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Collective Rights Organizations and Investment in Upstream R&D

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Abstract

We examine third-party collective rights organisations (CROs) such as clearinghouses that license innovations on behalf of inventors when downstream uses require licenses to multiple complementary innovations. We consider two simple royalty redistribution schemes, two different innovation environments and two different antitrust rules. We show that in most cases CROs increase incentives to invest in R&D as they increase profits from licensing. However, incentives to invest of inventors who have the unique ability to develop a crucial component may be weakened. We also show that CROs may increase or decrease expected welfare, and are more likely to be beneficial when R&D costs are relatively high, and/or the probability of success for inventors is relatively low.

Keywords: Intellectual property, licensing, collective rights organizations, anticommons.

JEL: L24, O31, O34

1 Introduction

Many new innovations or products depend on multiple complementary upstream intellectual property rights. When different upstream components have different owners, licensing for downstream uses that combine these components may suffer from various inefficiencies dubbed the "tragedy of the anticommons" (Heller & Eisenberg 1998, Buchanan & Yoon 2000). Specifically, negotiating with multiple licensors may entail high transaction costs, and independent uncoordinated licensors may set royalties that are inefficiently high in total. For example, development of a new medical genetic diagnostic test may require licensing multiple patented inventions, owned by different inventors, related to gene sequences, gene expression technologies, and so on (Van Overwalle *et al* 2006, OECD 2002). This may retard downstream innovation and/or lead to end-users paying high prices for downstream products. As well as genetics, similar situations can also arise in information technology and communications industries, for example (Shapiro 2001, Aoki & Nagaoka 2005).

In response to these licensing inefficiencies, a number of "collective rights" organizations (CROs) and arrangements have emerged or been promoted, including patent pools, cross-licensing, copyright collectives, and third-party clearinghouses (Shapiro 2001, van Zimmeren *et al* 2006, Aoki & Schiff 2008, Aoki, 2008) discusses various types of CROs (excluding clearinghouses) and how these may be used to mitigate anticommons problems in licensing. Patent pools in particular have received much attention in the literature, for example, Lerner & Tirole (2004) examine when patent pools are efficiency enhancing ex post, and Lerner *et al* (2007) empirically examine the types of licensing rules used by patent pools. Layne-Farrar & Lerner (2008) and Aoki & Nagaoka (2004) examine royalty distribution rules of patent pools and incentives of patent owners to join pools, which is are issues that also arises in the current paper. Hoppe and Ozdenoren (2005) examine the role of CROs as intermediaries to reduce informational problems in licensing markets. In contrast to our paper, all of these papers take an existing set of intellectual property rights as given. We concentrate on the effects of collective licensing on incentives to innovate. Most similar to our work is Gilbert & Katz (2007) and Meniere (2008) who consider division of profits among innovators who are racing to develop complementary components, however they do not examine collective licensing. In this paper we focus on the ef-

fects of CROs on incentives to invest in upstream R&D for complementary components and the consequences for economic welfare.

We use a simple product innovation framework where a downstream innovation or product requires the development of two complementary upstream components. A number of upstream research firms can invest in developing these components, and each has some probability of success. When multiple firms invest, there is some chance that multiple substitute versions of either or both components will be developed independently. All successful innovators earn revenues by licensing their innovations to downstream users. After research firms invest and the outcome of the innovation process is realized, each successful inventor can choose to license independently, or join a CRO that licenses on behalf of its members. The CRO sets a single royalty to maximize the joint profits of its members.

We evaluate several different modes of operation for the CRO relating to its royalty distribution scheme and antitrust policy. Antitrust policy either does or does not allow the CRO to license substitute innovations jointly. The CRO may also distribute royalty revenues equally or unequally among its members according to whether they are the sole inventor of a component or whether there are substitutes for a component. Ex post, we show that banning licensing of substitutes can generate the same welfare level as not banning but permitting the CRO to use an unequal redistribution rule. In addition, an unequal redistribution rule can perform better than an equal redistribution rule as it can ensure that sole inventors of a component do not prefer to license independently from the CRO. However, unless licensing of substitutes is banned, a CRO may reduce ex post welfare if both components have multiple substitutes.

In the long run, the effects of a CRO on the ex ante incentives of upstream innovators to invest are arguably more important than the ex post effects on licensing of existing innovations. We therefore consider two different innovation models within which we compare the ex ante performance of CROs. In the first model, both components are symmetric and a large number of competitive research firms have the ability to develop each. In the second model, one component is unique and a single firm has the ability to develop it while the other component has many possible inventors.

We find that CROs generally increase ex ante incentives to invest in upstream R&D, as the expected ex post profit gains from joint licensing

outweigh any losses from royalty sharing. A possible exception is when one component can only be developed by one firm and the CRO is permitted to license substitutes jointly. In this case the unique inventor only benefits from the CRO if the other component has a single inventor, which occurs with relatively high probability only when investment in the other component is relatively low. Further, since the CRO increases ex post profits of inventors of substitute components, it increases investment in such components, and thus is more likely to make the unique inventor worse off.

CROs may also increase or decrease ex ante expected welfare. We show that a CRO that distributes royalties unequally can always generate higher expected welfare for a given level of investment than no CRO, as it can achieve participation of all successful innovators and solve the "anticommons" inefficiencies without introducing excessive anticompetitive distortions ex post. In the symmetric investment model, this means that an unequal CRO that can license substitutes jointly is equivalent to a CRO that is not permitted to license substitutes jointly. Thus unequal redistribution rules can replace antitrust rules without affecting welfare. In contrast, a CRO that distributes royalties equally and can license substitutes jointly does not always perform better than no CRO for a given investment level, as it cannot achieve full participation of innovators. We show that an equal CRO only performs better than no CRO when the level of investment in R&D is relatively low, so that the probability that one or both components has multiple successful inventors is not too high.

These basic welfare comparisons do not take account of the change in the R&D investment level induced by the CRO. Once investment is made endogenous, an unequal CRO or a CRO that cannot license substitutes jointly can reduce ex ante expected welfare if it causes an excessive increase in investment. We use a numerical simulation based on a binomial innovation process to compare the equilibrium expected welfare of the different CROs under the different innovation models. In general, a CRO that redistributes royalties unequally or a CRO that cannot license substitutes jointly performs better than one that distributes royalties equally and can license substitutes jointly, except for some relatively small subset of parameter values. In addition, the CROs tend to perform better than no CRO when costs of innovation are high, and/or the probability of an inventor's success is low, as these are the cases where stimulating R&D investment through increased

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licensing profits is most likely to be beneficial.

The organization of the rest of this paper is as follows. In the next section we present a simple model of ex post licensing with a CRO. Then in section 3 we embed this in two different upstream investment models, and compare different types of CRO in terms of ex ante expected profits and welfare. In section 4 we perform further welfare analysis using numerical simulations with endogenous investment. Section 5 concludes.

2   Effects of CROs on ex post licensing

Our model of IP licensing is as follows. There are two complementary components or research tools, A and B, that are needed for the production of a downstream innovation or product. Upstream research firms invest in R&D to develop these components and earn royalties by licensing their innovations to downstream users. An inventor of either component cannot earn any royalties unless the other component has also been invented. There are a large number of research firms, each of which has the capacity to undertake a single research 'project' at some cost. Research firms are specialized in the development of A or B. Any research project may result in the invention of one of the components or it may be unsuccessful and invent nothing. We allow for the possibility that perfect substitute versions of either component may be independently invented by different inventors.

A third-party CRO may also exist and can license innovations on behalf of member inventors. All successful inventors have the option to join the CRO or license independently. The CRO seeks to maximize the total royalty revenues of its members from licensing, and distributes these revenues among its members according to a distribution rule that it announces in advance. The CRO may also be subject to an antitrust rule that prohibits it from jointly licensing substitute innovations.

Definition 1 *The CRO operates under a* strict antitrust rule *if joint licensing of substitutes is prohibited.*

If a strict antitrust rule applies and substitute inventors of either component have joined the CRO, we assume that the downstream licensee picks one of the substitute versions at random to license and only the chosen version receives royalty payments. If the antitrust rule is not strict, joint licensing

of substitute innovations is permitted and royalties are shared among all members.

Given this setup, innovation and licensing takes place in four stages:

Stage 1: The antitrust rule is set and announced.

Stage 2: The CRO sets and announces a royalty redistribution rule consistent with the anti-trust rule.

Stage 3: Each research firm decides whether or not to invest in an R&D project and those that invest invent a component according to their type, with some probability.

Stage 4: Successful inventors simultaneously decide whether or not to join the CRO or license independently, and then innovations are licensed by the CRO and/or any independent inventors and royalties are paid by licensees.

In this section we describe our model of the final (ex-post) stage of this process and find the ex post equilibrium payoffs of successful inventors and equilibrium welfare, for a given outcome of the earlier stages. The next section examines two alternative models of the third stage and compares different antitrust and redistribution rules.

We look for a subgame perfect equilibrium. Provided that both components have been invented, successful inventors can earn royalties from licensing. Let π_M denote the total monopoly royalties obtained by licensing all successful inventions of both components jointly and let π_D denote the duopoly royalties each component receives when there is one independent licensor for each component. Similarly, let W_M denote the total welfare level that arises when both components are licensed jointly, W_D denote the welfare level when the two components are licensed by two independent licensors, and $W_0 > W_M$ denote the welfare level when both components are licensed for zero royalties. Since components A and B are perfect complements, we make the following assumption about ex post profit and welfare levels:

Assumption 1 *The 'tragedy of the anticommons' reduces joint profits and welfare when the two components are licensed by two independent licensors compared to when they are licensed jointly: $\pi_M \geq 2\pi_D$ and $W_M \geq W_D$.*

The payoffs of successful inventors depend on the redistribution rule of the CRO and the antitrust rule. If the antitrust rule is strict, the CRO can

license at most one innovation for each component. If it licenses innovations for both components, we assume the total royalties are shared equally between the two specific innovations chosen by the downstream user.

If the antitrust rule is not strict, the CRO licenses all the innovations of its members jointly and shares royalty revenues among all members. In this case we consider two different policies:

Definition 2 *An* equal CRO *distributes its royalty revenues equally among its members. If the CRO earns π and has n members, each member receives π/n.*

Definition 3 *An* unequal CRO *distributes disproportionate royalty revenues to a member (if any) who is the sole successful inventor of a component when the other component is competitive. If the CRO earns π and one component has a single inventor and the other component has $n \geq 2$ inventors, the monopoly inventor receives $z\pi$ and all other inventors receive $(1-z)\pi/n$, where $z \in \left(\frac{1}{n+1}, 1\right)$. In all other situations, the CRO distributes revenues equally among its members.*

There are three cases where downstream production is possible:

Case 'MM': Both components have a single successful inventor;

Case 'MC': One component has a single inventor and the other component has two or more substitute (competitive) inventors; and

Case 'CC': Both components have two or more substitute inventors.

In cases MC and CC, inventors of a competitive component cannot earn any royalties unless they all join a CRO, since competition between them will drive royalties down to zero. Thus such inventors always join the CRO, if it exists.

In cases MM and MC a monopoly inventor of a component may or may not want to join the CRO. In case MM, if both inventors license independently they each receive π_D, while if both join any type of CRO they receive $\pi_M/2$. If one inventor joins the CRO but the other does not, the situation is effectively the same as where both do not join, and both receive π_D. Therefore, by Assumption 1, both successful inventors have a weakly dominant strategy to join a CRO in case MM.

If case MC arises, the successful inventors of the competitive component will all join the CRO, as explained above. Suppose the competitive

CRO Type	$\boldsymbol{\pi}_{MM}$	$\boldsymbol{\pi}_{MC}^{M}$	$\boldsymbol{\pi}_{MC}^{C}\left(n\right)$	$\boldsymbol{\pi}_{CC}\left(n_A,n_B\right)$
None	π_D	π_M	0	0
Equal (not strict)	$\pi_M/2$	π_D	π_D/n	$\pi_M/\left(n_A+n_B\right)$
Unequal (not strict)	$\pi_M/2$	$z\pi_M$	$\left(1-z\right)\pi_M/n$	$\pi_M/\left(n_A+n_B\right)$
Strict	$\pi_M/2$	$\pi_M/2$	$\frac{1}{n}\pi_M/2$	$\frac{1}{n_i}\pi_M/2;\, i=A,B$

Table 1: Equilibrium payoffs of successful inventors under different types of CRO and different outcomes of the innovation process.

component has n inventors. Under a strict antitrust rule, the CRO can license at most one invention of the competitive component together with the sole invention of the other component. Thus the inventor of the monopoly component receives $\pi_M/2$ from joining the CRO and π_D from not joining, so the monopoly inventor will join. If the antitrust rule is not strict, the monopoly inventor will join an equal CRO if $\pi_M/\left(n+1\right)\geq\pi_D$ and will join an unequal CRO if $z\pi_M\geq\pi_D$. To differentiate equal and unequal CROs, we make the following assumption:

Assumption 2 *A monopoly inventor of a component does not join an equal CRO when there are $n\geq2$ inventors of the other component, but does join an unequal CRO. That is, $\pi_M\leq3\pi_D$ and $z\geq\pi_D/\pi_M$.*[1]

We can now summarize the equilibrium payoffs of successful inventors in stage 4, in each of the three ex post cases above. Let π_{MM} be the royalties that a successful inventor receives in case MM, let π_{MC}^{M} be the royalties that the monopoly inventor receives in case MC, let $\pi_{MC}^{C}\left(n\right)$ be the royalties that a successful inventor of the competitive component receives in case MC when there are $n\geq2$ inventors of that component, and let $\pi_{CC}\left(n_A,n_B\right)$ be the royalties that a successful inventor receives in case CC when there are $n_A\geq2$ and $n_B\geq2$ successful inventors of A and B respectively.

Table 1 shows the values of these payoffs for different types of CRO. In comparison with no CRO, an equal CRO increases an inventor's royalties if there are multiple inventors of the same component, or if there is only one inventor of both components. However, such a CRO decreases royalties from π_M to π_D when the inventor is the sole inventor of a component but

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[1]Such a value of z achieves the CRO's objective of maximising the total royalties of its members, since it ensures that the total CRO royalties are π_M.

the other component is competitive. In this situation, the existence of the CRO reduces competition among inventors of the competitive component, which benefits them but harms the sole inventor of the other component.

An unequal CRO increases a successful inventor's royalties compared to no CRO unless the inventor is the sole inventor of one component while the other component is competitive. In this case the value of z is sufficient to induce the monopoly inventor to join the CRO, but she is still worse off compared to when no CRO exists, because the CRO gives some fraction of π_M to the competitive inventors of the other component. An unequal CRO may also make successful inventors better or worse off compared to an equal CRO. If, for example, A has a single inventor but B is competitive, the inventors of B receive π_D/n_B under an equal CRO, but $(1-z)\,\pi_M/n_B$ under an unequal CRO. Since $z \geq \pi_D/\pi_M$ to attract the inventor of A to join the unequal CRO, this reduces the payoffs of the inventors of B relative to the equal CRO.

Finally, if the antitrust rule is strict, the CRO induces all inventors to join and total ex-post licensing revenues are π_M, which is the same outcome as an unequal CRO without a strict antitrust rule. From Table 1, a CRO under a strict antitrust rule makes all inventors better off compared to no CRO except the monopoly inventor in case MC (like an unequal CRO). In cases MC and CC, all inventors of the competitive components join the CRO, but only one is chosen by the downstream licensor. Thus competitive licensors receive a payoff of $\pi_M/2$ with probability $1/n_i$ where n_i is the number of inventors of the same component.

Similarly, let W_{MM}, W_{MC} and W_{CC} be the equilibrium welfare levels attained in the three ex-post cases where production is possible. Table 2 shows the welfare levels (ignoring R&D costs) that result under each type of CRO in each case. Compared to no CRO, an equal CRO improves welfare when both components have a single inventor (case MM), but reduces welfare in all other cases, as the CRO allows substitute inventors of the same component to reduce competition among themselves. An unequal CRO with an appropriate value of z always attracts all inventors to join, and thus always achieves the welfare level W_M. Compared to no CRO, this increases welfare in case MM, but reduces welfare when both components have multiple inventors (case CC), and leaves welfare unchanged in case MC. In every case an unequal CRO generates at least as much welfare as an equal CRO, and

CRO Type	$\mathbf{W}_{MM}$	$\mathbf{W}_{MC}$	$\mathbf{W}_{CC}$
None	W_D	W_M	W_0
Equal (not strict)	W_M	W_D	W_M
Unequal (not strict)	W_M	W_M	W_M
Strict	W_M	W_M	W_M

Table 2: Equilibrium ex-post welfare (ignoring sunk investment costs) from licensing under different types of CRO.

outperforms it in case MC. A CRO under a strict antitrust rule achieves the same ex-post outcome as an unequal CRO, as it always induces all successful inventors to join.

3 Effects of CROs on ex ante expected profits and welfare

In this section we examine and compare CROs under two alternative models of the innovation process.

3.1 Investment model 1: All research projects are equal

In this model, each research project costs c and has the same chance of developing a component or developing nothing. Research firms and projects are exogenously specialized towards the development of A or B and a large number of firms are capable of undertaking projects of each type. Let N_A and N_B be the total number of projects undertaken to develop A and B respectively. The success of any project is independent of that of any other project. Given that $N_i \geq 1$ projects are undertaken for component $i = A, B$, the probability that $n_i \leq N_i$ successfully develop the component is denoted by $P\left(n_i, N_i\right)$, where $\sum_{n_i=0}^{N_i} P\left(n_i, N_i\right) = 1$ and $\lim_{N_i \to \infty} P\left(n_i, N_i\right) = 0$ for all $n_i \in \{0, 1, ..., N_i\}$.

Since the components are identical, we consider symmetric situations where $N_A = N_B = N$, thus $2N$ projects are undertaken in total. The expected profit of a research firm given N is denoted $\pi\left(N\right)$. The probability of case MM and a given research firm is one of the successful ones is $\frac{1}{N} P\left(1, N\right)^2$. The probability that a research firm is the sole inventor

of their component while the other component has $n \geq 2$ inventors (case MC, monopoly) is $\frac{1}{N}P(1,N)P(n,N)$. The probability that a research firm is one of $n \geq 2$ competitive inventors of their component in case MC is $\frac{n}{N}P(n,N)P(1,N)$. The probability that a research firm is one of $m \geq 2$ inventors of their component while the other component has $n \geq 2$ inventors (case CC) is $\frac{m}{N}P(m,N)P(n,N)$. Considering all possibilities under which the three cases can occur, using the payoff definitions from Table 1, the expected ex-ante profit of a research firm is

$$
\begin{aligned}
\pi(N) \;=\;& \tfrac{1}{N}P(1,N)^2\,\pi_{MM} + \tfrac{1}{N}P(1,N)\sum_{n=2}^{N}P(n,N)\left[\pi_{MC}^M + n\pi_{MC}^C(n)\right] \\
& + \sum_{m=2}^{N}\sum_{n=2}^{N}\tfrac{m}{N}P(m,N)P(n,N)\,\pi_{CC}(m,n) - c. \qquad (1)
\end{aligned}
$$

First let us consider the effect of imposing the strict antitrust rule on the CRO. From Table 1, both the unequal CRO and a strict CRO generate total royalties of π_M, but the distribution of these royalties among successful inventors differs except in case MM. Let $\pi^{UC}(N)$ and $\pi^{SC}(N)$ denote the expected ex-ante profits of an inventor under an unequal CRO and a strict CRO respectively. Substituting the appropriate ex-post payoffs from Table 1 into (1), we obtain

$$
\begin{aligned}
\pi^{UC}(N) \;=\;& \frac{1}{N}\left[\frac{1}{2}P(1,N)^2 + P(1,N)\sum_{n=2}^{N}P(n,N)\right]\pi_M \\
& + \frac{1}{N}\sum_{m=2}^{N}\sum_{n=2}^{N}\frac{m}{m+n}P(m,N)P(n,N)\,\pi_M - c \qquad (2)
\end{aligned}
$$

and

$$
\begin{aligned}
\pi^{SC}(N) \;=\;& \frac{1}{N}\left[\frac{1}{2}P(1,N)^2 + P(1,N)\sum_{n=2}^{N}P(n,N)\right]\pi_M \\
& + \frac{1}{N}\sum_{m=2}^{N}\sum_{n=2}^{N}P(m,N)P(n,N)\frac{\pi_M}{2} - c. \qquad (3)
\end{aligned}
$$

Note that $\pi^{UC}(N)$ is independent of z, due to the symmetry of research projects. Comparing $\pi^{UC}(N)$ and $\pi^{SC}(N)$ gives the following result.

Proposition 1 *Given N, expected profit of a research firm is identical under an unequal CRO with a not strict antitrust rule, and a CRO with a strict antitrust rule: $\pi^{UC}(N) = \pi^{SC}(N)$ for all $N \geq 1$.*

Proof. From (2) and (3), $\pi^{UC}(N) = \pi^{SC}(N)$ if

$$\sum_{m=2}^{N}\sum_{n=2}^{N} \tfrac{m}{m+n} P(m,N) P(n,N) = \frac{1}{2} \sum_{m=2}^{N}\sum_{n=2}^{N} P(m,N) P(n,N),$$

which is true because given any set of numbers $x_1, ..., x_N$, $2\sum_{i=1}^{N}\sum_{j=1}^{N} \tfrac{i}{i+j} x_i x_j = \sum_{i=1}^{N}\sum_{j=1}^{N} x_i x_j = \left[\sum_{i=1}^{N} x_i\right]^2$. ∎

Proposition 1 says that, in spite of the different ex-post distributions of revenues, an unequal CRO with no antitrust restrictions generates the same expected profits to inventors as a CRO that is prohibited from jointly licensing substitutes. Equilibrium investment levels will therefore be the same under these two regimes.

Similarly, let $\pi^{NC}(N)$ and $\pi^{EC}(N)$ be a research firm's expected profit under no CRO and an equal CRO respectively. Recall from Table 1 that the existence of a CRO potentially involves both ex post gains and losses for research firms depending on the outcome of the innovation process. The following proposition shows that, in terms of ex ante expected profits, the gains always outweigh the losses, for any given N.

Proposition 2 *Given N, the expected profit of a research firm is highest with an unequal (or strict) CRO and lowest with no CRO, that is, $\pi^{UC}(N) = \pi^{SC}(N) \geq \pi^{EC}(N) \geq \pi^{NC}(N)$ for all $N \geq 1$.*

Proof. Substituting payoffs from Table 1 into (1), $\pi^{UC}(N) \geq \pi^{EC}(N)$ if $P(1,N)\sum_{n=2}^{N} P(n,N)[\pi_M - 2\pi_D] \geq 0$, which is true by Assumption 1. Similarly, $\pi^{UC}(N) \geq \pi^{NC}(N)$ is equivalent to $P(1,N)^2\left[\frac{1}{2}\pi_M - \pi_D\right] + \sum_{m=2}^{N}\sum_{n=2}^{N} \tfrac{m}{m+n} P(m,N) P(n,N) \pi_M \geq 0$, which is also true by Assumption 1. Finally, $\pi^{EC}(N) \geq \pi^{NC}(N)$ if $f(N)\pi_M \geq g(N)2\pi_D$ where

$$g(N) = P(1,N)^2 - 2P(1,N)\sum_{n=2}^{N} P(n,N)$$

and

$$f(N) = g(N) + 2\sum_{m=2}^{N}\sum_{n=2}^{N} \tfrac{m}{m+n} P(m,N) P(n,N).$$

Since $\pi_M \geq 2\pi_D$ and $f(N) \geq g(N)$, we have $\pi^{EC}(N) \geq \pi^{NC}(N)$ if $f(N) \geq 0$ for all $N \geq 1$. To show this is true, note that $f(N) \geq 0$ is the same as

$$1 - 2 \sum_{n=2}^{N} R(n, N) + 2 \sum_{m=2}^{N} \sum_{n=2}^{N} \frac{m}{m+n} R(m, N) R(n, N) \geq 0,$$

with $R(n, N) = P(n, N) / P(1, N)$, and this last inequality can be rewritten as $\left[\sum_{n=2}^{N} R(n, N) - 1 \right]^2 \geq 0$, which is true. $\blacksquare$

Since research firms are competitive, the equilibrium number of projects, N^*, satisfies $\pi(N^*) \geq 0$ and $\pi(N^* + 1) < 0$. Introducing any type of CRO thus generates greater incentive to invest in R&D, for a given level of per-project costs.

Using the welfare definitions from Table 2, ex-ante expected total welfare as a function of N is

$$W(N) = P(1, N)^2 W_{MM} + 2P(1, N) \sum_{n=2}^{N} P(n, N) W_{MC}$$
$$+ \sum_{m=2}^{N} \sum_{n=2}^{N} P(m, N) P(n, N) W_{CC} - 2Nc. \tag{4}$$

Let $W^{NC}(N)$, $W^{EC}(N)$, $W^{UC}(N)$ and $W^{SC}(N)$ be the total expected welfare with no CRO, an equal CRO, an unequal CRO and a strict CRO respectively. From Table 2 it is obvious that $W^{UC}(N) = W^{SC}(N)$ for all N. The following proposition examines the expected welfare change from introducing a CRO.

Proposition 3 *Given N, expected welfare with an unequal CRO (or a strict CRO) is always higher than that with an equal CRO: $W^{UC}(N) = W^{SC}(N) \geq W^{EC}(N)$ for all $N \geq 1$. In addition, expected welfare with no CRO is highest when N is sufficiently large but lowest when N is small: $W^{UC}(N) = W^{SC}(N) \geq W^{EC}(N) \geq W^{NC}(N)$ for sufficiently small N, and $W^{NC}(N) \geq W^{UC}(N) = W^{SC}(N) \geq W^{EC}(N)$ for sufficiently large N.*

Proof. From Table 2 it is clear that $W^{UC}(N) \geq W^{EC}(N)$ since $W_M \geq W_D$. From Table 2 and (4), $W^{UC}(N) \geq W^{NC}(N)$ if

$$P(1, N)^2 [W_M - W_D] \geq \sum_{m=2}^{N} \sum_{n=2}^{N} P(m, N) P(n, N) [W_0 - W_M].$$

Since $\sum_{n=2}^{N} P(n,N) = 1 - P(0,N) - P(1,N)$, this can be rewritten as

$$\left[\frac{1 - P(0,N) - P(1,N)}{P(1,N)}\right]^2 \leq \frac{W_M - W_D}{W_0 - W_M}.$$

The right-hand side of this inequality is positive since $W_0 \geq W_M \geq W_D$. If $N = 1$ the left-hand side equals zero since $P(0,1) + P(1,1) = 1$, so $W^{UC}(1) > W^{NC}(1)$. At higher values of N, the left-hand side eventually becomes arbitrarily large, since $\lim_{N \to \infty} P(n,N) = 0$ for all n, thus for sufficiently large N this inequality does not hold and $W^{UC}(N) < W^{NC}(N)$.

Finally, $W^{EC}(N) \geq W^{NC}(N)$ if

$$\left[1 - 2\sum_{n=2}^{N} \frac{P(n,N)}{P(1,N)}\right][W_M - W_D] \geq \sum_{m=2}^{N}\sum_{n=2}^{N} \frac{P(m,N)}{P(1,N)}\frac{P(n,N)}{P(1,N)}[W_0 - W_M]$$

which can be rewritten as

$$\frac{P(1,N)[2P(0,N) + 3P(1,N) - 2]}{[1 - P(0,N) - P(1,N)]^2} \geq \frac{W_0 - W_M}{W_M - W_D}.$$

The right-hand side is positive while the left-hand side is arbitrarily large at $N = 1$ and converges to zero as N increases. Thus $W^{EC}(1) > W^{NC}(1)$, and $W^{EC}(N) \leq W^{NC}(N)$ for sufficiently large N. ∎

Intuitively, an unequal (or strict) CRO always generates more welfare than an equal CRO because, given that both components are invented, it guarantees that the welfare level with a single licensor, W_M, is achieved, while the equal CRO only achieves $W_D \leq W_M$ in case MC. However, no CRO outperforms all types of CRO when N is large. This is because when N is large, the most likely outcome is case CC. In this case, with no CRO, competition among inventors drives royalties for both components to zero, and the highest possible welfare level, W_0, is achieved from licensing. Similarly, no CRO generates low welfare levels relative to any type of CRO when N is low, because then it is more likely that both components have a single licensor and thus joint licensing through a CRO achieves W_M instead of W_D.

Propositions 2 and 3 also imply that there is a potential tradeoff in terms of the equilibrium effects of a CRO on expected welfare once changes in investment are taken into account. Even if welfare increases given N, it is not guaranteed to increase once the increase in investment caused by introducing a CRO is taken into account, since R&D is costly. Without making

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additional assumptions it is impossible to solve the zero-profit condition on (1) to determine the equilibrium R&D investment. We therefore use a numerical simulation model in section 4 to examine this tradeoff further.

There may also be a conflict between the incentives of existing intellectual property owners and research firms who have not yet invested, in terms of their willingness to use and support a CRO. For example, Table 1 shows that if case MC arises, the monopoly inventor is made worse off by the existence of any type of CRO relative to when there is no CRO. Sole successful inventors of an essential component may thus be reluctant to use a CRO if it means that they have to share some royalties with competitive inventors of another component. On the other hand, Proposition 2 showed that the ex ante expected profit of a research firm in this model is always increased by the creation of a CRO. Thus innovators who have not yet invested are more likely to support the creation of the CRO, even if, ex post, there is some chance that they will be made worse off by its existence. In addition, ex ante, imposing a strict antitrust rule has no effect on innovators relative to an unequal CRO, but it *increases* expected profits relative to an equal CRO. Thus inventors may actually prefer that antitrust conditions are imposed on the CRO if it redistributes royalties equally, although successful inventors in case CC may be made worse off by prohibiting joint licensing.

3.2 Investment model 2: Component A is unique

The above analysis showed that ex post asymmetries between research firms can be important, even though all firms are symmetric ex ante. In this version of the model we investigate the effects of asymmetry further, by imposing it at the research stage. We assume that a single research firm ('firm A') has the unique ability to develop component A. We assume its success is deterministic, and it can develop A for certain if it invests c_A. As before, there are also competitive research firms that each can undertake one research project to try to develop B at a cost of c_B. Given that N projects are undertaken by these component B firms, the probability that n of them are successful is $P(n, N)$. We let $\pi_A(N)$ denote firm A's expected profit given that it invests and given that N projects invest in B, and let $\pi_B(N)$ denote the expected profit of an individual project aimed at developing B given that firm A invests.

Of the three licensing cases considered earlier, only MM and MC are

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possible in this model. Given that firm A invests, the probability of case MM is $P(1, N)$ and the probability of case MC is $P(n, N)$ for $n \geq 2$. Thus firm A's expected profit is

$$\pi_A(N) = P(1, N) \pi_{MM} + \sum_{n=2}^{N} P(n, N) \pi_{MC}^M - c_A. \tag{5}$$

The following proposition compares CROs when a strict antitrust rule is not imposed, in terms of firm A's expected profits.

Proposition 4 *Given N, Firm A's expected profit is always higher under an unequal CRO compared to an equal CRO when Assumption 2 holds. In addition, firm A's expected profit is highest with no CRO for relatively high values of N, but is highest with an unequal CRO for relatively low values of N. That is, $\pi_A^{NC}(N) \geq \pi_A^{UC}(N) \geq \pi_A^{EC}(N)$ for sufficiently high N and $\pi_A^{UC}(N) \geq \pi_A^{EC}(N) \geq \pi_A^{NC}(N)$ for sufficiently low N.*

Proof. From Table 1 and (5), $\pi_A^{UC}(N) \geq \pi_A^{EC}(N)$ if

$$[1 - P(0, N) - P(1, N)](z\pi_M - \pi_D) \geq 0$$

which is true for all N under Assumption 2. Similarly $\pi_A^{UC}(N) \geq \pi_A^{NC}(N)$ if

$$\frac{P(1, N)}{1 - P(0, N) - P(1, N)} \geq \frac{2(1 - z)\pi_M}{\pi_M - 2\pi_D}.$$

The right-hand side of this expression is positive by assumption. The left-hand side is arbitrarily large when $N = 1$, so $\pi_A^{UC}(1) \geq \pi_A^{NC}(1)$. As N increases, the left-hand side converges to zero, since $\lim_{N \to \infty} P(n, N) = 0$ for all n, thus for sufficiently large N, $\pi_A^{UC}(N) < \pi_A^{NC}(N)$. Finally, $\pi_A^{EC}(N) \geq \pi_A^{NC}(N)$ if

$$\frac{P(1, N)}{1 - P(0, N) - P(1, N)} \geq \frac{\pi_M - \pi_D}{\frac{1}{2}\pi_M - \pi_D}.$$

Again the right-hand side is positive and this expression holds at $N = 1$, but the left-hand side converges to zero as N increases. ∎

Firm A always prefers an unequal CRO to an equal one provided that the unequal CRO sets z high enough so that it induces firm A to join ex post. In comparison to no CRO, firm A prefers a CRO exist only when N is small and the probability that component B has a single inventor is relatively large. In that case, firm A benefits from the existence of a CRO because

joint licensing with a single inventor of B increases A's profits. However, if B has multiple inventors, competition among them drives the royalty for B to zero, and firm A is able to appropriate all of the monopoly profits from licensing when there is no CRO. If an equal CRO exists, the inventors of B will license jointly, which hurts firm A, while if an unequal CRO exists, firm A also joins, but has to share some royalties with the inventors of B. In either case, firm A is worse off compared to when no CRO exits.

In terms of the anti-trust rule, from Table 1 it is clear that firm A always prefers a CRO under a strict rule to an equal CRO without a strict rule as it prevents collusive behavior of component B firms and guarantees firm A an ex-post payoff of $\pi_M/2$. Comparing an unequal CRO to a CRO with a strict rule, from (5) and Table 1 it is straightforward to verify the following.

Proposition 5 *Given N, firm A's expected profit under an unequal CRO exceeds that of a CRO with a strict antitrust rule when $z \geq \frac{1}{2}$.*

Since both the unequal CRO and the strict CRO get firm A to participate, the only factor that differentiates them from firm A's point of view is the distribution rule of the unequal CRO.

The expected profit of a research firm that develops B, given that firm A invests, is

$$\pi_B(N) = \frac{1}{N} P(1, N) \pi_{MM} + \sum_{n=2}^{N} \frac{n}{N} P(n, N) \pi_{MC}^C(n) - c_B. \qquad (6)$$

The following proposition compares CROs in terms of a component B firm's expected profits, when a strict antitrust rule is not imposed.

Proposition 6 *For any given N, a research firm that invests in component B is always better off under either an equal or unequal CRO compared to no CRO. Such a firm is better off under an unequal CRO compared to an equal CRO if $z \leq 1 - \pi_D/\pi_M$.*

Proof. From Table 1 and (6), it is straightforward to verify that the assumption that $\pi_M \geq 2\pi_D$ guarantees that $\pi_B^{EC}(N) \geq \pi_B^{NC}(N)$ and $\pi_B^{UC}(N) \geq \pi_B^{NC}(N)$ for all $N \geq 1$. We also have $\pi_B^{UC}(N) \geq \pi_B^{EC}(N)$ if

$$\frac{1}{N} [1 - P(0, N) - P(1, N)] [(1 - z) \pi_M - \pi_D] \geq 0$$

which is true provided that $z \leq 1 - \pi_D/\pi_M$. ∎

Unlike firm A, having either an equal or unequal CRO (without a strict antitrust rule) never makes a component B research firm worse off because the firm always gets a strictly higher ex post payoff whatever the outcome of the random innovation process compared to when there is no CRO in this model, as shown in Table 1. Whether an unequal CRO is better than an equal CRO for these firms depends on the fraction of revenues that the unequal CRO gives to firm A. Both types of CRO give the same payoff, $\pi_M/2$, to a component B inventor when he is the only successful inventor of that component. When there are multiple successful inventors of B, an equal CRO does not induce firm A to join, so an inventor of B gets π_D/n. With an unequal CRO, firm A joins and the CRO revenues rise to π_M, but a fraction z is given to firm A to induce it to join. Thus component B inventors are only better off relative to an equal CRO if z is not too large. Note that there is always some range of z that both induces firm A to join an unequal CRO and makes component B inventors better off compared to an equal CRO. This requires $z \in [\pi_D/\pi_M, 1 - \pi_D/\pi_M]$, which is always feasible since $\pi_D/\pi_M \leq \frac{1}{2}$.

If a strict antitrust rule is imposed, from Table 1 it is clear that component B firms prefer a CRO with a strict rule to an equal CRO, since the strict rule guarantees the participation of firm A in the CRO and generates higher ex-post profits for component B firms even though it prevents them from licensing jointly. However, comparing an unequal CRO without a strict antitrust rule to a CRO with a strict antitrust rule, from (6) and Table 1 it is straightforward to verify:

Proposition 7 *Given N, a component B firm's expected profit under an unequal CRO exceeds that of a CRO with a strict antitrust rule when $z \leq \frac{1}{2}$.*

Comparing propositions 5 and 7, firm A and the component B firms have opposite preferences in terms of an unequal CRO without a strict antitrust rule versus a CRO with a strict antitrust rule. Both the unequal CRO and the strict CRO are able to get firm A to participate. However, if z is high under the unequal CRO, the competitive component B firms may actually prefer to be bound by a strict antitrust rule that prevents them from licensing jointly, if this gets firm A to participate in the CRO more 'cheaply' than the share that is given to firm A under the unequal CRO.

Combining Propositions 4 and 6, the existence of a CRO increases the

incentive of component B firms to invest in R&D, but may increase or decrease firm A's incentive to invest. In addition, if the introduction of a CRO increases the level of investment by component B firms, this in turn may increase or decrease firm A's *ex ante* profit. Overall, introducing a CRO will increase investment in component B, but has an ambiguous effect on firm A's incentive to invest.

As in the first investment model, there may also be a conflict between existing and potential innovators. For example, if firm A has already invested, it will be opposed to a CRO if there are multiple inventors of component B even if the CRO would make firm A better off ex ante. In addition, if investment has not yet taken place, ex ante firm A may be willing to sacrifice some of its ex post profits, by supporting an equal CRO or a lower value of z, to give greater incentive to the component B firms to invest, since A cannot earn any revenues unless B is also invented. We examine these tradeoffs further numerically in the next section.

The expected welfare given that firm A invests and $N \geq 1$ component B firms invest is

$$W(N) = P(1, N) W_{MM} + \sum_{n=2}^{N} P(n, N) W_{MC} - c_A - N c_B. \qquad (7)$$

Proposition 8 *Given N, expected welfare is always highest with an unequal CRO or CRO with a strict antitrust rule. An equal CRO without a strict antitrust rule generates higher welfare compared to no CRO only for sufficiently low N. That is, $W^{UC}(N) = W^{SC}(N) \geq W^{EC}(N) \geq W^{NC}(N)$ for sufficiently low N, and $W^{UC}(N) = W^{SC}(N) \geq W^{NC}(N) \geq W^{EC}(N)$ for high N.*

Proof. From Table 2 and (7), it is straightforward to show that $W_M \geq W_D$ implies $W^{UC}(N) \geq W^{EC}(N)$ and $W^{UC}(N) \geq W^{NC}(N)$ for all $N \geq 1$. Since the strict and unequal CROs always give the same ex-post outcomes, we also have $W^{UC}(N) = W^{SC}(N)$. Finally, $W^{EC}(N) \geq W^{NC}(N)$ if

$$[2P(1, N) + P(0, N) - 1] [W_M - W_D] \geq 0.$$

This is true at $N = 1$ since $P(1, 1) + P(0, 1) = 1$ and $W_M \geq W_D$. However the first bracket converges to -1 as N becomes large, thus $W^{EC}(N) < W^{NC}(N)$ for sufficiently large N. ∎

In this model the unequal CRO or a CRO with a strict antitrust rule always does best in terms of expected welfare. This is because with a unique inventor for component A, a situation in which there are multiple inventors of both components never arises, and the ex post welfare level W_0 is never achieved. Thus since the unequal CRO or strict CRO guarantees the welfare level W_M, it always performs better than either no CRO or an equal CRO. On the other hand, an equal CRO without a strict antitrust rule only outperforms no CRO if N is low so that the chance that component B has a single inventor is relatively high. When N is large, it is relatively likely that competition among inventors of B will drive the royalty for that component to zero, resulting in welfare level W_M with no CRO. However, an equal CRO permits substitute inventors of B to reduce competition, resulting in welfare of W_D.

Finally, as in model 1, these rankings of expected profits and welfare take the level of investment in R&D as given. While an unequal CRO or CRO with a strict antitrust rule always results in the highest expected welfare level given N, once the change in investment induced by the CRO is taken into account, the effect on welfare is unclear. The next section investigates further by simulation.

4   Endogenous investment: Simulation analysis

Here we use numerical simulations of our two investment models to investigate further some of the tradeoffs that were identified.[2] For the simulation we assume total demand for licenses from both components is linear and is given by $Q = 100 - \rho$ where Q is the number of licenses sold and ρ is the total per-unit royalty for licensing both A and B. Under this assumption, the royalty revenues of licensor i setting a royalty of r_i is $R_i = (100 - \rho) r_i$ where $\rho = \sum r_i$, and total welfare generated by licensing is $W = 50 (1 - \rho) (1 + \rho)$. When there is a single licensor, ρ is chosen to maximize $(100 - \rho) \rho$, which gives $\rho_M = \frac{1}{2}$. Under duopoly, it is straightforward to show that the non-cooperative equilibrium total royalty is $\rho_D = \frac{2}{3}$. These give the parameter values shown in Table 3. It is clear that these values satisfy Assumption 1. To satisfy Assumption 2, the unequal CRO must set $z \in \left(\frac{4}{9}, 1 \right)$. We

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Parameter	π_M	π_D	W_0	W_M	W_D
Value	25	$\frac{100}{9}$	50	$\frac{75}{2}$	$\frac{250}{9}$

Table 3: Simulation parameters with linear demand for licensing.

also assume that the random investment processes are binomial, with the probability of success of any given project given by σ, thus

$$\Pr(n, N) = \sigma^n (1 - \sigma)^{N-n} \frac{N!}{n! (N - n)!}.$$

4.1 Model 1 simulations

The key question from model 1 is the effect of a CRO on equilibrium investment in R&D and hence the expected equilibrium welfare level. For each pair of the parameters c and σ, we simulated the equilibrium investment level by repeatedly evaluating (1) under each type of CRO and numerically searching for the highest level of N at which $\pi(N) \geq 0$ and $\pi(N+1) < 0$. Since the probability that any individual project is successful tends to zero as N becomes large, $\pi(N)$ eventually approaches $-c$ under all CRO types. Thus provided that $\pi(N) > 0$ for some relatively low values of N, an equilibrium with investment in both components exists. Otherwise, we record the equilibrium as $N = 0$, representing no investment.

Recall that in model 1, ex-ante expected profits and welfare are identical under a CRO with a strict antitrust rule and an unequal CRO without a strict rule for any given N. Thus for each combination of c and σ, the equilibrium search was repeated assuming no CRO, an equal CRO and an unequal CRO, and the equilibrium level of investment N^* was recorded in each case.[3] Under each type of CRO, the welfare level at N^* was calculated by evaluating (4).

Figure 1 illustrates a single simulation of model 1, for $c = 2.5$ and $\sigma = 0.7$. The left panel shows the expected profit of an individual research firm under each type of CRO as a function of N. As in Proposition 2, introducing a CRO increases expected profit for all N. In this particular case, there is very little difference in expected profit between an equal and an unequal (or strict) CRO. Under no CRO, the equilibrium investment level is $N = 2$,

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[3]Note also that in model 1 with an unequal CRO, it is straightforward to show that expected profits are independent of z, by substituting the payoffs from Table 1 into (1).
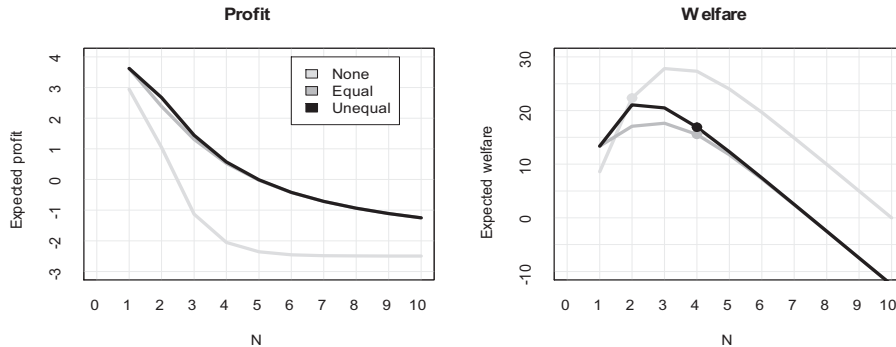
Figure 1: Illustration of a single simulation of model 1, for $c = 2.5$ and $\sigma = 0.7$. The left plot shows expected profits of a research firm given that N projects are undertaken for each component, under each type of CRO. The right plot shows expected welfare as a function of N. The large dots are the equilibrium welfare levels.

while under an equal or unequal CRO it is $N = 4$. The right panel plots expected welfare as a function of N under each type of CRO, and the large dots show the equilibrium expected welfare levels.

In this case, the increase in equilibrium investment from $N = 2$ to $N = 4$ would increase expected equilibrium welfare if the CRO had no effect on ex post licensing. However, once changes in ex post royalties are taken into account, introducing any type of CRO reduces equilibrium expected welfare for these parameter values.

Table 4 shows the simulated equilibrium investment levels in model 1 for various values of σ and c for different types of CRO. Again reflecting Proposition 2, introducing a CRO increases the investment level, and investment under an unequal (or strict) CRO is weakly greater than that under an equal CRO. As well as increasing the investment level, the CRO can make investment profitable when it would otherwise not be, such as for $c = 4$ and $\sigma = 0.6$.

Table 5 shows the equilibrium welfare levels corresponding to these investment levels. Introducing a CRO raises welfare provided that the additional investment is beneficial relative to its costs, and that any ex-post licensing inefficiencies are not too large. The CRO is obviously always beneficial in cases where there is positive investment with a CRO but no invest-

	σ								
CRO	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
$c = 2$									
No	0	0	0	2	3	2	2	2	2
E	0	0	0	5	5	6	6	6	6
U/S	0	0	0	5	6	6	6	6	6
$c = 4$									
No	0	0	0	0	0	0	1	1	1
E	0	0	0	0	0	2	2	3	3
U/S	0	0	0	0	0	2	2	3	3
$c = 6$									
No	0	0	0	0	0	0	0	1	1
E	0	0	0	0	0	0	1	1	1
U/S	0	0	0	0	0	0	1	1	2

Table 4: Simulated equilibrium investment levels in model 1. 'No': No CRO, 'E': Equal CRO, 'U/S': Unequal or strict CRO.

ment without a CRO. In other cases, however, the CRO may reduce welfare. The results indicate that this is most likely to happen if c is low, so that a CRO induces a large increase in investment that does not bring sufficient benefits to offset the costs. A CRO is also likely to reduce welfare when σ is high, in which case it is likely that there are multiple competing successful inventors and the ex-post licensing inefficiencies of having a CRO are large.

4.2 Model 2 simulations

Simulations of model 2 were conducted in a similar manner as for model 1. In model 2, for there to be some probability of production, firm A and at least one component B firm must both invest. Using (5) and (6) we search for the largest value of N where $\pi_A(N) \geq 0$, $\pi_B(N) \geq 0$ and $\pi_B(N+1) < 0$. As in model 1, the expected profit of a component B firm converges to $-c_B$ as N becomes large, thus an equilibrium with investment occurs if $\pi_B(N) \geq 0$ and $\pi_A(N) \geq 0$ for some relatively small N. As well as the parameters

	σ								
CRO	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
$c = 2$									
No	0	0	0	5.44	18.47	17.84	24.34	30.68	36.64
E	0	0	0	8.55	12.72	12.51	13.25	13.47	13.50
U/S	0	0	0	11.89	12.34	13.19	13.45	13.50	13.50
$c = 4$									
No	0	0	0	0	0	0	5.61	9.78	14.50
E	0	0	0	0	0	7.10	11.05	11.23	12.91
U/S	0	0	0	0	0	10.46	15.05	12.90	13.43
$c = 6$									
No	0	0	0	0	0	0	0	5.78	10.50
E	0	0	0	0	0	0	6.38	12.00	18.38
U/S	0	0	0	0	0	0	6.38	12.00	12.75

Table 5: Simulated equilibrium welfare levels in model 1. 'No': No CRO, 'E': Equal CRO, 'U/S': Unequal or strict CRO.

from Table 3, the other parameters in model 2 are c_A, c_B, σ and z. For the simulations we fix c_A and allow c_B to vary. Unlike in model 1, the asymmetry between the component A and B research firms means that z has an effect on the expected profits of all research firms under an unequal CRO.

Figure 2 illustrates a single simulation of model 2, for some particular parameter values. The equilibria are $N^* = 3$, 8, 5 and 9 with no CRO, an equal CRO, an unequal CRO and a CRO with a strict antitrust rule respectively. In this illustration, $z > 1 - \pi_D/\pi_M$ and $z > \frac{1}{2}$, so this ordering of investment levels reflects Propositions 6 and 7. In all of these four cases, the expected profit of firm A at N^* is positive, so it invests. For these parameter values, expected equilibrium welfare is highest with an unequal CRO. However, an equal CRO or a strict CRO would reduce expected welfare compared to no CRO as they stimulate too much investment in component B.

As noted above, the value of z under an unequal CRO is not neutral in this model, in contrast with model 1 where the research firms are symmetric.
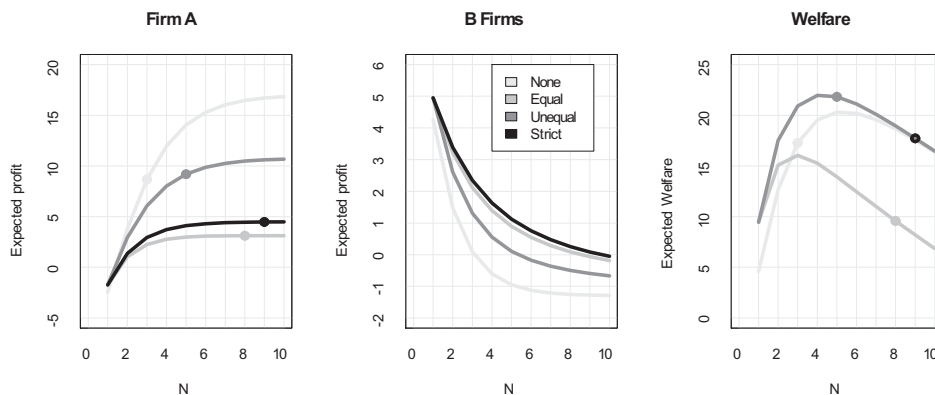
Figure 2: Illustration of a single simulation of model 2, for $c_A = 8$, $c_B = 1.3$, $\sigma = 0.5$ and $z = 0.75$. The left plot shows expected profits of firm A. The middle plot shows the expected profit of a component B research firm. The right plot shows expected welfare as a function of N and the large dots are the equilibrium welfare levels. Note that the expected welfare curves for an unequal CRO and a strict CRO are identical, but the equilibrium welfare levels are different.

Given any $N \geq 2$, a higher value of z increases the expected profit of firm A and reduces the expected profit of a component B research firm. Figure 3 illustrates this tradeoff by showing firm A's expected profit and expected equilibrium welfare as functions of z, taking account of the equilibrium investment in component B, for some specific values of c_A, c_B and σ. The discrete steps observed in the results correspond to different discrete levels of equilibrium investment in component B.

When the probability of success for component B firms (σ) is low, Figure 3 shows that expected profits and welfare generally decline as z increases. With low σ, equilibrium investment in component B is low, while equilibrium welfare is increasing in N provided that c_B is not too large, since additional investment raises the probability that component B is invented. In this case, increasing z reduces investment in component B and reduces expected welfare. Reduced investment in component B also negatively affects firm A in this case as it can only earn profits if component B is also invented. Thus when σ is low, ex ante firm A prefers a low value of z as this stimulates investment in component B, even though it may reduce firm A's ex post
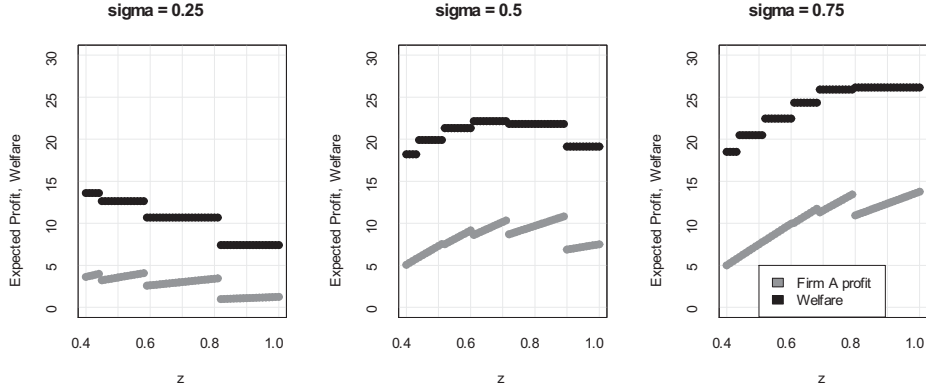
Figure 3: Firm A's expected equilibrium profit and expected equilibrium welfare under an unequal CRO as a function of z, for $c_A = 5$ and $c_B = 3$.

licensing profits.

At higher values of σ, Figure 3 shows that equilibrium expected profits of firm A and welfare may be increasing and then decreasing in z. Again increasing z reduces investment in component B under an unequal CRO. However, this may increase welfare if σ is sufficiently high, since the cost savings from reduced investment can outweigh the reduced probability that component B is invented. Indeed, if σ is very high then expected welfare and firm A's expected profit maximized by setting $z = 1$. In such a situation, investment in B is low since research only get a return if they are the sole successful inventor, but the high probability of success means that this does not have a large adverse effect on firm A's expected profits or expected welfare.

Table 6 shows the simulated equilibrium investment levels of component B firms in model 2 for different values of σ and c, under different types of CRO. As in model 1, introducing a CRO increases equilibrium investment levels. Higher values of z under the unequal CRO discourage investment by component B firms, while a CRO under a strict antitrust rule promotes relatively high levels of investment even though it prevents component B firms from licensing together.

Table 7 shows the simulated equilibrium welfare levels corresponding to the investment levels from Table 6. As in model 1, introducing a CRO may or may not be welfare-enhancing. However, a CRO is welfare-reducing in

relatively fewer parameter cases under this model. The biggest welfare gains occur when the cost of R&D is high or the probability of innovation success is low. Reflecting Figure 3, welfare performance depends on the value of z under an unequal CRO, and higher z can improve welfare relative to an equal CRO or a strict CRO if the latter two types of CRO lead to excessive investment by component B firms. In addition, an equal CRO performs relatively poorly compared to the other types of CRO. If the value of z can be specifically tailored to industry conditions, an unequal CRO generally has the best performance. Otherwise, a CRO with a strict antitrust rule generally performs better than an equal CRO without requiring detailed knowledge of the underlying parameters.

5 Conclusion

Our analysis has shown that CROs can have both positive and negative effects on ex ante and ex post profits and welfare from licensing innovations. Taking a long-run perspective, the ex ante effects are arguably the most important. In this case we showed that CROs typically increase expected profits from licensing. An exception is when there is a unique potential inventor for one component (our model 2), in which case a CRO may reduce that inventor's expected profits when investment in the other component is relatively high. Aside from this case, CROs generally increase incentives to invest in R&D. However, as we showed, this increase in investment does not always increase ex ante expected welfare, if the benefits in terms of the increased probability that all necessary components are developed does not outweigh the additional cost of the R&D investment and any anticompetitive ex post effects of the CRO.

The possibility that a CRO reduces welfare is particularly acute in the case where royalties are distributed equally among members. If a CRO does not have the ability to differentiate royalty payments to inventors whose innovations have no substitutes versus payments to those who do have competitive substitutes, the CRO increases expected profits from R&D but is likely to reduce expected welfare. Therefore, we reach the policy conclusion that CROs should be given flexibility in their royalty distribution scheme, and the royalty distribution should favor inventors of unique components. Our analysis also showed that the optimal asymmetry of royalty payments

by a CRO varies depending on parameters such as the costs of R&D and the probability of success. If a CRO spans multiple industries, for example, it may therefore be appropriate for it to use different royalty distribution arrangements in different cases, depending on industry characteristics. Alternatively, imposing a strict antitrust rule banning joint licensing of substitutes results in welfare performance as good (in model 1) or almost as good (in model 2) as an unequal CRO, without requiring specific knowledge of the underlying parameters.

Finally, our analysis highlighted some potential conflicts among different types of inventors in terms of their support for a CRO. CROs are most likely to be supported by successful inventors of competitive innovations. However, their support should be viewed with some scepticism, as it is essentially a collusive device for them. On the other hand, symmetric inventors who have not yet invested and who all have an equal chance of being successful are also likely to support a CRO, and this may enhance both profits and welfare if it does not induce excessive investment. Opposition to a CRO is likely to come from successful inventors of a component that does not have any substitutes, or inventors who have not yet invested but have the unique ability to develop a crucial component. In either case, an unequal royalty distribution scheme or antitrust rules are necessary to earn their support.

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CRO	σ								
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
$c_B = 2$									
No	0	0	2	2	2	2	2	1	1
E	0	0	4	5	5	5	5	5	5
U (0.45)	0	3	5	6	6	6	6	6	6
U (0.75)	0	0	3	3	3	3	3	3	3
S	0	3	5	5	6	6	6	6	6
$c_B = 4$									
No	0	0	0	0	1	1	1	1	1
E	0	0	0	0	2	2	2	2	2
U (0.45)	0	0	0	2	2	3	3	3	3
U (0.75)	0	0	0	0	1	2	2	1	1
S	0	0	0	2	2	2	3	3	3
$c_B = 6$									
No	0	0	0	0	0	1	1	1	1
E	0	0	0	0	1	1	1	1	1
U (0.45)	0	0	0	0	1	1	1	2	2
U (0.75)	0	0	0	0	1	1	1	1	1
S	0	0	0	0	1	1	1	1	2

Table 6: Simulated equilibrium investment by component B firms in model 2. 'No': No CRO, 'E': Equal CRO, 'U (z)': Unequal CRO, 'S': Strict CRO.

	σ								
CRO	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
$c_B = 2$									
No	0	0	6.04	10.33	14.26	17.83	21.04	15.22	18.00
E	0	0	12.11	13.13	13.42	13.24	12.99	12.83	12.78
U (0.45)	0	7.30	16.20	18.75	19.91	20.35	20.47	20.50	20.50
U (0.75)	0	0	13.64	18.40	21.81	24.10	25.49	26.20	26.46
S	0	7.30	16.20	19.58	19.91	20.35	20.47	20.50	20.50
$c_B = 4$									
No	0	0	0	0	4.89	7.67	10.44	13.22	16.00
E	0	0	0	0	12.69	15.00	16.36	16.78	16.25
U (0.45)	0	0	0	11.00	15.13	18.10	19.49	20.20	20.46
U (0.75)	0	0	0	0	9.75	18.50	21.13	21.00	24.75
S	0	0	0	11.00	15.13	18.50	19.49	20.20	20.46
$c_B = 6$									
No	0	0	0	0	0	5.67	8.44	11.22	14.00
E	0	0	0	0	7.75	11.50	15.25	19.00	22.75
U (0.45)	0	0	0	0	7.75	11.50	15.25	19.00	20.13
U (0.75)	0	0	0	0	7.75	11.50	15.25	19.00	22.75
S	0	0	0	0	7.75	11.50	15.25	19.00	20.13

Table 7: Simulated equilibrium welfare levels in model 2 given $c_A = 5$. 'No': No CRO, 'E': Equal CRO, 'U (z)': Unequal CRO, 'S': Strict CRO.