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 $x_1, ..., x_N$, $2\sum_{i=1}^{N}\sum_{j=1}^{N}\frac{i}{i+j}x_i x_j = \sum_{i=1}^{N}\sum_{j=1}^{N} x_i x_j = \left[\sum_{i=1}^{N} x_i\right]^2$. ■

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 $P(1,N)\sum_{n=2}^{N} P(n,N)\left[\pi_M - 2\pi_D\right] \geq 0$, which is true by Assumption 1. Similarly, $\pi^{UC}(N) \geq \pi^{NC}(N)$ is equivalent to $P(1,N)^2\left[\frac{1}{2}\pi_M - \pi_D\right] + \sum_{m=2}^{N}\sum_{n=2}^{N}\frac{m}{m+n}P(m,N)\,P(n,N)\,\pi_M \geq 0$, 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. ■

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

$$\begin{aligned} W(N) &= P(1,N)^2 W_{MM} + 2P(1,N)\sum_{n=2}^{N} P(n,N)\, W_{MC} \\ &\quad + \sum_{m=2}^{N}\sum_{n=2}^{N} P(m,N)\, P(n,N)\, W_{CC} - 2Nc. \qquad (4) \end{aligned}$$

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

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

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 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 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

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

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

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

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

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

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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[2] Simulations were programmed in R 2.6.0 for Windows, and source codes are available from the authors on request.

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).

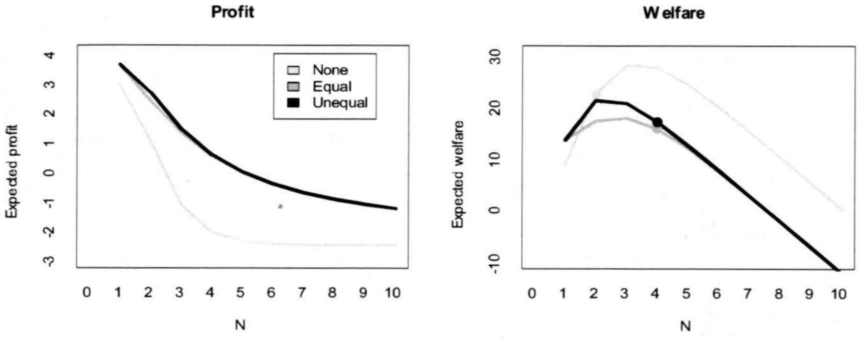

Figure 1: Illustration of a single simulation of model 1, for $c = 2.5$ and $\sigma = 0.7$. The left plot shows expected profits of a research firm given that N projects are undertaken for each component, under each type of CRO. The right plot shows expected welfare as a function of N. The large dots 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.

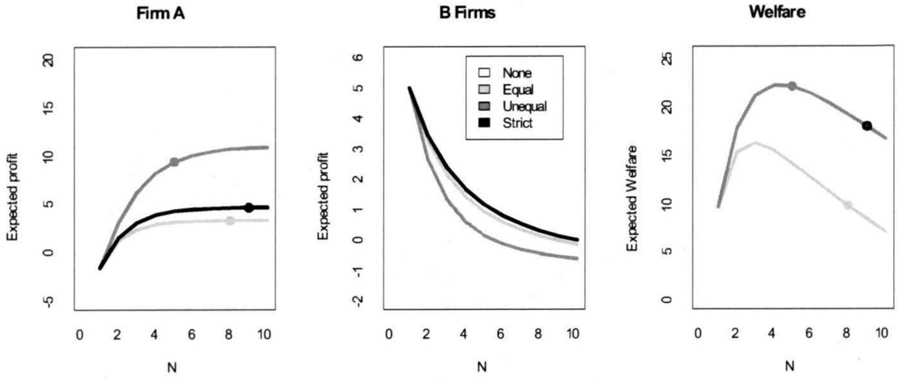
Firm A B Firms Welfare

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

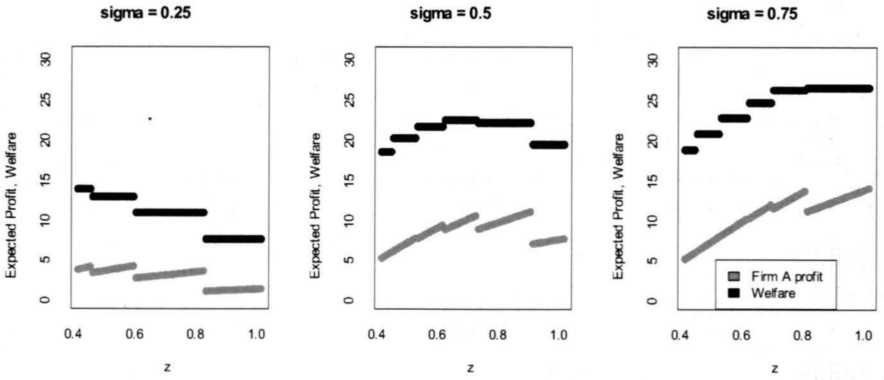

Figure 3: Firm A's expected equilibrium profit and expected equilibrium welfare under an unequal CRO as a function of z, for $c_A = 5$ and $c_B = 3$.

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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	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	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.