective. Filippini et al., (2006, 2009) and Filippini and Masiero (2012) investigate habit and persistence in antibiotic use and regional variations in consumption patterns. Their studies reveal that past consumption of antibiotics will indeed lead to its future consumption. But even in Switzerland, a small country, such regional variations can be significant, too large to be attributable to price variations. The most recent empirical estimation concerning the issue of resistance to antibiotics is by Mariuzzo et al. (2024). Using a nested logit model, they demonstrate how taxes can shift demand from broad-spectrum to narrow-spectrum antibiotics, a shift that could help mitigate resistance.

Our model integrates these key insights to demonstrate how the different market structures, including competition, monopoly, and Cournot competition impact antibiotic usage and the development of resistance. In competitive markets, because consumers do not internalize the social

cost of antibiotic use, there will be overconsumption, these costs and resistance levels escalating over time. In light of this argument, our analysis also says that market-driven consumption typically results in suboptimal outcomes. We extend this further by examining how the entry of new firms, particularly those producing higher-quality drugs, can be deterred by incumbent firms in manipulating consumption patterns in a manner so as to secure their dominance in the market.

In this paper, we focus on how such strategic interventions by incumbents affect incentives for potential entrants, investigating pathways that could lead to more socially optimal outcomes. Building on the work of Outterson et al. (2015), who proposed delinking profitability from sales volume as a solution to the broken market for antibiotic innovation, we explore how different market structures and entry conditions influence innovation incentives, especially with regards to how drug resistance alters cost dynamics.

3 Model

3.1 Consumers

There is a unit mass of consumers who may benefit from taking a medicine. The quality of the medicine is set at 1. (We first study the market with only this medicine available. In Section 6, we consider two drugs, which have qualities 1 and $q > 1$.) Consumer benefits are described by a random variable v defined on a positive interval $[\underline{v}, \overline{v}]$ with distribution $F(v)$, which is assumed to be absolutely continuous. If a consumer with benefit parameter v pays a price p to buy the medicine, the net utility is $v - p$. (For now we ignore the usual prescription requirement to purchase antibiotics.)

From the benefit random variable v, we define a new random variable by the function: $w \equiv 1 - F(v)$, which is the share of consumers with benefits higher than v. Now w has a uniform

distribution on $[0,1]$. We will use the term consumer w to denote a consumer with benefit $v = F^{-1}(1-w) \equiv G(w)$. When $v = \underline{v}$, $w = 1$ and when $v = \overline{v}$, $w = 0$. In other words, consumer w (or type-w consumer) gets a benefit $G(w)$ from the medicine. On paying a price p for the medicine, the consumer's utility is $G(w) - p$. If consumer w purchases the medicine at price p, so do all consumers with types lower than w. The downward sloping function G is the demand function; $G(w)$ is the maximum price to sell to a mass of w consumers.

3.2 Drug resistance and cost

Microbe drug resistance is studied in a two-period model. Consumers consider using the medicine in each of two periods; consumer benefits are independently and identically drawn from the same distribution in each period. We also assume that there is no discounting. Denote the masses of consumers using medicine in periods 1 and 2 by w_1 and w_2, respectively.

The marginal cost of medicine in period 1 is $c_0 \geq 0$, and its marginal cost in period 2 depends on total consumption in period 1. If w consumers use medicine in period 1, the marginal cost in period 2 becomes $C(w)$, which is an increasing function $C : [0,1] \to \Re_+$. We set $C(0) = c_0$ and $C(1) = \overline{c}$. In other words, if there is no consumption in period 1, the marginal cost remains at c_0, and if all consumers use medicine, the marginal cost in period 2 is at its highest at $\overline{c}$. We further normalize c_0 to 0. This normalization is without loss of generality. If $c_0 > 0$, then consumers with $G(w) < c_0$ would never consume medicine, so we might just redefine the mass of consumers with benefits higher than c_0 as 1.

We model drug resistance by a cost increase: when more consumers use the medicine (a higher value of w), its future marginal cost goes up. We do not mean that present consumption raises future production cost. The interpretation is that certain amounts of medicine and resource are required for a treatment. Resistance may mean that more medicine and resources, and the extra

cost is will be needed to deliver the same quality (normalized at 1). The cost increase may also be due to changes in treatment regiment if the antibiotic is part of a set of drugs.

We can model antibiotic resistance as a quality or valuation reduction, and perhaps that is a more natural interpretation of resistance. Suppose that consumption by w_1 consumers in period 1 reduces valuation by $R(w_2)$ in period 2. Let consumer v obtains a benefit $v - R(w_1)$ in period 2. Using, $v = G(w)$, we have $v - R(w_1) = G(w) - R(w_1)$. This is a parallel shift downward of the (period 2) demand function $G(w)$ by $R(w_1)$. If we set the cost increase in period 2 from consumption w_1 in period 2 as $C(w_1) = R(w_1)$, we obtain the same model. All results work identically under the quality reduction formalism. Later in Section 6, we allow a new firm to enter with a more expensive, higher quality drug. For convenience, we have chosen to keep qualities exogenous, so antibiotic resistance is reflected in cost.

Remark. *Modeling antibiotic resistance as an increase in the constant marginal cost is equivalent to modeling it as a downward and parallel shift of the demand function; cost increase and quality reduction are equivalent formalization of antibiotic resistance.*

3.3 First best

We now write down a first-best benchmark. An allocation is defined by the sets of consumers who get the medicine in each period. Obviously, if a type-w consumer gets allocated the medicine, so should consumers with lower types (who have higher valuations than the w type). Thus, we can define an allocation by (w_1, w_2), where types $w \leq w_i$ will be allocated the medicine in period i, $i = 1, 2$.

In an allocation (w_1, w_2), consumers' total benefit in the two periods is

$$\int_0^{w_1} G(w)\mathrm{d}w + \int_0^{w_2} G(w)\mathrm{d}w.$$

The total cost incurred under this allocation is

$$\int_0^{w_2} C(w_1)\mathrm{d}w,$$

where we have used the normalization that medicine cost in period 1 is zero, as well as the relationship between period 1 consumption and period 2 cost. A first-best allocation is (w_1^*, w_2^*) that maximizes the total benefit less total cost:

$$U(w_1, w_2) \equiv \int_0^{w_1} G(w)\mathrm{d}w + \int_0^{w_2} [G(w) - C(w_1)]\mathrm{d}w. \tag{1}$$

We assume that the social welfare function (1) is concave, so U in (1) has a negative definite second-order derivative matrix.[8]

Using standard first-order conditions, we have the following (with the proof omitted):.

Proposition 1. *The first-best allocation* (w_1^*, w_2^*) *is given by*

$$G(w_1^*) - w_2^* C'(w_1^*) = 0 \tag{2}$$

$$G(w_2^*) - C(w_1^*) = 0. \tag{3}$$

Equation (3) in Proposition 1 states that, in period 2, consumers with benefits higher than cost should use the medicine. Equation (2) in the Proposition shows an intertemporal tradeoff. Raising the threshold w_1 reduces benefit by $G(w_1)$ in period 1. However, this period-one consumption reduction lowers period-two cost by $w_2 C'(w_1)$. At the first best, these two effects must be equal. If there was no cost reduction (so that $C' \equiv 0$), we would have a solution of all consumers getting the medicine in both periods. Proposition 1 explains the rationale for medicine use restraint to avoid higher costs in the future.

[8]Straightforward calculation yields: $\partial^2 U/\partial w_1^2 = g(w_1) - w_2 C''(w_1)$, $\partial^2 U/\partial w_2^2 = g(w_2)$, $\partial^2 U/\partial w_1 \partial w_2 = -C'(w_1)$, where $g \equiv G' < 0$ because G' has the opposite sign as $F' > 0$. Hence we assume that $g(w_1) - w_2 C''(w_1) < 0$, $g(w_2) < 0$, and $[g(w_1) - w_2 C''(w_1)]g(w_2) - C'(w_1)^2 > 0$.

4 Competition and internalization failure

Medicine gives benefits to consumers, but present consumption raises future costs. Individual consumers, however, do not internalize the cost increase because a single consumer cannot affect aggregate consumption. In a competitive market, the medicine's price is the marginal cost $c_0 = 0$. At this price, all consumers will purchase medicine in period 1. The (marginal) cost of medicine in period 2 becomes the highest $C(1) = \overline{c}$, and consumers with types below w_2, where $G(w_2) = \overline{c}$ will purchase medicine. Consumer surplus becomes

$$\int_0^1 G(x)\mathrm{d}x + \int_0^{w_2} [G(x) - C(1)]\mathrm{d}x < \int_0^{w_1^*} G(x)\mathrm{d}x + \int_0^{w_2^*} [G(x) - C(w_1^*)]\mathrm{d}x. \tag{4}$$

The inequality follows because the first best allocation (w_1^*, w_2^*) gives higher social surplus than any other feasible allocation. In other words, allocation $(1, \underline{w}_2)$ where $G(\underline{w}_2) = C(1) \equiv \overline{c}$, is feasible in (1) but only the first-best allocation (w_1^*, w_2^*) yields the highest surplus. In a competitive market, prices always at marginal costs, so the first-period price does not reflect the true social cost of consumption. We summarize the "tragedy of the commons" result by the following (with proof omitted):

Proposition 2. *In a competitive market where medicine costs are always equal to marginal costs, compared to the first best, consumers use medicine excessively in period 1, which drives up cost in period 2. The total social surplus is below first best.*

4.1 Drug plans and internalization

Competition leads to low prices which result in consumers' excessive use. Can a nonprice mechanism, such as managed care, alleviate the antibiotic resistance problem? A managed care organization designs a drug plan, a contract consisting of a premium and provision thresholds (π, w_1, w_2). In exchange for a premium π, paid to the plan before consumers learn their types, ex post a consumer

of type w is given medicine, at no cost, in periods 1 and 2 if w is less than w_i in period i, $i = 1, 2$. Consumers' type information is assumed available to the drug plan, so contract implementation is credible. The drug plan uses efficient rationing. Given quantity w_i available in period i, those consumers with valuations or benefits higher than $G(w_i)$ with be allocated the medicine. This interpretation of managed care as delegation and efficient rationing is standard. In recent theoretical literature, Frank et al. (2000), Glazer and McGuire (2000, 2006) explicitly use rationing allocations to characterize health plans.

We continue to assume perfect competition, so there are potentially many identical drug plans, and the medicine, at marginal cost, is available to consumers who do not enroll in a drug plan. It is important to assume that drug plan enrollees could not pay out of pocket ex post to get around rationing. Medicines require prescriptions, so a drug plan's physicians would not prescribe medicine if doing so would violate the rationing rule. We postulate that a drug plan allows consumers to gain some benefits (besides the zero out-of-pocket drug expenses). These are common benefits in managed care networks such as health and treatment information and referral advantages. We denote this benefit by $B > 0$; the plan benefit is needed to motivate consumers to surrender their decisions to a managed care organization. Those consumers who have not enrolled make independent choices about medicine at costs but cannot get the plan benefit B. We assume that B is exogenous, but will show how its magnitude will affect allocations.

We consider a representative drug plan; the analysis is the same if we consider multiple plans and if consumers choose identical plans randomly. Suppose a drug plan sets premium and periods 1 and 2 thresholds (π, w_1, w_2). Consumers decide whether to join the plan or stay independent before they learn their types. Suppose that s, $0 \leq s \leq 1$, is the mass of consumers who have enrolled in the plan; so $1 - s$ have not and these consumers always choose to use medicine in period 1. The total consumption amount in period 1, given the plan contract, is $1 - s + sw_1$ consisting

of independent consumers' and w_1 of enrollees' uses. Therefore the cost of medicine in period 2 is $C(1-s+sw_1)$.

Given the mass of enrolled consumers s, a consumer's expected utility from enrolling in the plan is

$$\int_0^{w_1} G(x)\mathrm{d}x + \int_0^{w_2} G(x)\mathrm{d}x - \pi + B. \tag{5}$$

According to the thresholds those consumers with types below w_i will be given medicine in period i, $i = 1, 2$. The valuation of consumer w is $G(w)$, so the two integrals are the expected benefit from the plan's rationing rule. The consumer pays the premium π but enjoys the plan benefit B.

An independent consumer will always purchase the drug in period 1. Given the mass of enrolled consumers s and the rationing rule w_1 in period 1, the medicine's marginal cost will become $C(1-s+sw_1)$ in period 2. Those independent consumers with benefit $G(w) > C(1-s+sw_1)$ will purchase the medicine in period 2. A consumer's expected utility from staying unenrolled in a drug plan is

$$\int_0^1 G(x)\mathrm{d}x + \int_0^{\widehat{w}} [G(x) - C(1-s+sw_1)]\mathrm{d}x, \tag{6}$$

where $G(\widehat{w}) = C(1-s+sw_1)$. The first integral is the benefit in period 1 from consuming medicine at cost 0; the second integral is the benefit of the consumer optimally choosing to purchase when benefit is higher than cost.

The drug plan's profit per enrollee is

$$\pi - w_2 C(1-s+sw_1). \tag{7}$$

It receives a premium π per enrollee; with total medicine consumption $1-s+sw_1$ in period 1, in period 2 the cost for providing the medicine to consumers with types below w_2 is $w_2 C(1-s+sw_1)$.

We have focused on one representative drug plan. This might have created the impression that there was no competition. The single-plan focus is for expositional convenience. The fraction s of

drug-plan enrollees is interpreted as the aggregate enrollment fraction. One particular drug plan may only enroll a fraction of s but the cost in period 2 remains the same, namely $C(1-s+sw_1)$ when each plan sets the threshold w_1 in period 1. Now we define an equilibrium.

Definition 1. *A Drug Plan Competitive Equilibrium is a drug plan contract* (π^e, w_1^e, w_2^e) *and an enrollment share* s^e, $0 \leq s^e \leq 1$, *such that*

1) given $s = s^e$, (π^e, w_1^e, w_2^e) *maximizes the enrollees' expected utility in (5), subject to the plan making a zero profit in (7);*

2) consumers maximize their utilities choosing between staying independent and enrolling in the drug plan, and a fraction s^e *optimally choose to enroll.*

Given the enrollment share, a competitive drug plan must choose a premium and rationing thresholds to maximize ex ante consumer surplus, and make a zero profit. This is the first requirement in the definition. Ex ante consumers are identical, so in order for a fraction of consumers to enroll, all consumers must be indifferent between enrolling in the plan and staying independent. This is the second requirement. We now characterize drug plan competitive equilibria.

Consider a given share s of consumers enrolling in a drug plan. In a Drug Plan Competitive Equilibrium, the plan chooses w_1 and w_2 to maximize consumer's surplus and charge a zero-profit premium. Using (5) and setting (7) to zero to obtain the premium $\pi = w_2 C(1-s+sw_1)$, for any given s, we have the optimal drug-plan thresholds as follows:

$$(\widetilde{w}_1(s), \widetilde{w}_2(s)) = \arg\max_{w_1, w_2} \left\{ \int_0^{w_1} G(x)\mathrm{d}x + \int_0^{w_2} G(x)\mathrm{d}x - w_2 C(1-s+sw_1) \right\}, \tag{8}$$

where we have emphasized that the optimal thresholds depend on s. It is obvious that at $s=0$ (zero drug plan enrollment), $(\widetilde{w}_1, \widetilde{w}_2) = (1, \underline{w}_2)$, the competitive equilibrium allocation, and that at $s=1$ (full drug plan enrollment), $(\widetilde{w}_1, \widetilde{w}_2) = (w_1^*, w_2^*)$, the first best.

As s increases from 0, a drug plan internalizes more of the cost increase in period 2 due to period

1 consumption. Hence, it optimally reduces consumption of the medicine in period 1. Because of the more favorable cost in period 2, the drug plan also raises consumption in period 2. We provide mild conditions to confirm these monotone effects in the following Lemma, with proof is presented in the Appendix.

Lemma 1. *Suppose that C is linear or its second-order derivative does not take on very large values. As s increases from 0 towards 1, $\widetilde{w}_1(s)$ monotone decreases from 1 to w_1^*, and $\widetilde{w}_2(s)$ monotone increases from $\underline{w}_2$ to w_2^*.*

Next we define a cutoff value on B. Let $\overline{B} \equiv \int_{w_1^*}^1 G(x)\mathrm{d}x$. The integral $\int_{w_1^*}^1 G(x)\mathrm{d}x$ is a consumer's surplus loss forgoing consumption at $0 < G(w) < G(w_1^*)$. As we will see, any $B > \overline{B}$ will induce all consumers to join the drug plan. The proof of the following Proposition is in the Appendix.

Proposition 3. *At each B, $0 \leq B \leq \overline{B}$, there is a unique Drug Plan Competitive Equilibrium $(\pi^e, w_1^e, w_2^e; s^e)$ given by the unique solution of the following*

$$\int_{w_1^e}^1 G(x)\,dx = B \tag{9}$$

$$G(w_1^e) - w_2^e s^e C'(1 - s^e + s^e w_1^e) = 0 \tag{10}$$

$$G(w_2^e) - C(1 - s^e + s^e w_1^e) = 0 \tag{11}$$

$$w_2^e C(1 - s^e + s^e w_1^e) = \pi^e. \tag{12}$$

The equilibrium threshold in period 1 is strictly less than 1 but above the first best: $w_1^* < w_1^e < 1$. At $B > \overline{B}$, the unique Drug Plan Competitive Equilibrium is first best, with all consumers enrolling.

In period 2, the concern for further cost increase is irrelevant, independent consumers and managed care plan enrollees have the same consumption allocation.[9] Upon joining a drug plan,

[9]It is true that enrollees do not pay ex post, but independent consumers do. Managed care plans,

a consumer experiences a loss of expected surplus in period 1: the consumer will not be given the medicine if the valuation is less than $G(w_1^e)$. Hence, the drug plan benefit must compensate for the loss, and this is the requirement in (9). Now, drug plans compete, so must maximize consumer surplus. For a given share of consumers joining a drug plan, thresholds w_1^e and w_2^e maximize enrollees' surplus, so must satisfy the first-order conditions in (10) and (11). However, w_1^e is already pinned down by (9). Hence, the drug plan enrollee share s^e in (10) and (11) must adjust accordingly. The premium must make the drug plan earn zero profit, which is (12). Finally, (9) and (11) say that consumers are ex ante indifferent between enrolling and staying independent, so a share s^e joining is (part of) an equilibrium.

A drug plan bears enrollees' costs. When a drug plan has enrolled a fraction s of consumers, it internalizes the cost increase in period 2 due to members' period 1 consumption. However, it cannot stop nonmembers from purchasing in period 1. Suppose that the plan reduces members' period 1 consumption at w_1 by 1 unit, the cost increase in period 2 is still $C'(1 - s + sw_1) > C'(w_1)$. Consumers accept drug-plan rationing because of the plan benefit B. When B is small, the equilibrium rationing in period 1 cannot be very strong, so w_1^e is still close to 1, maximum consumption. When the benefit B increases, more consumers are willing to join, and the drug plan can internalize more of the cost consequence of excessive consumption in period 1. As B increases towards $\overline{B}$, the internalization becomes stronger and approaches the first best.

A drug plan with quantity rationing offers a way to alleviate the competitive market's failure to internalize the cost increase. But it does have a caveat: there is, indeed, no free lunch. Consumers have to be "bribed" to give up their control and use of the competitive prices. The importance of Proposition 3 is that it explains the channel through which the bribe B leads to rationing to reduce

however, are able to enforce their rationing rule. In each case, those consumers with valuations higher than the marginal cost will be allocated the medicine.

period 1 consumption—even when drug plans operate in a competitive environment.

A drug plan can be likened to a notion of antibiotic stewardship, a guideline offered by public health policy makers for practitioners. The CDC has developed the Outpatient Antibiotic Stewardship program, which lays out best prescription practices to guide healthcare providers in outpatient settings[10] Our results here can be used as a framework to establish the stewardship guidelines, but we also warn that the implementation of stewardship may not be costless.

5 Monopoly and internalization

Monopoly is in sharp contrast with competition. Now we let a single pharmaceutical firm sell to consumers directly. Let the monopolist set medicine prices at p_1 and p_2 in periods 1 and 2, respectively. These prices are set up at the beginning of period 1. The alternative of the monopolist sequentially setting p_i at the beginning of period i, $i = 1, 2$, turns out to be exactly the same. With complete information, the monopolist can anticipate demand responses, so the timing of the monopolist's pricing decisions is inconsequential.

Given (p_1, p_2), let $G(w_1) = p_1$ and $G(w_2) = p_2$; consumer w_i is just indifferent between buying and forgoing consumption in period i, $i = 1, 2$. The quantities sold in period i is w_i. The marginal cost in period 2 is $C(w_1)$. The monopolist's profit is

$$\pi(w_1, w_2) \equiv w_1 G(w_1) + w_2[G(w_2) - C(w_1)]. \tag{13}$$

The monopolist recognizes that the sales amount in period 1, w_1, affects its cost in period 2, which becomes $C(w_1)$. The monopolist does internalize the cost increase, but exploits its market power.

We assume that the profit function in (13) is concave. The first-order derivatives of (13) with

[10]https://www.cdc.gov/antibiotic-use/media/pdfs/Core-Elements-Outpatient-508.pdf

respect to w_1 and w_2 are:

$$\frac{\partial \pi}{\delta w_1} = w_1 g(w_1) + G(w_1) - w_2 C'(w_1) \quad \text{and} \quad \frac{\partial \pi}{\delta w_2} = w_2 g(w_2) + G(w_2) - C(w_1), \tag{14}$$

where $g \equiv G' < 0$. The first two terms in each of the partial derivatives are marginal revenues in the two periods, each being less than the demands, $G(w_1)$ and $G(w_2)$. The term $w_2 C'(w_1)$ is the incremental cost for serving w_2 consumers in period 2 when w_1 consumers are served in period 1, so that is the marginal cost for selling to consumers in period 1. Obviously, the marginal cost in period 2 is $C(w_1)$. Setting the first-order derivatives to zero yield the necessary and sufficient conditions for profit maximization.

In period 2, the optimal price $G(w_2^M)$ (or quantity w_2^M) is characterized by the familiar marginal-revenue-marginal-cost condition:

$$\frac{G(w_2^M) - C(w_1^M)}{G(w_2^M)} = -\frac{w_2^M g(w_2^M)}{G(w_2^M)} \tag{15}$$

which says that the price-cost margin is inversely proportional to the demand elasticity. (Quantity is w_2, so the proportional change in quantity is simply $\frac{1}{w_2}$; price is $G(w_2)$, so the proportional change in price is $\frac{g(w_2)}{G(w_2)}$.) This is the usual under-production result in a monopoly.

In period 1, the optimal price $G(w_1^M)$ is given by $G(w_1^M) + w_1^M g(w_1^M) = w_2^M C'(w_1^M)$, which can be rewritten as

$$\frac{G(w_1^M) - w_2^M C'(w_1^M)}{G(w_1^M)} = -\frac{w_1^M g(w_1^M)}{G(w_1^M)}, \tag{16}$$

which also has an inverse-elasticity interpretation, except that the marginal cost pertains to the incremental cost in period 2 due to period 1 production. We summarize the above as follows (with its proof having been laid out above):

Proposition 4. *The monopolist's profit-maximizing prices, $(G(w_1^M), G(w_2^M))$, are given by (15) and (16).*

Obviously, the consumer surplus from the monopolist's profit-maximizaing prices will be below the first best. However, the comparison of consumer surpluses between monopoly and perfect competition seems to be ambiguous generally. Under competition, the cost in period 2 is at its maximum due to free riding. Even when consumers purchase at cost, their surplus may be small. Under monopoly, the usual price-cost margins will mean diminished consumptions in both periods. The lower consumption in period 1 means a lower cost in period 2, which is a gain from the allocation under perfect competition.

5.1 Consumer surplus comparison between monopoly and competition

We state the following and then explain the proof.

Proposition 5. *i) Suppose that period 1 consumer surplus under competition is more than two times the consumer surplus in period 1 under monopoly if the monopolist chooses the period 1 profit-maximizing price ignoring any cost increase in period 2; that is*

$$\int_0^1 G(x)\,dx \geq 2\int_0^{\widetilde{w}} [G(x) - G(\widetilde{w})]\,dx, \tag{17}$$

where $\widetilde{w} = \arg\max_w wG(w)$. *Consumer surplus under competition is at least as high as under monopoly.*

ii) Conversely, if

$$\int_0^1 G(x)dx < 2\int_0^{\widetilde{w}} [G(x) - G(\widetilde{w})]dx, \tag{18}$$

there exist cost functions C such that consumer surplus under competition is lower than under monopoly.

Period 1 consumer surplus under competition, $\int_0^1 G(x)\mathrm{d}x$, is a lower bound of total consumer surplus for the two periods. The worst that can happen is the complete lack of consumption in period 2. This will be the case when, after all the consumers purchase in period 1, the cost in

period 2, $C(1)$, becomes higher than the maximum consumer valuation. So consumers must be able to do better than the left-hand side of the condition in (17) under competition.

The monopolist will internalize the cost increase, and the profit function in (13), rewritten here, is $w_1 G(w_1) + w_2[G(w_2) - C(w_1)]$. Generally the monopolist will price more than $G(\widetilde{w})$, where $\widetilde{w} = \arg\max_w wG(w)$, so period 1 consumer surplus cannot exceed $\int_0^{\widetilde{w}} [G(x) - G(\widetilde{w})]\mathrm{d}x$. Now in period 2, the cost cannot decrease (and may actually rise), so again the monopolist must not sell more than $\widetilde{w}$. For periods 1 and 2 together, consumer surplus cannot exceed $2\int_0^{\widetilde{w}} [G(x) - G(\widetilde{w})]\mathrm{d}x$ under monopoly.

The first part of Proposition 5 simply says that if the lower bound of consumer surplus under competition is greater than the upper bound under monopoly, consumers will be hurt even when the monopolist internalizes antibiotic-resistance cost increase. This part of Proposition 5 only refers to the demand function G, so it is valid for all cost functions.

Next, in the second part of Proposition 5, we present costs functions for which monopoly may improve welfare. For that we suppose that (17) is violated, so (18) holds. Consider a class of (increasing and convex) cost functions C indexed by $w^\dagger$, defined as follows

$$\left\{ \begin{array}{llll} \text{at } 0 \leq w < w^\dagger, & C'(w) < \varepsilon & \text{where } \varepsilon \text{ is close to 0} \\ \text{at } w^\dagger < w < 1, & C'(w) > \delta & \text{where } \delta \text{ is very large.} \end{array} \right\}$$

The cost function C has arbitrarily small derivatives for w smaller than $w^\dagger$, but very large derivatives once w exceeds $w^\dagger$. Now let $w^\dagger$ be close to 1. The graph of this cost function example is (mirror-imaged) L-shaped. For such a cost function, in the competitive market, $C(1)$ becomes very high, so few, if any, consumers purchase in period 2. Therefore, the lower bound consumer surplus in competition $\int_0^1 G(x)\mathrm{d}x$ is approximately the actual consumer surplus.

When $C'(w)$ is very small for $w < w^\dagger$ (which is close to 1), the monopolist will choose a period 1 quantity close to $\widetilde{w}$; and because the monopolist's cost only increases slightly, the period 2 quantity

is also close to $\widetilde{w}$. Hence, consumer surplus will be approximately $2\int_0^{\widetilde{w}}[G(x)-G(\widetilde{w})]\mathrm{d}x$. Now (18) says that consumer surplus is higher under monopoly. We have exhibited a whole class of cost functions for consumer-surplus improvements under monopoly.

In this scenario, cost increase due to antibiotic resistance becomes strong only at very high consumption. Competition results in very high consumption, and that is detrimental. A monopolist will avoid that high-cost scenario. The deadweight loss due to monopoly pricing is less than the complete loss of the medicine. Clearly, there are many such examples that will be consistent with monopoly welfare being higher than competition.

5.2 Monopoly drug plan

Earlier we have considered competitive drug plans. However, full efficiency cannot be maintained unless such plans confer high benefits aside from drug coverage. We now consider drug plans offered by a monopolist. Such a drug plan contract is defined by a premium and two thresholds: (π, w_1, w_2). In exchange for a premium π, consumers receive the medicine in period 1 if the type is less than w_i in period i, $i = 1, 2$. The price π is paid upfront, before consumers learn their types. Consumers do not have to pay any more expenses, but they are rationed according to the contract. There is no need to include a drug plan benefit here because consumers have no other market options.

Under the contract (π, w_1, w_2), a consumer's expected utility is $\int_0^{w_1} G(x)\mathrm{d}x + \int_0^{w_2} G(x)\mathrm{d}x - \pi$. The monopolist's profit is $\pi - w_2C(w_1)$. Assume that the consumer's utility of refusing the contract is 0. Then given w_1 and w_2, the highest price Π that will be accepted is

$$\Pi = \int_0^{w_1} G(x)\mathrm{d}x + \int_0^{w_2} G(x)\mathrm{d}x.$$

At this price the monopolist's profit becomes

$$\int_0^{w_1} G(x)\mathrm{d}x + \int_0^{w_2} G(x)\mathrm{d}x - w_2C(w_1),$$

which is the social welfare function (1). The monopolist, internalizing cost increase and extracting all consumer surplus, chooses the first best (w_1^*, w_2^*) to maximize profit. The next result is obvious and its proof is omitted.

Proposition 6. *If the monopolist offers a drug plan, it chooses the first best, and sets a premium to extract all consumer surplus.*

A drug plan is the same as a two-part tariff. For a price Π, a monopolist sells consumers the rights to purchase medicine at price $G(w_1)$ in the first period and price $G(w_2)$ in the second period. The price Π is collected before consumers learn their types. Under this contract $(\Pi, G(w_1), G(w_2))$, the consumer's expected utility is

$$\int_0^{w_1} [G(x) - G(w_1)]\mathrm{d}x + \int_0^{w_2} [G(x) - G(w_2)]\mathrm{d}x - \Pi.$$

From contract $(\Pi, G(w_1), G(w_2))$, the monopolist's profit is

$$\Pi + w_1 G(w_1) + w_2[G(w_2) - C(w_1)].$$

Next given w_1 and w_2, when the consumer's reservation utility is 0, the highest price Π is

$$\Pi = \int_0^{w_1} [G(x) - G(w_1)]\mathrm{d}x + \int_0^{w_2} [G(x) - G(w_2)]\mathrm{d}x$$

At this maximum price, the monopolist's profit is

$$\int_0^{w_1} [G(x) - G(w_1)]\mathrm{d}x + \int_0^{w_2} [G(x) - G(w_2)]\mathrm{d}x + w_1 G(w_1) + w_2[G(w_2) - C(w_1)],$$

which again simplifies to the social welfare function (1). We record this as:

Corollary 1. *The monopolist's first-best drug plan can be implemented by a two-part tariff.*

6 Entry in period 2: Cournot competition with differentiated products

We now let there be a potential entrant. Firm 1 is the incumbent monopolist in period 1; Firm 2, the potential entrant in period 2. In period 1, Firm 1 produces Drug 1, at quality 1. Firm 1's cost structure remains the same; if it sells w_1 units of Drug 1 in period 1, its marginal cost becomes $C(w_1)$ in period 2. For convenience, we now denote Firm 1's period 2 cost by $c_1 = C(w_1)$, due to its sales of w_1 in period 1.

The potential entrant Firm 2 produces Drug 2, a superior medicine, say at quality $q > 1$, at constant marginal cost $c_2 > 0$. The entrant has to incur a fixed cost, $FC > 0$, to enter the market in period 2. We assume that for some $v \in [\underline{v}, \overline{v}]]$ we have $v = vq - c_2$, so at costs, high-valuation consumers prefer Drug 2 and low-valuation consumers prefer Drug 1.

If Firm 2 has entered in period 2, the two firms compete by choosing quantities. Suppose in period 2, Firm 1 produces w_ℓ units of the lower quality Drug 1, and Firm 2 produces w_h units of the higher quality Drug 2. The Cournot construct postulates that there are two prices, p_ℓ for Drug 1 and p_h for Drug 2, that will clear the market. When consumers are free to choose which product to purchase, the demand for Drug 1 will be w_ℓ at price p_ℓ and the demand for Drug 2 will be w_h at price p_h.

The prices that clear the market satisfy the following:

$$p_\ell = G(w_h + w_\ell) \quad \text{and} \quad G(w_h)q - p_h = G(w_h) - p_\ell. \tag{19}$$

According to prices in (19) consumer w_h is indifferent between buying Drug 2 at quality q and price p_h and buying Drug 1 at quality 1 and price p_ℓ, so all consumers with types below w_h prefer to purchase Drug 2. The consumer with type $w_\ell + w_h$ is indifferent between buying Drug 1 and nothing; all consumers with types between w_h and $w_\ell + w_h$ prefer to purchase Drug 1. The prices

in (19) clear the market.

After substitution, we write the market-clearing prices as

$$p_\ell = G(w_h + w_\ell) \quad \text{and} \quad p_h = G(w_h)(q-1) + G(w_h + w_\ell).$$

In period 2, variable profits for Firm 1 and Firm 2 are, respectively, $[p_\ell - c_1]w_\ell$ and $[p_h - c_2]w_h$, where again $c_1 = C(w_1)$ is Firm 1's cost in period 2 after it has produced w_1 in period 1. Taking into account Firm 2's fixed cost, we write profits as

$$\pi_1(w_\ell, w_h) = w_\ell[G(w_h + w_\ell) - c_1] \tag{20}$$

$$\pi_2(w_\ell, w_h) = w_h[G(w_h)(q-1) + G(w_h + w_\ell) - c_2] - FC. \tag{21}$$

Definition 2. *A Cournot equilibrium is (w_ℓ^e, w_h^e) that are mutual best responses:*

$$w_\ell^e = \arg\max_{w_\ell} w_\ell[G(w_h^e + w_\ell) - c_1] \tag{22}$$

$$w_h^e = \arg\max_{w_h} w_h[G(w_h)(q-1) + G(w_h + w_\ell^e) - c_2] - FC \tag{23}$$

provided that Firm 2's equilibrium profit is positive. If Firm 2's Cournot equilibrium profit is negative, it does not enter and Firm 1 continues to be a monopolist in period 2.

Lemma 2. *For any given Firm 2's quantity w_h, Firm 1's maximum profit*

$$\max_{w_\ell} w_\ell[G(w_h + w_\ell) - c_1],$$

and profit-maximizing quantity

$$\arg\max_{w_\ell} w_\ell[G(w_h + w_\ell) - c_1]$$

are decreasing in cost c_1.

Firm 2's maximum profit

$$\max_{w_h} \{w_h[G(w_h)(q-1) + G(w_h + w_\ell) - c_2] - FC\}$$

is decreasing in Firm 1's quantity w_ℓ.

As Firm 1's cost increases, its profit falls, and its profit-maximizing quantity also decreases. It is also obvious that Firm 2's profit falls as Firm 1's quantity increases, because Firm 2's residual demand becomes smaller (proof of Lemma 2 in Appendix).

How do Cournot equilibrium profits vary with costs? In period 2, Firm 1's cost is $c_1 = C(w_1)$ due to w_1 units of Drug 1 production in Period 1. To emphasize the subgame defined by $c_1 = C(w_1)$, we write explicitly the Cournot equilibrium as $(w_\ell^e(c_1), w_h^e(c_1))$. A Cournot equilibrium is given by mutual quantity best responses from the maximization of profits in (20) and (21). The Cournot equilibrium quantities (w_ℓ^e, w_h^e) satisfy the respective first-order conditions of the maximization of (22) with respect to w_ℓ, and the maximization of (23) with respect to w_h:

$$G(w_h^e + w_\ell^e) - c_1 + w_\ell^e g(w_h^e + w_\ell^e) = 0 \tag{24}$$

$$G(w_h^e)(q-1) + G(w_h^e + w_\ell^e) - c_2 + w_h^e[g(w_h^e)(q-1) + g(w_h^e + w_\ell^e)] = 0. \tag{25}$$

We assume that these reaction functions uniquely determine the Cournot equilibrium. Then we write the Cournot equilibrium profits as

$$\pi_1^e(c_1) \equiv \pi_1(w_\ell^e(c_1), w_h^e(c_1)) = w_\ell^e(c_1)[G(w_h^e(c_1) + w_\ell^e(c_1)) - c_1] \tag{26}$$

$$\pi_2^e(c_1) \equiv \pi_2(w_\ell^e(c_1), w_h^e(c_1)) = w_h^e(c_1)[G(w_h^e(c_1))(q-1) + G(w_h^e(c_1) + w_\ell^e(c_1)) - c_2] - FC. \tag{27}$$

Firm 2's equilibrium profit is its maximized profit from choosing w_h optimally against Firm 1's quantity $w_\ell^e(c_1)$. Hence, we apply the envelope theorem to obtain

$$\frac{\mathrm{d}\pi_2^e(c_1)}{\mathrm{d}c_1} = \frac{\partial \pi_2(w_\ell^e(c_1), w_h^e(c_1))}{\partial w_\ell} \frac{\mathrm{d}w_\ell^e(c_1)}{\mathrm{d}c_1} = w_h^e(c_1) g(w_h^e(c_1) + w_\ell^e(c_1)) \frac{\mathrm{d}w_\ell^e(c_1)}{\mathrm{d}c_1},$$

which is positive if Firm 1's Cournot equilibrium quantity is decreasing in Firm 1's own cost, namely $\dfrac{\mathrm{d}w_\ell^e(c_1)}{\mathrm{d}c_1} < 0$.

The following is standard comparative static results on Cournot equilibria, and its proof is in the Appendix.

Lemma 3. *Suppose that the demand function G is concave. Firm 1's Cournot equilibrium quantity $w_\ell^e(c_1)$ is decreasing in its own cost. Firm 2's Cournot equilibrium quantity $w_h^e(c_1)$ is increasing in the rival's cost.*

6.1 Entry deterrence and accommodation

What are incumbent Firm 1's choices in period 1 to affect entry? We begin with:

Definition 3 (Entry deterrence)**.** *Given any FC, suppose that Firm 1 chooses a quantity in period 1 so low that in period 2, Firm 1's cost will not allow Firm 2 to earn a positive profit, then we call it an entry deterrence quantity.*

Formally, define w_1^D, with $c_1^D = C(w_1^D)$, by

$$\pi_2^e(c_1^D) = w_h^e(c_1^D)[G(w_h^e(c_1^D))(q-1) + G(w_h^e(c_1^D) + w_\ell^e(c_1^D)) - c_2] - FC = 0, \tag{28}$$

where $\pi_2^e(c_1^D) \equiv \pi_2(w_\ell^e(c_1^D), w_h^e(c_1^D))$ is Firm 2's Cournot equilibrium profit post entry. Firm 1's quantity in period 1, w_1, is said to deter entry if $w_1 \leq w_1^D$.

Firm 1 deters entry by producing w_1 smaller than the critical level w_1^D which makes Firm 2's Cournot equilibrium profit vanish in period 2. By Lemmas 2 and 3, the value of w_1^D is well defined. Equation (28) defines a functional relationship between the fixed cost FC and c_1^D. Firm 2's Cournot equilibrium profit is decreasing in Firm 1's cost. Hence, inverting (28), we obtain $c_1 = \phi(FC)$. The function ϕ gives Firm 1's period 1 (highest) cost to deter entry. In case Firm 2's fixed cost is so low that entry cannot be prevented, then we just set $\phi(FC)$ to be an arbitrary negative number.

If the monopoly quantity w_1^M in Proposition 4 results in a cost $C(w_1^M) \leq \phi(FC)$, then entry is deterred automatically. Next, if the monopoly quantity is higher, $C(w_1^M) > \phi(FC)$, Firm 1 can still deter entry by suppressing production; in this case, it retains monopoly power. So suppose that Firm 1 produces $w_1 \leq w_1^D < w_1^M$. The profit in period 1 becomes $w_1 G(w_1)$. Then in period 2 its

cost is $c_1 = C(w_1)$. Because entry has been deterred, Firm 1's period 2 profit is $w[G(w) - C(w_1)]$ from producing w in period 2. Given entry deterrence, Firm 1's period 2 maximum profit is $\max_w w[G(w) - C(w_1)]$. The optimal quantity to deter entry is given by

$$\arg \max_{w_1 \leq w_1^D} \{w_1 G(w_1) + \max_w w[G(w) - C(w_1)]\}. \tag{29}$$

We present the following results, and its proof is in the Appendix.

Proposition 7. *If Firm 1 deters entry by producing w_1 with $C(w_1) \leq \phi(FC)$, it reduces antibiotic resistance compared to the monopoly level in Proposition 4. That is, in an equilibrium without entry, in period 1 Firm 1 produces less than w_1^M in Proposition 4, Firm 1's profit falls from the monopoly level, but the cost increase in period 2 is lower than the monopoly regime.*

Suppose the entry deterrence quantity is below the monopoly level: $\phi(FC) = C(w_1^D) < C(w_1^M)$. Without the restriction $w_1 \leq w_1^D$, Firm 1 would have chosen the monopoly quantities w_1^M and w_2^M in Proposition 4, but doing so violates the entry-deterrence requirement that Firm 1 must produce less than w_1^M. Hence, Firm 1's period 1 quantity must be w_1^D. As a result, the cost increase in period 2 would be lower than the monopoly level. Firm 1 effectively raises its price in period 1, but the cost in period 2 becomes lower. Firm 1 would be earning less than the full monopoly profit, but is able to deter entry.

Next, we consider the entry-accommodation strategy. Here, in period 1 Firm 1 produces w_1 with $C(w_1) > \phi(FC)$. This means a higher profit in period 1 than deterrence, but now Firm 2 enters, and the Cournot equilibrium results. In this case, Firm 1's profit in the two periods sum to

$$w_1 G(w_1) + \max_{w_\ell} w_\ell [G(w_h^e + w_\ell) - C(w_1)] = w_1 G(w_1) + w_\ell^e [G(w_h^e + w_\ell^e) - C(w_1)],$$

where (w_ℓ^e, w_h^e) are the Cournot equilibrium quantities. Firm 1's period 1 equilibrium quantity w_1

solves

$$\max_{w_1 \geq w_1^D} \{w_1 G(w_1) + w_\ell^e(w_1)[G(w_h^e(c_1) + w_\ell^e(c_1)) - c_1]\}, \tag{30}$$

where $c_1 = C(w_1)$, and $(w_\ell^e(c_1), w_h^e(c_1))$ are the Cournot equilibrium quantities in period 2. We present the following (with its proof in the Appendix).

Proposition 8. *If Firm 1 accommodates entry by producing w_1 where $C(w_1) > \phi(FC)$, it may or may not exacerbate antibiotic resistance compared to the monopoly level in Proposition 4. That is, Firm 1's profit falls from the monopoly level, but the cost in period 2 may be higher or lower than the monopoly regime.*

Under entry accommodation, the first-order derivative of Firm 1's profit with respect to quantity w_1 is

$$w_1 g(w_1) + G(w_1) + w_\ell^e(w_1)[g(w_h^e(w_1) + w_\ell^e(w_1))]\frac{\mathrm{d}w_h^e(w_1)}{\mathrm{d}w_1} - w_\ell^e(w_1)C'(w_1).$$

This is to be compared with the optimal monopoly choice of period 1 quantity, characterized by

$$w_1 g(w_1) + G(w_1) - w_2 C'(w_1),$$

where w_1 and w_2 are optimal quantities in the two periods under monopoly. The extra term under entry accommodation in Cournot competition is

$$w_\ell^e(w_1)[g(w_h^e(w_1) + w_\ell^e(w_1))]\frac{\mathrm{d}w_h^e(w_1)}{\mathrm{d}w_1}. \tag{31}$$

By Lemma 3, Firm 2's quantity is increasing in Firm 1's period 1 cost, so the derivative $\dfrac{\mathrm{d}w_h^e(w)}{\mathrm{d}w}$ is positive, but g is negative, being the slope of the demand function. This extra, negative term compared to the monopoly situation can be interpreted as follows.

A monopoly Firm 1 fully internalizes the cost increase in period 2, so reduces quantity from the one-period monopoly level. In the accommodated entry Cournot competition scenario, Firm 1

faces a residual demand function, not the full market of consumers, so there is less of an incentive to reduce cost in period 1; this is an incentive to produce more in period 1, leading to more drug resistance. But there is an additional, strategic consideration, and this is reflected by the extra term in (31). Firm 1 earns more period 2 profit when its cost is low; this lower cost actually makes Firm 2 reduce its quantity (w_h), which raises Firm 1's residual demand. All else equal, Firm 1 has an incentive to reduce cost in period 2 by restricting quantity in period 1. This reduces drug resistance. Whether entry accommodation leads to more or less drug resistance relative to the monopoly regime is due to two opposite effects, so is ambiguous.

The policy implications of results in potential entry are these. Market equilibria are inefficient, partly because of imperfect competition, and partly because of the incumbent Firm 1 failing to internalizing the cost increase due to antibiotic resistance. The obvious consideration is whether entry is to be encouraged, and to what extent. Cost subsidization for the entrant encourages entry. Marginal-cost subsidization and fixed-cost subsidization work somewhat different. Fixed-cost does not affect quantity decisions after entry (in period 2), given the incumbent's cost in period 2. However, for the same incumbent cost, marginal cost subsidization will alter the Cournot equilibrium. We do not attempt an analysis of subsidization of the entrant's cost; it appears to be a fairly mechanical way to crank out pros and cons.

7 Conclusion

We set up a formal theory of antibiotic resistance. The excessive use of an antibiotic degrades its power to kill micro-organisms. We model it as an increase in cost or a decrease in quality. The degradation like the depletion of a common resource, a sort of the tragedy of the commons. Whereas the extant literature has recognized this, we analyze equilibrium outcomes in perfect competition, monopoly, and imperfect competition under potential entry.

It is not the purpose here to propose new policy recommendations. Indeed, many scholars and practitioners have thought long and hard about policies to combat antibiotic resistance. Our purpose here is simply to reframe the resistance problem in the light of market structures. Indeed, we do not take it as given that resistance is to be completely eliminated. The cost of doing so may be exceedingly high because current consumer surplus loss may be too high to compensate future consumer surplus gain.

The primitives in our model are a demand function and a cost function. The role of educating consumers and persuading them to use antibiotics more judiciously is like changing the demand function. The ultimate technological advance is to avoid resistance, so that the cost function is flat, not increasing in current consumption. Welfare improvement may originate from policies other than taxes, subsidies, or some sort of performance based contracting.

Appendix

Proof of Lemma 1

The first-order conditions with respect to w_1 and w_2 are (10) and (11) in Proposition 3. Equations (10) and (11) define w_1 and w_2 as implicit functions of s. We differentiate (10) to obtain

$$G'(w_1)\frac{\mathrm{d}w_1}{\mathrm{d}s} - w_2\left[sC''(1-s+sw_1)(-1+w_1+s\frac{\mathrm{d}w_1}{\mathrm{d}s}) + C'(1-s+sw_1)\right] - sC'(1-s+sw_1)\frac{\mathrm{d}w_2}{\mathrm{d}s} = 0.$$

Next, we differentiate (11) to obtain

$$G'(w_2)\frac{\mathrm{d}w_2}{\mathrm{d}s} - C'(1-s+sw_1)(-1+w_1) - sC'(1-s+sw_1)\frac{\mathrm{d}w_1}{\mathrm{d}s} = 0.$$

Collecting terms and simplifying, we obtain

$$\begin{aligned}
&[G'(w_1) - s^2 w_2 C''(1-s+sw_1)]\frac{\mathrm{d}w_1}{\mathrm{d}s} - sC'(1-s+sw_1)\frac{\mathrm{d}w_2}{\mathrm{d}s} \\
&\qquad = w_2\left[sC''(1-s+sw_1)(-1+w_1) + C'(1-s+sw_1)\right] \\
&-sC'(1-s+sw_1)\frac{\mathrm{d}w_1}{\mathrm{d}s} + G'(w_2)\frac{\mathrm{d}w_2}{\mathrm{d}s} = C'(1-s+sw_1)(-1+w_1).
\end{aligned}$$

We rewrite the two simultaneous equations in matrix form

$$\begin{aligned}
&\begin{bmatrix} G'(w_1) - s^2 w_2 C''(1-s+sw_1) & -sC'(1-s+sw_1) \\ -sC'(1-s+sw_1) & G'(w_2) \end{bmatrix}\begin{bmatrix} \frac{\mathrm{d}w_1}{\mathrm{d}s} \\ \frac{\mathrm{d}w_2}{\mathrm{d}s} \end{bmatrix} \\
= &\begin{bmatrix} w_2\left[sC''(1-s+sw_1)(-1+w_1) + C'(1-s+sw_1)\right] \\ C'(1-s+sw_1)(-1+w_1) \end{bmatrix}.
\end{aligned}$$

The determinant of the left-hand side parameter matrix is positive due to the second-order conditions for the maximization of (8); we call this determinant $|A|$. We then apply Cramer's rule to solve for the derivatives $\frac{dw_1}{ds}$ and $\frac{\mathrm{d}w_2}{\mathrm{d}s}$. After simplification we have

$$\frac{\mathrm{d}w_1}{\mathrm{d}s} = \frac{w_2 G'(w_2)\left[C'(1-s+sw_1) - sC''(1-s+sw_1)(1-w_1)\right] - sC'(1-s+sw_1)^2(1-w_1)}{|A|}.$$

Next, we have

$$\begin{aligned}\frac{\mathrm{d}w_2}{\mathrm{d}s} &= \frac{-\left[G'(w_1) - s^2 w_2 C''(1-s+sw_1)\right] C'(1-s+sw_1)(1-w_1)}{|A|} \\ &\quad + \frac{sC'(1-s+sw_1)w_2\left[C'(1-s+sw_1) - sC''(1-s+sw_1)(1-w_1)\right]}{|A|}.\end{aligned}$$

Hence, if C'' is sufficiently small, $\frac{\mathrm{d}w_1}{\mathrm{d}s}$ is negative, and $\frac{\mathrm{d}w_2}{\mathrm{d}s}$ is positive.

Proof of Proposition 3

We construct the unique Drug Plan Competitive Equilibrium in the following way. First, for any given $B < \overline{B}$, find w_1^e to satisfy (9). Because $B < \overline{B}$, such a w_1^e satisfies $w_1^* < w_1^e < 1$. Second, given w_1^e, choose s^e and w_2^e to satisfy (10) and (11). Finally, set premium π^e by (12).

Now we confirm that we have a Drug Plan Competitive Equilibrium. Because $B < \overline{B}$, such a w_1^e from (9) has $w_1^* < w_1^e < 1$. Equations (10) and (11) are the first-order conditions for $(\widetilde{w}_1(s), \widetilde{w}_2(s))$ in (8). The concavity of the social welfare function (1) implies that the objective in (8) is concave. Hence, given s, $(\widetilde{w}_1(s), \widetilde{w}_2(s))$ is unique. By Lemma 1, as s varies between 0 and 1, $\widetilde{w}_1(s)$ monotone decreases from 1 to w_1^*. Hence, there is an s^e such that (10) and (11) would hold for that $s = s^e$. Then obviously , $w_2^e = \widetilde{w}_2(s^e)$. By construction, consumers, ex ante, are indifferent between enrolling and staying independent, so it is optimal for s^e of consumers to join. We have constructed the unique Drug Plan Competitive Equilibrium for $B < \overline{B}$.

Finally, consider $B > \overline{B}$. At $B = \overline{B}$, all consumers optimally choosing the drug plan is an equilibrium. Any higher B will not change the equilibrium.

Proof of Lemma 2

By the envelope theorem, Firm 1's maximum profit has a derivative with respect to cost c_1 equal to the partial derivative of the profit function with respect to cost c_1, and this partial derivative is

$-w_\ell < 0$. Next, the cross partial of Firm 1's profit with respect to cost c_1 and quantity w_ℓ is

$$\frac{\partial^2 w_\ell[G(w_h + w_\ell) - c_1]}{\partial c_1 \partial w_\ell} = -1.$$

The derivative of Firm 1's profit-maximizing quantity with respect to cost has the same sign as this cross partial, so it is also negative.

By the envelope theorem again, Firm 2's maximum profit has a derivative with respect to Firm 1's quantity equal to the partial derivative with respect to w_ℓ, which is $w_h G'(w_h + w_\ell) < 0$ because the demand G is a decreasing function.

Proof of Lemma 3

Totally differentiating the first-order conditions respectively for the maximizations of (20) and (21) (which then define a Cournot equilibrium in (22) and (23)) we have

$$\frac{\partial^2 \pi_1(w_\ell^e, w_h^e)}{\partial w_\ell^2} \mathrm{d}w_\ell + \frac{\partial^2 \pi_1(w_\ell^e, w_h^e)}{\partial w_\ell \partial w_h} \mathrm{d}w_h = -\frac{\partial^2 \pi_1(w_\ell^e, w_h^e)}{\partial w_\ell \partial c_1} \mathrm{d}c_1$$

$$\frac{\partial^2 \pi_2(w_\ell^e, w_h^e)}{\partial w_h \partial w_\ell} \mathrm{d}w_\ell + \frac{\partial^2 \pi_2(w_\ell^e, w_h^e)}{\partial w_h^2} \mathrm{d}w_h = -\frac{\partial^2 \pi_2(w_\ell^e, w_h^e)}{\partial w_h \partial c_2} \mathrm{d}c_2,$$

and from (24) and (25) they turn out to be

$$\left[2g(w_h^e + w_\ell^e) + g'(w_h^e + w_\ell^e)\right] \mathrm{d}w_\ell + \left[g(w_h^e + w_\ell^e) + w_\ell^e g'(w_h^e + w_\ell^e)\right] \mathrm{d}w_h = \mathrm{d}c_1$$

$$\left[g(w_h^e + w_\ell^e) + w_h^e g'(w_h^e + w_\ell^e)\right] \mathrm{d}w_\ell + \{2g(w_h^e + w_\ell^e) + w_h^e g'(w_h^e + w_\ell^e) + (q-1)[2g(w_h^e) + g'(w_h^e)]\} \mathrm{d}w_h = 0.$$

We express this system in matrix form

$$\begin{bmatrix} 2g(w_h^e + w_\ell^e) + g'(w_h^e + w_\ell^e) & g(w_h^e + w_\ell^e) + w_\ell^e g'(w_h^e + w_\ell^e) \\ g(w_h^e + w_\ell^e) + w_h^e g'(w_h^e + w_\ell^e) & 2g(w_h^e + w_\ell^e) + w_h^e g'(w_h^e + w_\ell^e) + (q-1)[2g(w_h^e) + g'(w_h^e)] \end{bmatrix} \begin{bmatrix} \mathrm{d}w_\ell \\ \mathrm{d}w_h \end{bmatrix} = \begin{bmatrix} \mathrm{d}c_1 \\ 0 \end{bmatrix}.$$

We use Cramer's Rule to compute

$$\frac{\mathrm{d}w_\ell^e}{\mathrm{d}c_1} = \frac{\det(A_\ell)}{\det(A)},$$

where $\det(A)$ is the determinant of the coefficient matrix A and $\det(A_\ell)$ is the determinant of the matrix obtained by replacing the first column of A with the transpose of $(1, 0)$.

The determinant of A is

$$\begin{aligned}\det(A) = &\left[2g(w_h^e + w_\ell^e) + g'(w_h^e + w_\ell^e)\right] \times \left\{2g(w_h^e + w_\ell^e) + w_h^e g'(w_h^e + w_\ell^e) + (q-1)[2g(w_h^e) + g'(w_h^e)]\right\} \\ &- \left[g(w_h^e + w_\ell^e) + w_\ell^e g'(w_h^e + w_\ell^e)\right] \times \left[g(w_h^e + w_\ell^e) + w_h^e g'(w_h^e + w_\ell^e)\right].\end{aligned}$$

The determinant of A_ℓ is

$$\begin{aligned}\det(A_\ell) &= [\mathrm{d}c_1] \times \left\{2g(w_h^e + w_\ell^e) + w_h^e g'(w_h^e + w_\ell^e) + (q-1)[2g(w_h^e) + g'(w_h^e)]\right\} \\ &\quad - \left[g(w_h^e + w_\ell^e) + w_\ell^e g'(w_h^e + w_\ell^e)\right] \times 0 \\ &= \mathrm{d}c_1 \times \left\{2g(w_h^e + w_\ell^e) + w_h^e g'(w_h^e + w_\ell^e) + (q-1)[2g(w_h^e) + g'(w_h^e)]\right\}.\end{aligned}$$

By the concavity of the demand function, we have $g'(w) \leq 0$, so $\det(A)$ is positive and $\det(A_\ell)$ is negative. Therefore,

$$\frac{\mathrm{d}w_\ell^e}{\mathrm{d}c_1} = \frac{\det(A_\ell)}{\det(A)} < 0.$$

Next, $\det(A_h)$ is the determinant of the matrix obtained by replacing the second column of A with $(\mathrm{d}c_1, 0)^T$ and therefore

$$\begin{aligned}\det(A_h) &= \left[2g(w_h^e + w_\ell^e) + g'(w_h^e + w_\ell^e)\right] \cdot 0 - \left[g(w_h^e + w_\ell^e) + w_h^e g'(w_h^e + w_\ell^e)\right] \cdot \mathrm{d}c_1 \\ &= -\left[g(w_h^e + w_\ell^e) + w_h^e g'(w_h^e + w_\ell^e)\right] \cdot \mathrm{d}c_1.\end{aligned}$$

By the concavity of the demand function, we have $g'(w) \leq 0$, so $\det(A_h)$ is positive. Recall that $\det(A)$ is positive; thus we get

$$\frac{\mathrm{d}w_h^e}{\mathrm{d}c_1} = \frac{\det(A_h)}{\det(A)} > 0.$$

Proof of Proposition 7

Let $c_1^M = C(w_1^M)$, where w_1^M is the monopoly period 1 quantity in Proposition 4. Either the monopoly period 1 quantity yields a cost $c_1^M = C(w_1^M)$ below or above the deterrence threshold. That is, either $c_1^M \leq \phi(FC)$, or $c_1^M > \phi(FC)$. If $c_1^M \leq \phi(FC) = C(w_1^D)$, Firm 1's monopoly quantity w_1^M already deters entry, so the cost increase in period 2 will remain the same. If $c_1^M > \phi(FC)$, then Firm 1 must produce a period 1 quantity less than w_1^D. The constraint $w_1 \leq w_1^D$ in (29) binds. Because $c_1^M > \phi(FC) = C(w_1)$, we have $w_1 < w_1^M$. Firm 1 produces less than the monopoly level. Firm 1's total profit must decrease because of the binding constraint $w_1 \leq w_1^D < w_1^M$.

Proof of Proposition 8

Recall that $w_1^M > w_1^D$ so that the period 1 monopoly quantity is larger than the entry deterrence threshold. To accommodate entry, Firm 1 chooses quantities according to (30). The monopolist chooses (w_1, w_2) to maximize profit in (13). The two maximization problems are respectively:

$$\max_{w_1 \geq w_1^D} \{w_1 G(w_1) + w_\ell^e(w_1)[G(w_h^e(w_1) + w_\ell^e(w_1)) - C(w_1)]\} \quad \text{and}$$

$$\max_{w_1, w_2} w_1 G(w_1) + w_2[G(w_2) - C(w_1)].$$

The first-order derivative of Firm 1's entry-accommodating equilibrium profit with respect to w_1 is

$$w_1 g(w_1) + G(w_1) - w_\ell^e(w_1) C'(w_1) + w_\ell^e(w_1)[g(w_h^e(w_1) + w_\ell^e(w_1))] \frac{\mathrm{d}w_h^e(w_1)}{\mathrm{d}w_1},$$

where we have ignored the derivatives with respect to $w_\ell^e(w_1)$, by the envelope theorem. Notice that $w_\ell^e(w_1)$ must be less than what Firm 1 would have chosen if it was the only firm in period 2. Also, the last term, $w_\ell^e(w_1) g(w_h^e(w_1) + w_\ell^e(w_1)) \frac{\mathrm{d}w_h^e(w_1)}{\mathrm{d}w_1}$, is negative because g is negative and $\frac{\mathrm{d}w_h^e(w_1)}{\mathrm{d}w_1} > 0$ by Lemma 3. It is possible that w_1 may be higher or lower than w_1^M.

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