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Agreement theorems with interactive information: possibilities and impossibilities

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Abstract Following from Tarbush (2011a), we explore the implications of using two different definitions of informativeness over kens; one that ranks objective, and the other subjective information. With the first, we create a new semantic operation that allows us to derive agreement theorems even when decision functions are based on interactive information (for any $r \geq 0$). Effectively, this operation, unlike information cell union captures the notion of an agent becoming “more ignorant” *for all modal depths*. Using the definition that ranks subjective information however, we show an impossibility result: In generic models, agreement theorems using the standard Sure-Thing Principle do not hold when decision functions depend on interactive information (when $r > 0$).

Keywords Agreeing to disagree, knowledge, common knowledge, belief, information, epistemic logic.

JEL classification D80, D83, D89.

1 Introduction

Bacharach (1985) proved an agreement theorem showing that if the agents of like-minded agents are common knowledge, then their actions must be the same. This result is proven with general decision functions, $D_i : \mathcal{F} \rightarrow \mathcal{A}$, that map from a field \mathcal{F} of subsets of Ω into an arbitrary set \mathcal{A} of *actions*. To derive the result, it is assumed that agents have the same decision function (termed “like-mindedness”), and that the decision functions satisfy what we call the Disjoint Sure-Thing Principle (*DSTP*): $\forall E \in \mathcal{E}$, if $D_i(E) = x$ then $D_i(\cup_{E \in \mathcal{E}} E) = x$, where \mathcal{E} is a set of disjoint events. The idea is that if one decides to perform action x in each case

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when one is more informed (when E and when F), then one must also decide to perform action x when one is more ignorant (when $E \cup F$). Moses and Nachum (1990) show that taking the union of information cells is conceptually problematic because it does not adequately capture the notion of being “more ignorant”.

Tarbush (2011a) shows that the union of information cells does capture the notion of being “more ignorant”, but only for non-interactive information (see Lemma 6), and thus proposes a solution to the conceptual problem by providing explicit accounts of the information that each agent has at each state, and then truncating the information so that decisions only depend on non-interactive information. Effectively, the paper preserves a similar semantic operation to cell union and bypasses the problem by focussing on the non-problematic information that remains after the operation.

In that paper, it is not shown however, that truncating the information is *necessary* to obtain the agreement result, only that it is sufficient - given that the semantic operation is cell union. This leaves open the possibility that agreement results hold for non-truncated, that is, interactive information, if an operation other than cell union is used - which is what we explore here.

So, in this paper, we define a new operation (called private ignorance) that allows us to talk about agents becoming “more ignorant” *even* when considering interactive information. The upshot is that Bacharach’s result does hold, but requires a different operation from cell union; and indeed, any paper that resorts to cell union to capture more ignorance in an interactive agent setting should really be using the operation proposed here.

Note that all the notation and definitions referred to in the rest of this paper are drawn from Tarbush (2011a).

To carry out the analysis regarding interactive information, we need to be careful how we rank information at the interactive level: In Tarbush (2011a) a notion of informativeness was defined in order to rank kens, both for a single agent, and across agents. Here, we show that we can define at least two different versions of this ranking; and which one we decide to use has far-reaching implications for the results we eventually obtain.

The following is the definition of informativeness given in Tarbush (2011a):

Definition 1 (Informativeness). Create an order $\succ \subseteq V_i \times V_j$ for all $i, j \in N$. We say that the ken ν_i is *more informative* than the ken μ_j , denoted $\nu_i \succ \mu_j$, if and only if whenever i knows that ψ then j either also knows that ψ or does not know whether ψ , and whenever i does not know whether ψ , then j also does not know whether ψ . Formally,

- If $\nu_i^n \psi_n = \square_i \psi_n$ then $(\mu_j^n \psi_n = \square_j \psi_n \text{ or } \mu_j^n \psi_n = \dot{\square}_j \psi_n)$,
- If $\nu_i^n \psi_n = \hat{\square}_i \psi_n$ then $(\mu_j^n \psi_n = \hat{\square}_j \psi_n \text{ or } \mu_j^n \psi_n = \dot{\square}_j \psi_n)$, and
- If $\nu_i^n \psi_n = \dot{\square}_i \psi_n$ then $(\mu_j^n \psi_n = \dot{\square}_j \psi_n)$.

Finally, note that $\nu_i \sim \mu_j$ denotes $\nu_i \succsim \mu_j$ and $\mu_j \succsim \nu_i$; which is interpreted as ν_i and μ_j carrying the *same* information, but seen from the perspectives of agents i and j respectively.

This means that if the n^{th} entry of ν_i is $\square_i \square_j p$, and $\nu_i \sim \mu_j$ then the n^{th} entry of μ_j is $\square_j \square_i p$. This notion, in a sense, captures a comparison about what information the agents *objectively* have about the world: Here, we are asking what each of the agents know about j 's knowledge about p .

Contrast this with the alternative definition of informativeness given below.

Definition 2 (Informativeness*). Create an order $\succsim^* \subseteq V_i \times V_j$ for all $i, j \in N$, defined by:

- If $\nu_i^n \psi_n = \square_i \psi_n$ then $(\mu_j^{\sigma(n)} \psi_{\sigma(n)} = \square_j \psi_{\sigma(n)} \text{ or } \mu_j^{\sigma(n)} \psi_{\sigma(n)} = \dot{\square}_j \psi_{\sigma(n)})$,
- If $\nu_i^n \psi_n = \hat{\square}_i \psi_n$ then $(\mu_j^{\sigma(n)} \psi_{\sigma(n)} = \hat{\square}_j \psi_{\sigma(n)} \text{ or } \mu_j^{\sigma(n)} \psi_{\sigma(n)} = \dot{\square}_j \psi_{\sigma(n)})$, and
- If $\nu_i^n \psi_n = \dot{\square}_i \psi_n$ then $(\mu_j^{\sigma(n)} \psi_{\sigma(n)} = \dot{\square}_j \psi_{\sigma(n)})$.

This definition is applicable if there are only two agents in the model. σ is a bijection. If ψ_n is an atomic formula, σ maps n into itself. On the other hand, if ψ_n has modal depth one or greater, then $\psi_{\sigma(n)}$ is identical to ψ_n except that all the i and j indices are switched.

Now, this means that if the n^{th} entry of ν_i is $\square_i \square_j p$, and $\nu_i \sim^* \mu_j$ then the $\sigma(n)^{\text{th}}$ entry of μ_j is $\square_j \square_i p$. This notion captures a comparison about the *subjective* states of minds of the agents: Here, for example, we are saying that i knows that j knows that p , and we say that j is in a “similar” state of mind if we can simply switch their indices around - that is, if they can somehow stand in each other’s shoes, in which case we would say that j knows that i knows that p .

Note that both orderings are identical over atomic propositions, so all results in Tarbush (2011a) that imposed $r = 0$ are unchanged by our choice of definition for informativeness. Also, regardless of which definition of informativeness we use, our definition of the infimum of kens is unchanged, since it is only applicable to the kens of a single agent. The infimum of ν_i and μ_i , denoted $\inf\{\nu_i, \mu_i\}$, is the most informative ken that is less informative than ν_i and μ_i .

Lemma 1. For any $\nu_i, \mu_i \in V_i$, $\inf\{\nu_i, \mu_i\}$ exists in V_i and is characterised by:

$$\inf\{\nu_i, \mu_i\}^n \psi_n = \square_i \psi_n \text{ iff } (\nu_i^n \psi_n = \mu_i^n \psi_n = \square_i \psi_n)$$

$$\inf\{\nu_i, \mu_i\}^n \psi_n = \hat{\square}_i \psi_n \text{ iff } (\nu_i^n \psi_n = \mu_i^n \psi_n = \hat{\square}_i \psi_n)$$

$$\inf\{\nu_i, \mu_i\}^n \psi_n = \dot{\square}_i \psi_n \text{ iff } (\nu_i^n \psi_n \neq \mu_i^n \psi_n \text{ or } \nu_i^n \psi_n = \mu_i^n \psi_n = \dot{\square}_i \psi_n)$$

In this paper, we show that with the ordering \succsim , all the previous results found in Tarbush (2011a) and Tarbush (2011b) still hold. In fact, they can be extended: Unlike the *cell merge* and *sink merge* operations defined in Tarbush (2011a), in section 2, we show that there is an operation that recovers the infimum of kens in a component for all agents and for all $r \geq 0$, and this allows us to derive agreement theorems that hold for all $r \geq 0$ - in contrast with our previous results that only held for $r = 0$.

However, if we had used the ordering \succsim^* then many of the results in Tarbush (2011a) and Tarbush (2011b) would only hold for $r = 0$. In particular, the results would all be unchanged in Tarbush (2011a), but Proposition 3 would only hold for $r = 0$. Furthermore, in Tarbush (2011b), Lemmas 2 and 5, and therefore all the theorems in that paper, would only hold for $r = 0$.

In fact, with \succsim^* , we demonstrate a rather stark result in section 3: In generic models, agreement theorems (using the standard versions of the Sure-Thing Principle) do not hold when decisions are based on interactive information (that is, when $r > 0$).

2 New operation: Private ignorance

Definition 3 (Private ignorance). Consider any model $\mathcal{M} = \langle \Omega, R_i, \mathcal{V} \rangle$. Now create a new model $\mathcal{M}^+ = \langle Q, Z_i, \mathcal{T} \rangle$, where:

$$Q = \Omega \cup \{s_\omega | \omega \in \Omega_G(\omega) \text{ and if } \omega' \in \Omega_G(\omega) \text{ then } s_\omega = s_{\omega'}\} \quad (1)$$

$$Z_i = R_i \cup \{(s_\omega, \omega') | \omega' \text{ is in an equivalence class for } i \text{ in component } \Omega_G(\omega)\} \quad (2)$$

$$\mathcal{T} = \mathcal{V} \quad (3)$$

This means that \mathcal{M}^+ is the same model as \mathcal{M} except that for every component $\Omega_G(\omega)$, there is one extra state, s_ω , and for each agent, there are arrows pointing from s_ω to *every* other state that is in an equivalence class for that agent within that component. The valuation maps for the atomic propositions are identical in both models, and the atomic propositions that are true at s_ω itself are irrelevant since s_ω does not point to itself.

We will show below that the ken of every agent at the state s_ω is the infimum of all the kens at all other states in the component $\Omega_G(\omega)$, for all $r \geq 0$.

Proposition 1. For all $i \in G$, \mathcal{M}^+ , $s_\omega \models \inf\{\nu_i | \omega' \in \Omega_G(\omega) \ \& \ \omega' \models \nu_i\}$ (for any $r \geq 0$).

Proof. This holds for *S5* or *KD45*. Consider agent i , and any formula ψ of some modal depth $r \geq 0$. If ψ is true in every one of i 's information cells (or sinks) in the component $\Omega_G(\omega)$, then clearly, $s_\omega \models \Box_i \psi$. If ψ is true at some states and false in others in the component, then $s_\omega \models \dot{\Box}_i \psi$. That is, whenever i knows that ψ in the component, this information is preserved in s_ω ; and in all other cases - when i does not know whether ψ or has contradictory information about ψ in different information cells (or sinks) in the component, then i does not know whether ψ at the state s . This is precisely the characterisation of the infimum, and holds for any r . \square

The above suggests that in order to derive his agreement theorem, Bacharach (1985) should have used this operation (private ignorance) rather than the union of information cells.

Consider the following characterisation of a class of models, which we denote by **M**:

- If the modal operator of the n^{th} entry of *every* ken of some agent i is \Box_i , then the modal operator of the n^{th} entry of *every* ken of all other agents j is also \Box_j (within the same component).
- If the modal operator of the n^{th} entry of *every* ken of some agent i is $\hat{\Box}_i$, then the modal operator of the n^{th} entry of *every* ken of all other agents j is also $\hat{\Box}_j$ (within the same component).
- If the modal operators of the n^{th} entry of different kens of some agent i are different, or if the modal operator of the n^{th} entry of *every* ken of the agent is $\dot{\Box}_i$, then *either* the modal operators of the n^{th} entry of different kens are also different for all other agents j , *or*, the modal operator of the n^{th} entry of *every* ken of all other agents j is $\dot{\Box}_j$ (within the same component).

Proposition 2. \mathcal{M}^+ , $s_\omega \models \inf\{\nu_i | \omega' \in \Omega_G(\omega) \ \& \ \omega' \models \nu_i\} \wedge \inf\{\nu_j | \omega' \in \Omega_G(\omega) \ \& \ \omega' \models \nu_j\}$ and $\inf\{\nu_i | \omega' \in \Omega_G(\omega) \ \& \ \omega' \models \nu_i\} \sim \inf\{\nu_j | \omega' \in \Omega_G(\omega) \ \& \ \omega' \models \nu_j\}$ if and only if $\mathcal{M} \in \mathbf{M}$.

Proof. Suppose \mathcal{M}^+ , $s_\omega \models \inf\{\nu_i | \omega' \in \Omega_G(\omega) \ \& \ \omega' \models \nu_i\} \wedge \inf\{\nu_j | \omega' \in \Omega_G(\omega) \ \& \ \omega' \models \nu_j\}$ and $\inf\{\nu_i | \omega' \in \Omega_G(\omega) \ \& \ \omega' \models \nu_i\} \sim \inf\{\nu_j | \omega' \in \Omega_G(\omega) \ \& \ \omega' \models \nu_j\}$.

Now, suppose the modal operator of the n^{th} entry of *every* ken of some agent i is \Box_i within component $\Omega_G(\omega)$. Then, the modal operator of the n^{th} entry of i 's ken at state s_ω is also \Box_i . If it is not the case that the modal operator of the n^{th}

entry of *every* ken of all other agents j is also \Box_j within that component, then the modal operator of the n^{th} entry of some agent j 's ken at state s_ω is not \Box_j ; thus contradicting our initial assumption that all agents have the “same” ken at state s_ω . Proceed similarly for the other cases.

The other direction is trivial. \square

One can easily verify that all $S5$ models are in fact models in the class **M**. Therefore, we can use the above proposition instead of Lemma 6 in Tarbush (2011a) to derive Theorems 1 and 2 in that paper; but now they would hold for all $r \geq 0$, as stated below.

Theorem 1. *Consider Ψ_0^r for any $r \geq 0$, the agents are like-minded, and the system is $S5$. Let $G = \{i, j\} \subseteq N$. If either, $NDSTP$ holds; or, $DSTP$ holds and the language is rich in every component, then $\models C_G(d_i^x \wedge d_j^y) \rightarrow (x = y)$.*

Proof. See proof of Theorems 1 and 2 in Tarbush (2011a) but replace Lemma 6 with Proposition 2 here. \square

Interestingly, *even* when heterogeneity holds (defined in Tarbush (2011a)), $KD45$ models are not models in the class **M**. However, $KD45$ models that satisfy the following “strong heterogeneity” assumption *are* in the **M** class; and therefore agreement theorems hold for such models as well. *Strong heterogeneity* can be expressed as: In any component $\Omega_G(\omega)$, if there is a state $\omega' \in \Omega_G(\omega)$ such that $\omega' \models \nu_i$ and $\nu_i^n \psi_n$, then there is a state $\omega'' \in \Omega_G(\omega)$ such that $\omega'' \models \mu_j$ and $\mu_j^n \psi_n$, where $\nu_i^n = \mu_j^n$. That is, if some agent has some information about some formula at some state of a component, there there is some state in the component in which the other agent has that same information about that formula.

Intuition There is an important distinction in terms of the interpretation of agreement theorems when using private ignorance instead of cell union as our semantic operation. With cell union (or cell merge), the agent becomes more ignorant about the state of the world, but the other agent *realises* that the first one became more ignorant. With private ignorance however, the agent becomes secretly more ignorant (at the state s): He/she becomes more ignorant about the state of the world, but the other agent does not notice anything change (as far as the first agent is concerned). This is as if the agent is performing (privately - in his/her mind) a thought experiment whereby he/she considers what he/she would do if he/she were more ignorant, *while, as fas as he/she can tell, the other agent remains just as informed as he/she currently is.*¹

¹It is also interesting to understand what “ignorance” means here. Suppose that agent i has $\Box_i p$ at the current state, but there is another state in a cell that is at one step j -arrow away in

In terms of our understanding of the mechanism that drives the agreement results, this is what we believe is the correct interpretation when private ignorance is our semantic operation: Consider agents i and j involved in an agreement problem and i performs action x while j performs action y . The actions are common knowledge, and we can simply see that as j truthfully telling i what action she performed. When i learns this, he, in some sense, privately introspects: “Agent j has the same objective as me, so would have performed action x if she had received the same information as me. But she performed y , so she must have received information different from mine. Her action therefore puts some of my information into question. What action would I perform if I ignored all such pieces of information (essentially, put a $\hat{\square}$ in front of all such formulas)?”. Effectively, agent i comes to the conclusion that he would perform action, say z , if he could only rely on that core information that is not put into question by j ’s action. Agent i is going through this thought experiment *privately*, and so from i ’s point of view, there is no reason why anything should change epistemically for agent j at that stage. The main lemma then shows that when j also performs this private thought experiment, she arrives at the same core information as i , and therefore also performs action z .²

This interpretation is also a little different from say Bayesian updating where the agent is somehow thought as making her information finer with each update. Rather here, each agent becomes more doubtful, considering more things are uncertain, and it is the decision that is based on *this* information that matters for the agreement.

We can also apply this interpretation to the mechanism underlying No Trade Theorems: Suppose there is a seller and a buyer of an object. When the seller indicates that he wants to sell the object, the buyer - who highly valued the object - privately becomes more doubtful, thinking to herself “He would not sell it to me if it really were as valuable as I think it is”. Again, this is a private thought process, and so from the buyer’s point of view, it should in no way affect the seller’s epistemic state; the buyer is *privately* thinking about what she would do if she were more ignorant. Similarly, when the buyer indicates that she want to buy the object, the seller privately become more doubtful, thinking to himself “She would not buy it from me if it really were as invaluable as I think it is”. The answer to what to do given this more doubtful state of information is to not buy and to not sell. There is no trade.

which $\hat{\square}_i p$. This means that agent i starts to doubt p in the infimum (in which we would have $\hat{\square}_i p$), because agent j thinks it is plausible that agent i had received information $\hat{\square}_i p$.

²By the Sure-Thing Principle, we guarantee that z is in fact equal to y and to x , and therefore that x equals y .

3 Impossibility in generic models

Consider the following characterisation of a class of two agent models, which we denote by \mathbf{M}^* :

- If the modal operator of the n^{th} entry of *every* ken of some agent i is \square_i , then the modal operator of the $\sigma(n)^{\text{th}}$ entry of *every* ken of agent j is also \square_j (within the same component).
- If the modal operator of the n^{th} entry of *every* ken of some agent i is $\hat{\square}_i$, then the modal operator of the $\sigma(n)^{\text{th}}$ entry of *every* ken of agent j is also $\hat{\square}_j$ (within the same component).
- If the modal operators of the n^{th} entry of different kens of some agent i are different, or if the modal operator of the n^{th} entry of *every* ken of the agent is \square_i , then *either* the modal operators of the $\sigma(n)^{\text{th}}$ entry of different kens are also different for agent j , *or*, the modal operator of the $\sigma(n)^{\text{th}}$ entry of *every* ken of agent j is \square_j (within the same component).

Proposition 3. $\mathcal{M}^+, s_\omega \models \inf\{\nu_i | \omega' \in \Omega_G(\omega) \ \& \ \omega' \models \nu_i\} \wedge \inf\{\nu_j | \omega' \in \Omega_G(\omega) \ \& \ \omega' \models \nu_j\}$ and $\inf\{\nu_i | \omega' \in \Omega_G(\omega) \ \& \ \omega' \models \nu_i\} \sim^* \inf\{\nu_j | \omega' \in \Omega_G(\omega) \ \& \ \omega' \models \nu_j\}$ if and only if $\mathcal{M} \in \mathbf{M}^*$.

Proof. Suppose $\mathcal{M}^+, s_\omega \models \inf\{\nu_i | \omega' \in \Omega_G(\omega) \ \& \ \omega' \models \nu_i\} \wedge \inf\{\nu_j | \omega' \in \Omega_G(\omega) \ \& \ \omega' \models \nu_j\}$ and $\inf\{\nu_i | \omega' \in \Omega_G(\omega) \ \& \ \omega' \models \nu_i\} \sim^* \inf\{\nu_j | \omega' \in \Omega_G(\omega) \ \& \ \omega' \models \nu_j\}$.

Now, suppose the modal operator of the n^{th} entry of *every* ken of some agent i is \square_i within component $\Omega_G(\omega)$. Then, the modal operator of the n^{th} entry of i 's ken at state s_ω is also \square_i . If it is not the case that the modal operator of the $\sigma(n)^{\text{th}}$ entry of *every* ken of all other agents j is also \square_j within that component, then the modal operator of the $\sigma(n)^{\text{th}}$ entry of some agent j 's ken at state s is not \square_j ; thus contradicting our initial assumption that all agents have the “same” ken at state s_ω . Proceed similarly for the other cases.

The other direction is trivial. □

The above proposition shows that in generic cases - that is, for any model $\mathcal{M} \notin \mathbf{M}^*$ -, the standard agreement theorems (using the assumptions of like-mindedness and the Sure-Thing Principle) will generally not hold if decision functions depend on interactive information (that is, when $r > 0$) - since Lemma 6 in Tarbush (2011a) would no longer hold (with the ordering \succ^*).

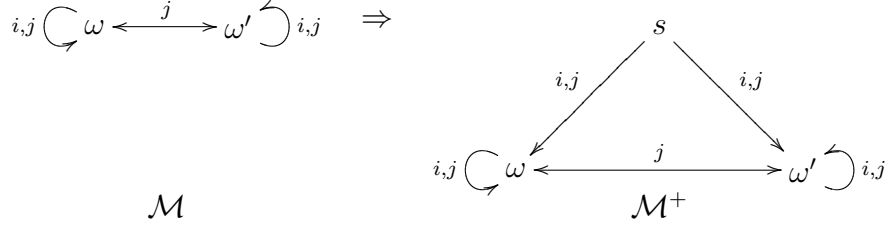


Figure 1: Impossibility with $r > 0$

3.1 Example

We consider a very simple example in which the agreement theorem cannot hold for $r > 0$, which suggests that it does not hold in generic cases when decision functions are allowed to depend on interactive information.

Model \mathcal{M} in Figure 1 is again the coin in a box example, where $\omega \models h$ and $\omega' \models t$. Agent j does not know whether the coin is facing heads up or tails up, but i does, and j knows that i knows. That is, at every state of \mathcal{M} it is the case that $\Box_j(\Box_i h \vee \Box_i t)$ and $\hat{\Box}_i(\Box_j h \vee \Box_j t)$.

It follows that at the state at which the infimum holds for each agent, we have $s \models \Box_j(\Box_i h \vee \Box_i t) \wedge \hat{\Box}_i(\Box_j h \vee \Box_j t)$. So clearly, it is *not* the case that $\inf\{\nu_i | \omega \in \Omega \ \& \ \omega \models \nu_i\} \sim^* \inf\{\nu_j | \omega \in \Omega \ \& \ \omega \models \nu_j\}$. (Note, this shows that model \mathcal{M} in Figure 1 does not belong to the class \mathbf{M}^*).

The simplicity of this case illustrates how general this phenomenon is, and therefore that in general, agreement theorems do not hold when decision functions are allowed to depend on interactive information (when $r > 0$).

In fact, it should be easy to see that unlike the class \mathbf{M} , the class \mathbf{M}^* is actually very special: In order to construct a model in \mathbf{M}^* , one would effectively need to create a “symmetric” model. That is, one in which, if $(\omega, \omega') \in R_i$, then $(\omega'', \omega''') \in R_j$ where for all $p \in P^*$, $\mathcal{V}(p, \omega) = \mathcal{V}(p, \omega'')$ and $\mathcal{V}(p, \omega') = \mathcal{V}(p, \omega''')$.

3.2 Other implications of \succsim^*

Note that Lemma 2 in Tarbush (2011b) does hold for $r = 0$ even with the ordering \succsim^* . However, it does not hold for all $r \geq 0$. Indeed, it is possible that $\omega \models \Box_i \Box_i p \wedge \hat{\Box}_j \Box_j p$ and $I_i(\omega) \subseteq I_j(\omega)$. Therefore, it is possible that $I_i(\omega) \subseteq I_j(\omega)$, $\omega \models \nu_i \wedge \mu_j$ without it being the case that $\nu_i \succsim^* \mu_j$.

For the same reason, Lemma 5 in Tarbush (2011b) also fails for $r > 0$; and since the theorems in the rest of the paper depend on these lemmas, those results also do not hold for $r > 0$.

Finally, the results in Tarbush (2011a) are largely unaffected since most already impose the restriction $r = 0$. However, the proof of Proposition 3 in that paper follows a similar logic to the proofs of Lemmas 2 and 5 in Tarbush (2011b); so although Proposition 3 still does hold for $r = 0$, it fails for $r > 0$ if the ordering \succ^* were used.

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