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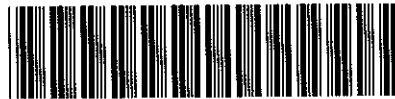
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**The Weak Axiom, the σ -Axiom
and Complete Non-Transitive Rationality**

by

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The Weak Axiom, the σ -Axiom and Complete Non-transitive Rationality

Luigi Brighi*

1 Introduction . . .

This paper deals with the characterization of choices satisfying two kinds of behavioural axioms, the Weak Axiom of Revealed Preference (WA), introduced in demand theory by Samuelson (1938), and the σ -Axiom formulated by Clark (1988) in the abstract context of the theory of choice.

The WA is a mild requirement of consistency of choice. In consumer theory, for example, the WA does not imply the hypothesis of utility maximization since, as shown by Gale (1960), Shafer (1977), Peters and Wakker (1994) and John (1998), there are demand functions satisfying the WA that cannot be rationalized by transitive preferences. The σ -Axiom places more stringent restrictions on choice as compared to the WA, however, even the σ -Axiom is not strong enough to allow for a characterization in terms of complete and transitive preferences (as it will be the case for choice behaviour satisfying the Strong Axiom of Revealed Preference). In fact, in the special case of single-valued choice (e.g. demand functions), the two types of behavioural assumptions are equivalent.

This paper addresses the problem of finding the type of rationality corresponding to the σ -Axiom and the WA. It will be shown that the above type

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of choice behaviour can be rationalized by preferences which are complete and feature a certain 'degree' of transitivity.

The results are obtained within the abstract context of the theory of choice so that they also apply to the special but important case of demand theory. We provide stronger characterizations of the σ -Axiom and also stronger characterizations of the WA when choice is single-valued.

Section 2 contains notation and definitions. Section 3 reviews earlier characterizations of the WA. Section 4 presents some preliminary results and Section 5 provides new characterizations of the σ -Axiom and the WA.

2 Definitions

Let X be a set of alternatives and Q a binary relation in X , i.e. $Q \subseteq X^2$. If $x \in X$ is related to $y \in X$ we write $(x, y) \in Q$ or, equivalently, xQy .

A *strict preference* Q is an *irreflexive* binary relation in X , i.e. $Q \subseteq X^2$ and $\neg xQx$ for all x in X . By $Q(x)$ we denote the set of strictly preferred alternatives, i.e. $Q(x) = \{z \in X \mid zQx\}$, while $Q^{-1}(x) = \{z \in X \mid xQz\}$ is the set of alternatives 'dominated' by x . The *non-comparability* relation $I \subseteq X^2$ associated with Q is defined by xIy iff $\neg xQy$ and $\neg yQx$. By $Q^\alpha \subseteq X^2$ we denote the asymmetric component of Q , i.e. $xQ^\alpha y$ iff xQy and $\neg yQx$. The symmetric component of Q is denoted by E , thus xEy iff xQy and yQx . Clearly, $Q = Q^\alpha \cup E$. A binary relation Q is *asymmetric* if xQy implies $\neg yQx$.

Definition 1. (SR and IR) The strict preference Q is

- i) *Superiorly Regular* (SR) if xIy implies $Q(x) = Q(y)$ or, equivalently, if zQx and xIy imply zQy .
- ii) *Inferiorly Regular* (IR) if xIy implies $Q^{-1}(x) = Q^{-1}(y)$ or, equivalently, if zIx and xQy imply zQy .

We notice that either SR or IR imply transitivity of the non comparability relation, i.e. if xIy and yIz then xIz . However, SR and IR do not imply transitivity of Q .

A non irreflexive binary relation $R \subseteq X^2$ is a *weak preference* or, simply, a preference. A preference R is *reflexive* if xRx for all $x \in X$. R is *complete* if for all $x, y \in X$ either xRy or yRx or both.

The asymmetric and the symmetric components of a preference R are respectively denoted by R^α and R^σ , i.e. $xR^\alpha y$ iff xRy and $\neg yRx$, and $xR^\sigma y$ iff xRy and yRx . Clearly, $R = R^\alpha \cup R^\sigma$.

Definition 2. The preference R is

- i) $\alpha\sigma$ -transitive if $zR^\alpha x$ and $xR^\sigma y$ imply $zR^\alpha y$
- ii) $\sigma\alpha$ -transitive if $zR^\sigma x$ and $xR^\alpha y$ imply $zR^\alpha y$
- iii) $\sigma\sigma$ -transitive if $zR^\sigma x$ and $xR^\sigma y$ imply $zR^\sigma y$

R is σ -transitive if i), ii) and iii) hold.

Notice that σ -transitivity does not imply transitivity of R .

Let \mathcal{A} be the set of all the subsets of X and \mathcal{B} any nonempty subset of \mathcal{A} which does not contain the empty set. A function $\Phi: \mathcal{B} \rightarrow \mathcal{A}$ is a choice if $\Phi(B) \subseteq B$ for all $B \in \mathcal{B}$. Φ is *decisive* if $\Phi(B) \neq \emptyset$ for all $B \in \mathcal{B}$. Φ is *single-valued* if $\Phi(B)$ is a singleton for all $B \in \mathcal{B}$.

A preference R rationalizes the choice function Φ if for all $B \in \mathcal{B}$

$$\Phi(B) = \{x \in B \mid xRy \text{ for all } y \in B\}.$$

Φ is *rational* if there exists some preference R satisfying the above condition.

A strict preference Q motivates the choice function Φ if for all $B \in \mathcal{B}$

$$\Phi(B) = \{x \in B \mid Q(x) \cap B = \emptyset\}.$$

Φ is *motivated* if there exists some strict preference Q satisfying the above condition.

To a choice function $\Phi: \mathcal{B} \rightarrow \mathcal{A}$ is associated the *revealed preference* $V \subseteq X^2$, which is defined by xVy iff there exists $B \in \mathcal{B}$ such that $x \in \Phi(B)$ and $y \in B$ (i.e. y is available when x is chosen). The revealed *strict preference*

V^* is defined by xV^*y iff there exists $B \in \mathcal{B}$ such that $x \in \Phi(B)$ and $y \in B - \Phi(B)$ (i.e. y is rejected when x is chosen).

Definition 3. The choice function $\Phi: \mathcal{B} \rightarrow \mathcal{A}$ satisfies the Weak Axiom of Revealed Preference (WA) iff xV^*y implies $\neg yVx$.

3 Earlier characterizations

Clark (1988) and Scapparone (2000) provide some interesting results on the characterization of single valued choices satisfying the WA. Their results are brought together in the following

Theorem 1. Let Φ be a single-valued choice. The following statements are equivalent:

- i) Φ satisfies the WA
- ii) Φ is rationalized by a σ -transitive preference R
- iii) Φ is motivated by a SR and IR strict preference Q

Proof. (i) to (ii). It is well known that a choice satisfying the WA is rationalized by the revealed preference V . Moreover, since Φ is single-valued V is antisymmetric, i.e. xVy and yVx imply $x = y$. Thus $V^\sigma \subseteq \Delta = \{(x, y) \in X^2 \mid x = y\}$ and V is trivially σ -transitive. Hence $R = V$ is σ -transitive and rationalizes Φ .

(ii) to (iii). Set¹ $Q = X^2 - R^{-1} - \Delta$, i.e. xQy iff $x \neq y$ and $\neg yRx$. Clearly, Q is irreflexive. Next, let us suppose that Q is not SR. Then, there exist x, y and z such that $x \neq y$, xIy , zQx and $\neg zQy$. By definition of Q we have $xR^\sigma y$ and from xIy and zQx we have $z \neq y$ so that $\neg zQy$ yields yRz . From $xR^\sigma y$ and yRz we obtain, by σ -transitivity, xRz which is impossible since zQx implies $\neg xRz$. Therefore, Q is SR. A similar argument shows that Q is also IR.

¹Recall that R^{-1} denotes the inverse of the binary relation R , i.e. $R^{-1} = \{(y, x) \in X^2 \mid (x, y) \in R\}$.

Next, we show that Q motivates Φ . It is easily seen that $\Phi(B) \subseteq \Psi(B) = \{x \in B \mid Q(x) \cap B = \emptyset\}$ for all $B \in \mathcal{B}$. To show the converse let us suppose that $x \in \Psi(B)$ and $x \notin \Phi(B)$ for some B . By definition of Ψ we have $\neg yQx$ for all $y \in B$ and, for $y \neq x$ we have xRy . Since $x \notin \Phi(B)$ it must be $\neg xRx$. However, since R rationalizes Φ and Φ is decisive, there exists $z \in \Phi(B)$, hence zRx . On the other hand, since $z \neq x$ and $z \in B$ we also have xRz , thus $zR^\sigma x$. By σ -transitivity, $xR^\sigma z$ and $zR^\sigma x$ imply xRx and this contradiction establishes the result.

(iii) to (i). Let us suppose that Φ violates the WA, i.e. there exist x and y such that xV^*y and yVx . Since Q motivates Φ we have xIy . Moreover, since xV^*y , there exists a set B such that x, y and $z \in B$, $x \in \Phi(B)$ and zQy . Thus, by SR, we have zQx which is impossible since x is chosen in B . \square

From the proof it can be noticed that (ii) and (iii) are sufficient conditions for the WA even when the choice function is not single-valued. Indeed, the assumption that Φ is single-valued is only used in step (i) to (ii). However, a counter-example provided by Scapparone (2000) shows that the above characterization of the WA cannot be extended to the case of multi-valued choice functions. In fact, Clark (1988) has shown that for not necessarily single valued choices σ -transitivity characterizes a stronger behavioural axiom than the WA, precisely the σ -Axiom that will be discussed in Sec. 5

In the following section we derive a preliminary result which allows us to strengthen the existing characterizations of the σ -Axiom and the WA.

4 A preliminary result

Given a SR strict preference Q we propose a general method for constructing a subrelation $P \subseteq Q$ which is asymmetric and preserves the SR property.

The construction of such a subrelation may seem a trivial matter. In fact, if we select 'one half' of E , i.e. an asymmetric set E^* such that $E^* \cup E^{*-1} = E$, we immediately obtain the asymmetric subrelation $P = Q^\alpha \cup E^*$. However, P need not preserve the SR property. For example, let $X = \{x, y, z\}$ and $Q =$

$\{(x, z), (z, x), (y, z), (z, y)\}$. Then $Q^\alpha = \emptyset$, $E = Q$ and $I = \{(x, y), (y, x)\}$. Clearly, Q has the SR property and is not asymmetric. Let us consider the asymmetric set $E^* = \{(x, z), (z, y)\}$. Then $E^* \cup E^{*-1} = E$ and the subrelation $P = E^*$ is asymmetric. However, P has not the SR property since xIy , $z \in P(y)$ but $z \notin P(x)$.

In this trivial example it is easy to find a subrelation P which fulfill the desired requirements, e.g. set $E^* = \{(z, x), (z, y)\}$. In general, however, things are not so simple especially when the number of alternatives is not finite. Below we shall provide a general method for finding the desired subrelations.

For the rest of this section we assume that $Q = Q^\alpha \cup E$ is a SR strict preference. Let us recall a few useful facts about the set E .

Fact 1. $(z, y) \in E$ if and only if there exists $(x, w) \in X^2$ such that (z, y) and (x, w) satisfy the following conditions:

$$\begin{array}{l} zQx, \quad xIy \\ yQw, \quad wIz \end{array} \quad (1)$$

Indeed, (1) and SR imply $(z, y) \in E$. Conversely, (1) trivially holds for $x = y$ and $w = z$.

Fact 2. If $(z, y) \in E$ and $(x, w) \in X^2$ satisfy (1) there are only three possible mutually exclusive cases:

- i) $wQ^\alpha x$ iff $zQ^\alpha x$
- ii) $xQ^\alpha w$ iff $yQ^\alpha w$
- iii) wEx .

Proof. Obviously, the three cases are mutually exclusive. To prove that they exhaust all the possibilities we must show that xIw is excluded. Indeed, by transitivity of I , wIz would imply xIz which is impossible since zQx .

Next, let us consider the equivalence in (i) and suppose that xQz . Then from zIw and SR we have xQw which contradicts $wQ^\alpha x$, thus $zQ^\alpha x$. The converse and the equivalence in (ii) are proved in a similar way. \square

Fact 3. If $(z, y) \in E$ and $(x, w), (x', w') \in X^2$ satisfy (1), then we cannot have $zQ^\alpha x$ and $yQ^\alpha w'$. Indeed, in that case (z, y) and (x, w') would satisfy (1) which, by Fact 2, is impossible.

In order to construct the desired subrelation of Q we start the analysis from the following two subsets of E .

Definition 4. The sets $E_1^* \subseteq E$ and $E_2 \subseteq E$ are as follows:

E_1^* : $(z, y) \in E_1^*$ if for some $(x, w) \in X^2$ satisfying (1) it holds $zQ^\alpha x$.

E_2 : $(z, y) \in E_2$ if $(z, y) \in E$ and for all $(x, w) \in X^2$ satisfying (1) it holds xEw .

Remark 1. It is easily seen that the sets E_1^* and E_2 are disjoint and that E_2 is symmetric, i.e. $(z, y) \in E_2$ implies $(y, z) \in E_2$. On the other hand, the set E_1^* is asymmetric. Indeed, if (z, y) and (y, z) were in E_1^* we would have the case excluded by Fact 3.

The next step consists in selecting an appropriate subset of E_2 . To this aim we define a new family of subsets of E_2 .

Definition 5. Let $(z, y) \in E_2$. The set $G(z, y)$ consists of all $(x, w) \in X^2$ satisfying (1).

A few useful properties of the sets $G(z, y)$ are listed below.

Lemma 1. The set $G(z, y)$ has the following properties:

- i) $G(z, y) \neq \emptyset$ and $G(z, y) \subseteq E_2$.
- ii) $G(z, y)$ is asymmetric.
- iii) $G(y, z) = G(z, y)^{-1} := \{(w, x) \in X^2 \mid (x, w) \in G(z, y)\}$.
- iv) If $(x, w) \in G(z, y)$ then $G(z, y) = G(z, x)$.

The proof is the Appendix.

The sets $G(z, y)$ allow us to obtain a partition of E_2 by considering the following binary relation. For all (z, y) and (z', y') in E_2 ,

$$(z, y)\mathcal{R}(z', y') \quad \text{iff} \quad G(z, y) = G(z', y')$$

It is easily seen that \mathcal{R} is an equivalence relation, i.e. it is reflexive, symmetric and transitive, therefore E_2 can be partitioned into equivalence classes. We denote by \mathcal{C} the family of equivalence classes and by C a generic element of \mathcal{C} , thus $E_2 = \cup_{C \in \mathcal{C}} C$ and $C \cap C' = \emptyset$ for all $C \neq C'$.

Lemma 2. Let $C \in \mathcal{C}$. Then (i) C is asymmetric and (ii) $C^{-1} \in \mathcal{C}$.

The proof is in the Appendix.

Definition 6. Let $E_2^* := \cup_{C \in \mathcal{D}} C$, where \mathcal{D} is a subset of \mathcal{C} such that, for all $C \in \mathcal{C}$ it holds either $C \in \mathcal{D}$ or $C^{-1} \in \mathcal{D}$ (but not both).

The existence of the set \mathcal{D} in the definition of E_2^* is guaranteed by the Axiom of Choice noticing that, by Lemma 2, the set \mathcal{C} can be partitioned by the family of sets $\{C, C^{-1}\}$.

Remark 2. The set E_2^* is asymmetric and $E_2^* \cup E_2^{*-1} = E_2$. The first claim follows trivially from Definition 6 and Lemma 2(i). As for the equality, the first inclusion is trivial. To show the converse, let $(z, y) \in E_2$ so that $(z, y) \in C$ for some $C \in \mathcal{C}$. If $C \in \mathcal{D}$ then $(z, y) \in E_2^*$. If $C \notin \mathcal{D}$ then $C^{-1} \in \mathcal{D}$ and $(y, z) \in E_2^*$ so that $(z, y) \in E_2^{*-1}$.

The final step of the construction is to set

$$E^* := E_1^* \cup E_2^*. \quad (2)$$

Lemma 3. The set E^* is asymmetric and $E^* \cup E^{*-1} = E$.

The proof is in the Appendix.

The main result of this section is the following

Theorem 2. Let Φ be a decisive choice (not necessarily single-valued) motivated by a strict preference Q satisfying the SR property. Then Φ is motivated by a strict preference P with the following properties:

- i) P is an asymmetric subrelation of Q , i.e. P is asymmetric and $P \subseteq Q$.
- ii) P has the same non comparability relation as Q , i.e. $I = X^2 - Q \cup Q^{-1} = X^2 - P \cup P^{-1}$.
- iii) P has the SR and IR properties.

Proof. Set $P = Q^\alpha \cup E^*$ where E^* is given by (2). Then, by Lemma 3, it is easily seen that P satisfies (i) and (ii).

As for (iii), let us suppose that P does not satisfy the SR property, i.e. there exist x, y and z such that $xIy, z \in P(x)$ and $z \notin P(y)$. Since Q is SR and $z \in P(x) \subseteq Q(x)$ we have $(z, y) \in Q$. Thus, since $(z, y) \notin P$ it must be $(z, y) \in E$ and specifically $(z, y) \in E^{*-1}$ or equivalently $(y, z) \in E^*$. We will show that this leads to a contradiction.

Let us suppose that $(y, z) \in E_1^*$, so that there exists $w \in X$ such that $yQ^\alpha w$ and wIz . Thus, we can write

$$\begin{array}{ll} yQ^\alpha w, & wIz \\ zQx, & xIy \end{array}$$

By Fact 2(ii) we have $xQ^\alpha w$ and it is easily seen that $(x, z) \in E_1^*$. Thus $x \in P(z)$, which is impossible since $z \in P(x)$ and P is asymmetric. Therefore, we conclude that $(y, z) \notin E_1^*$.

Next, let us suppose that $(y, z) \in E_2^*$ so that (y, z) belongs to an equivalence class, i.e. $(y, z) \in C$ for some $C \in \mathcal{C}$. Moreover, since $(y, z) \in E_2$ and (z, x) satisfy (1), by Lemma A (in the Appendix), we also have $(x, z) \in E_2$. We show that $(x, z) \in C$, i.e. $G(y, z) = G(x, z)$.

By symmetry of E_2 , $(y, z) \in E_2$ implies $(z, y) \in E_2$, thus there exists $w \in X$ such that $(x, w) \in G(z, y)$. Then by Lemma 1(iv), $G(z, y) = G(z, x)$, so that $G(z, y)^{-1} = G(z, x)^{-1}$ and by Lemma 1(iii) $G(y, z) = G(x, z)$. Since (y, z) and (x, z) belong to the same equivalence class C and $(y, z) \in E_2^*$, we also have $(x, z) \in E_2^*$. But that means $x \in P(z)$, which is impossible since P is asymmetric and $z \in P(x)$ by assumption. Hence $(y, z) \notin E_2^*$ and we conclude that P has the SR property. To complete point (iii) we show that an asymmetric and SR preference is also IR. Indeed, let us suppose that IR is violated, i.e. there exist xIy, xPz and $-yPz$. We have two cases: (a) zPy ,

then SR yields zPx which is impossible since P is asymmetric. (b) $\neg zPy$, so that zIy and since xPz SR yields xPy which is impossible since xIy . Thus we conclude that P is also IR.

Finally, we show that P motivates Φ . Let $\Psi(B) = \{x \in B; P(x) \cap B = \emptyset\}$. Since Φ is motivated by Q and $P(x) \subseteq Q(x)$, it is easily seen that $\Phi(B) \subseteq \Psi(B)$. To show the converse let $x \in \Psi(B)$ so that $P(x) \cap B = \emptyset$. Arguing by contradiction, let us suppose that $x \notin \Phi(B)$, which means that there exists z such that $z \in Q(x) \cap B$. Since Φ is decisive there exists $y \neq x$ such that $y \in \Phi(B)$, thus $y \in \Psi(B)$ since $P(x) \subseteq Q(x)$. Clearly, x and y are non comparable under P and, by (ii), also under Q , i.e. xIy . However, since Q has the SR property and zQx , it must be zQy so that $z \in Q(y) \cap B$ and y cannot be in $\Phi(B)$. Therefore, we conclude that P motivates Φ . \square

5 Characterizations by means of complete or asymmetric preferences

As we noticed in Sec. 3, Theorem 1 cannot be extended to the case of multi-valued choices. In fact, as shown by Clark (1987), σ -transitive preferences characterize choices satisfying a stronger property than the WA. In order to introduce this new behavioural axiom let us recall a few definitions. The composition of two relations S and T , denoted by $S \circ T$, is defined by $x(S \circ T)y$ iff there exists z such that xSz and zTy . The transitive closure of S , denoted by S^τ , is the smallest transitive relation containing S .

Definition 7. The choice function Φ satisfies the σ -Axiom iff the relation $V^* \circ (V^\sigma)^\tau$ is asymmetric.

It is easily seen that a choice satisfying the σ -Axiom obeys the WA.² The converse, however, is not generally true so that the σ -Axiom is stronger than

²Let us suppose that the WA does not hold, i.e. there are x and y such that xV^*y and yVx . Then $xV^\sigma y$ and $x(V^* \circ (V^\sigma)^\tau)x$ so that the σ -axiom is violated.

the WA. Clark [(1987), Corollary (VI)] shows that the σ -Axiom is characterized by σ -transitive rationality. The following theorem provides a stronger characterization.

Theorem 3. Let Φ be a decisive choice (not necessarily single-valued). The following statements are equivalent:

- i) Φ satisfies the σ -Axiom
- ii) Φ is rationalized by a σ -transitive preference
- iii) Φ is motivated by a SR and IR strict preference
- iv) Φ is motivated by an asymmetric SR and IR preference
- v) Φ is rationalized by a complete and σ -transitive preference

Proof. (i) and (ii) are equivalent by Corollary (VI) in Clark (1987). (ii) implies (iii) as it is shown in (ii) to (iii) of Theorem 1. (iii) implies (iv) by Theorem 2. To show that (iv) implies (v) let P be asymmetric, IR, SR and motivate Φ , then set $R = X^2 - P^{-1}$. It is easily seen that R is complete and rationalizes Φ . Moreover, $R^\alpha = P$ and $R^\sigma = I$ therefore, SR and IR imply σ -transitivity of R . Finally, (v) trivially implies (ii). \square

When the choice is single-valued, the WA is equivalent to the σ -Axiom. Indeed, the WA is equivalent to $V^* = V^\alpha$ and, when Φ is single-valued, it implies that V is antisymmetric, thus $V^\sigma \subseteq \Delta = \{(x, y) \mid x = y\}$. Hence $V^* \circ (V^\sigma)^\tau = V^* \circ V^\sigma \subseteq V^* = V^\alpha$ and the σ -Axiom holds.

Therefore, we obtain as a corollary of Theorem 3 the following characterization of the WA which improves upon Theorem 1.

Corollary. Let Φ be a single-valued choice. The following statements are equivalent:

- i) Φ satisfies the WA
- ii) Φ is motivated by an asymmetric SR and IR preference
- iii) Φ is rationalized by a complete and σ -transitive preference

The Corollary directly applies to the case of demand functions and can be compared to a result by Kim and Richter [1986, Th. 16] according to which the WA is characterized by complete and convex preferences. As a final remark we notice that both the characterizations of demand functions offered by the Corollary and Theorem 16 in Kim and Richter (1986) are not completely satisfactory, since the characterizing preferences do not ensure the existence of a demand function, i.e. there may not exist a best bundle in each budget set. It is an open question whether a more satisfactory subclass of complete and σ -transitive preferences can be found.

Appendix

Lemma A. If $(z, y) \in E_2$ and (x, w) satisfies (1) then (x, w) , (z, x) and (y, w) are in E_2 .

Proof. Let us first show that $(z, x) \in E_2$. By (1) we have zQx and by $(z, y) \in E_2$ we have xEw . Thus, by SR, xQw and wIz yield xQz . Thus (z, x) is in E .

Let (z, x) and $(x', w') \in X^2$ satisfy conditions (1), i.e.

$$\begin{array}{ll} zQx', & x'Ix \\ xQw', & w'Iz \end{array}$$

If $w'Q^{\alpha}x'$ then, by Fact 2, $zQ^{\alpha}x'$. Noting that, by SR, $x'Ix$ and xIy yield $x'Iy$ we see that (z, y) and (x', w') satisfy (1) so that $(z, y) \in E_1^*$ which contradicts $(z, y) \in E_2$.

Next, let us suppose that $x'Q^{\alpha}w'$. Then, by Fact 2, $xQ^{\alpha}w'$ and it is easily seen that (x, z) and (w', y) satisfy (1). By Fact 2 and $xQ^{\alpha}w'$ we then have $yQ^{\alpha}w'$, therefore (y, z) and (w', x) satisfy (1) and $(y, z) \in E_1^*$. But this contradicts $(z, y) \in E_2$ since E_2 is symmetric and E_1^* and E_2 are disjoint.

Thus, by Fact 2, we conclude that for all (x', w') it must be $x'Ew'$ so that $(z, x) \in E_2$.

The remaining two cases are shown similarly. For example, notice that $(x, z) \in E_2$ and (w, y) satisfy (1) so that, as shown above, $(x, w) \in E_2$. \square

Proof of Lemma 1.

(i) It is easily verified that $(y, z) \in G(z, y)$. Next, $(x, w) \in G(z, y)$ implies, by Lemma A, that $(x, w) \in E_2$.

(ii) Let $(x, w) \in G(z, y)$ then, by Definition 5, wIz . If (w, x) is in $G(z, y)$ then zQw which contradicts wIz .

(iii) We have to show that $(x, w) \in G(z, y)$ iff $(w, x) \in G(y, z)$. This follows trivially from (1).

(iv) By Lemma A, $(z, x) \in E_2$ thus $G(z, x)$ is well defined. First, we show that $G(z, y) \subseteq G(z, x)$.

Let $(x', w') \in G(z, y)$, i.e. (z, y) and (x', w') satisfy conditions (1) so that we have zQx' . Moreover, $x'Ix$ follows from SR, $x'Iy$ and yIx . Next, it is easily seen that (z, y) and (x, w') satisfy (1), therefore we have $w'Iz$ and, by Lemma A, xQw' . Hence (z, x) and (x', w') satisfy (1) and we conclude that $(x', w') \in G(z, x)$.

The inclusion $G(z, x) \subseteq G(z, y)$ is shown in a similar way. \square

Proof of Lemma 2.

(i) If (z, y) and (y, z) are in the same equivalence class we have $G(z, y) = G(y, z)$. Then, by Lemma 1(iii), $G(z, y) = G(z, y)^{-1}$, which is impossible since $G(z, y)$ is asymmetric and non empty.

(ii) Let $(z, y) \in C$. By (i), C is asymmetric thus $(y, z) \notin C$. Therefore $(y, z) \in C'$ for some $C' \in \mathcal{C}$ with $C' \neq C$. We have to show that $C' = C^{-1}$. Now, let $(y', z') \in C'$. Thus $G(y, z) = G(y', z')$ so that $G(y, z)^{-1} = G(y', z')^{-1}$ and, by Lemma 1(iii), $G(z, y) = G(z', y')$. Hence $(z', y') \in C$ and $(y', z') \in C^{-1}$. Therefore, we have shown that $C' \subseteq C^{-1}$. The converse is also true and is proved similarly. \square

Proof of Lemma 3.

Let $(z, y) \in E^*$ and $(y, z) \in E^*$. By Remark 1 and 2 E_1^* and E_2^* are asymmetric thus $(z, y) \in E_1^*$ and $(y, z) \in E_2^*$ (or vice versa). Since $(y, z) \in E_2^*$ we also have $(z, y) \in E_2$, which is impossible since E_1^* and E_2 are disjoint.

Next, we show that $E \subseteq E^* \cup E^{*-1}$. Let $(z, y) \in E$, then by Fact 1, 2 and 3 we have the following cases:

(a) For some $(x, w) \in X^2$ satisfying (1) it holds $xQ^\alpha w$. Then, by Definition 4, $(z, y) \in E_1^* \subseteq E^* \cup E^{*-1}$.

(b) For some $(x, w) \in X^2$ satisfying (1) it holds $wQ^\alpha x$. Then, by Definition 4, $(y, z) \in E_1^*$ thus $(z, y) \in E_1^{*-1} \subseteq E^* \cup E^{*-1}$.

(c) Finally, for all $(x, w) \in X^2$ satisfying (1) it holds xEw . Then, by Definition 4, $(z, y) \in E_2$ and, by Remark 3, $E_2 \subseteq E^* \cup E^{*-1}$.

This completes the proof, since the inclusion $E^* \cup E^{*-1} \subseteq E$ trivially holds. □

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