Nash–Walras equilibria of a large economy

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Individuals exchange contracts for the delivery of commodities in competitive markets and, simultaneously, act strategically; actions affect utilities across individuals directly or through the payoffs of contracts. This encompasses economies with asymmetric information. Nash–Walras equilibria exist for large economies, even if utility functions are not quasi-concave and choice sets are not convex, which is the case in standard settings; the separation of the purchase from the sale of contracts and the pooling of the deliveries on contracts guarantee that the markets for commodities clear.

asymmetric information | general equilibrium

1. Introduction

The extension, by Hicks (1) and then by Arrow (2) and Debreu (3), of the notion of a commodity to encompass time, uncertainty, and location allowed for a clear understanding of the scope of the main propositions of the theory of general competitive equilibrium, and it shifted the focus of research away from specific models and toward the essential logical structure of the theory.

With commodities differentiated according to time, uncertainty, and location, according to Radner (4), many trades are not be feasible because of differences in information. The restricting of trades to commodities whose characteristics are common knowledge leads, following ref. 5, to a an incomplete market: the objects of trade are not the commodities themselves, but contracts or assets for the delivery of commodities.

Even if trades in contracts are verifiable, the delivery of commodities need not be, which leaves room, according to refs. 6 and 7, for strategic manipulation.

The approach in ref. 7, which emphasizes the design of optimal contracts that reduce the possibility of strategic manipulation, has been the most influential; great effort has since been devoted to the study of game theoretic models of contracts between individuals with asymmetric information.

The purpose here is to reconsider and develop the approach in ref. 6: in a large market, what matters for an individual is not a precise knowledge of the choices of every other individual, but only the effect of these choices on the average deliveries of commodities.

Individuals exchange contracts in competitive markets. Simultaneously, they act strategically. Actions affect utilities across individuals directly or through the payoffs of contracts.

The specification encompasses economies with asymmetric information.

At a Nash–Walras equilibrium, individuals optimize given the prices of contracts and the actions of other individuals; and the markets for commodities, as well as for contracts, clear.

A Nash–Walras equilibrium is, simultaneously, a walrasian equilibrium for a market economy, as in ref. 8, and an equilibrium for a noncooperative game, as in ref. 9. In ref. 10, Nash–Walras equilibria were introduced and existence was proved under strong assumptions. The failure of these assumptions, which occurs naturally in economic settings, is the focus of the argument here.

Equilibria may fail to exist for two reasons: (i) market clearing in contracts need not imply market clearing in commodities; this is due to the individual specific deliveries on contracts that vary with the actions of individuals; (ii) the utility functions of individuals need not be quasi-concave in their choice variables, their trades in contracts and their actions, even if the underlying utilities over bundles of commodities are quasi-concave, and their choice sets need not be convex; this is the case in economies with asymmetric information.

Nash–Walras equilibria exist in large economies as long as the actions of individuals do not affect the payoffs of contracts they purchase; they may affect the deliveries on contracts they sell.

2. The Economy and Equilibrium

Actions are $a \in \mathcal{A}$, a nonempty, compact metric space. Distributions of actions are $\nu \in \Delta(\mathcal{A})$.*

Commodities are $l = 1, \ldots, L$. Trades in commodities are $z = (\ldots, z_l, \ldots) \in \mathcal{Z} = \{z : \underline{z} \leqslant z, \underline{z} \ll 0\}$.

Contracts for the delivery of commodities are $m = 1, \ldots, M$. Sales of contracts, portfolios of short positions, are $\phi = (\ldots, \phi_m, \ldots) \in \Phi = \{\phi : 0 \leqslant \phi \leqslant \bar{\phi}\}$, while purchases of contracts, portfolios of long positions, are $\theta = (\ldots, \theta_m, \ldots) \in \Theta = \{\theta : 0 \leqslant \theta\}$.

An individual is described by a continuous utility function, u, with domain $\mathcal{Z} \times \mathcal{A} \times \Delta(\mathcal{A})$, and by a continuous map D, with domain $\mathcal{A} \times \Delta(\mathcal{A})$ and range $\mathcal{R}$, a compact, convex subset of positive† matrices of dimension $L \times M$. The utility of the individual varies with (z, a, ν): the net trade in commodities, the action of the individual, and the distribution of actions. The matrix of deliveries on contracts sold by the individual is

$$D(a, \nu) = \{d_{l,m}\}_{m=1,\ldots,M}^{l=1,\ldots,L} \in \mathcal{R};$$

it varies with the action of the individual and the distribution of actions.

The matrix of payoffs of contracts purchased by an individual, which does not vary with the action of the individual, is

$$R = \{r_{l,m}\}_{m=1,\ldots,M}^{l=1,\ldots,L} \in \mathcal{R}.$$

The net trade in commodities by an individual is

$$z = R\theta - D(a, \nu)\phi.$$

Prices of contracts are $q = (\ldots, q_m, \ldots)$, with domain Δ^M.

The budget set of an individual varies with (q, R, ν), the prices of contracts, the matrix of payoffs of contracts and the distribution of actions; the budget set of an individual with characteristics (u, D) is

$$\beta(u, D, q, R, \nu) = \{(a, \theta, \phi, z) \mid q(\theta - \phi) \leqslant 0, \\ z = R\theta - D(a, \nu)\phi\} \subset \mathcal{C},$$

where $\mathcal{C} = \mathcal{A} \times \Theta \times \Phi \times \mathcal{Z}$ is the set of choices of individuals.

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*For $\mathcal{X}$, a metric space, $\Delta(\mathcal{X})$ denotes the set of Borel probability distributions on $\mathcal{X}$ with the weak topology. For n, a positive integer, Δ^n denotes the simplex of dimension $(n-1)$.

†A positive matrix has all entries nonnegative and at least one different from zero. The restriction to positive matrices implies that "no trade" is not a fortiori an equilibrium.

An individual chooses (a, θ, ϕ, z), an action, a sale of contracts a purchase of contracts and a net trade in commodities so as to

$$\max\ u(z, a, \nu), \quad \text{s.t. } (a, \theta, \phi, z) \in \beta(u, D, q, R, \nu).$$

The set of solutions to the optimization problem of an individual is $\psi(u, D, q, R, \nu)$.

The set of bounded, continuous utility functions of individuals is $\mathcal{U}$, and $\mathcal{D}$ is the set of continuous functions of deliveries on contracts, both with the supremum norm topology. The set $\mathcal{U} \times \mathcal{D}$, which is a metric space, is the set of characteristics of individuals.

An economy is $\mu \in \Delta(\mathcal{I})$, where $\mathcal{I} \subset \mathcal{U} \times \mathcal{D}$ is a compact subset of characteristics of individuals.

The utility functions of individuals are strictly monotonically increasing in the consumption of commodities: if (u, D) lies in the support of the distribution μ, $z' > z \Rightarrow u(z', a, \nu) > u(z, a, \nu)$.

A joint distribution of characteristics and choices of individuals is $\tau \in \Delta(\mathcal{I} \times \mathcal{C})$.

For (τ, q, R), a joint distribution of characteristics and choices of individuals, prices of contracts and payoffs of contracts purchased, the best response set is[‡]

$$B(\tau, q, R) = \{(u, D, a, \theta, \phi, z) \mid (a, \theta, \phi, z) \in \psi(u, D, q, R, \tau_{\mathcal{A}})\} \subset \mathcal{I} \times \mathcal{C}.$$

DEFINITION 1. *A Nash–Walras equilibrium for an economy, μ, is a joint distribution on the set of characteristics and the set of choices of individuals, τ^*, such that*

1. *the marginal distribution of characteristics of individuals coincides with the distribution in the economy:*

$$\tau^*_{\mathcal{I}} = \mu;$$

2. *there exist prices of contracts, q^*, and a matrix of payoffs of contracts purchased, R^*, such that individuals optimize:*

$$\tau^*(B(\tau^*, q^*, R^*)) = 1;$$

3. *the matrix of payoffs of contracts pools the deliveries on contracts:*

$$\int_{\mathcal{I}\times\mathcal{C}} \phi_m d\tau^* > 0 \quad \Rightarrow \quad r^*_{l,m} = \frac{\int_{\mathcal{I}\times\mathcal{C}} d_{l,m}(a, \tau^*_{\mathcal{A}})\phi_m d\tau^*}{\int_{\mathcal{I}\times\mathcal{C}} \phi_m d\tau^*};$$

4. *the markets for commodities clear:*

$$\int_{\mathcal{I}\times\mathcal{C}} z d\tau^* = 0.$$

This is an extension of the notions of a competitive equilibrium for an economy and of a Nash equilibrium for a game to a large set of individuals.

PROPOSITION 1. *Nash–Walras equilibria exist.*

Proof: For $0 < \epsilon < 1/M$, $\Delta^M_\epsilon = \{q : \sum_{m=1}^M q_m = 1, q_m \geqslant \epsilon, m = 1, \ldots M\}$.

The correspondence $\beta : \mathcal{I} \times \Delta^M_\epsilon \times \mathcal{R} \times \Delta(\mathcal{A}) \rightarrow \mathcal{C}$ is nonempty, compact valued and continuous.

If a sequence $((u_n, D_n, q_n, R_n, \nu_n) : n = 1, \ldots)$ converges to (u, D, q, R, ν), $(a, \theta, \phi, z) \in \beta(u, D, q, R, \nu)$, $q(\theta - \phi) = 0$, and $z = R\theta - D(a, \nu)\phi$, there exists $\eta > 0$, such that[§] $a' = a$, $\theta' = 0$, $\phi' = \eta \mathbf{1}_M$, $z' = R\theta' - D(a', \nu)\phi' = -\eta D(a, \nu)\mathbf{1}_M$ satisfies $q(\theta' - \phi') = -\eta < 0$, and $\underline{z} < z'$. A sequence converging to (a, θ, ϕ, z) is constructed by taking convex combinations. Since the action, a, remains fixed along the sequence, the possible nonconvexity of the budget set does not interfere with the argument.

The correspondence $B : \Delta^M_\epsilon \times \mathcal{R} \times \Delta(\mathcal{A}) \rightarrow \mathcal{I} \times \mathcal{C}$ is nonempty compact valued, and upper hemicontinuous.

If a sequence, $((q_n, R_n, \tau_n) : n = 1, \ldots)$, converges to (q, R, τ), and $(a_n, \theta_n, \phi_n, z_n) \in \psi(u_n, D_n, q_n, R_n, \tau_{\mathcal{A},n})$, for $n = 1, \ldots,$ there exists $(u, D, a, \theta, \phi, z)$ such that the sequence $((u_n, D_n, a_n, \theta_n, \phi_n, z_n) : n = 1, \ldots)$ converges to $(u, D, a, \theta, \phi, z)$. If $(a, \theta, \phi, z) \notin \psi(u, D, q, R, \tau_{\mathcal{A}})$, there exists a sequence $(a'_n, \theta'_n, \phi'_n, z'_n) \in \beta(u_n, D_n, q_n, R_n, \tau_{\mathcal{A},n})$ that converges to a point (a', θ', ϕ', z'), with $u(a', \tau_{\mathcal{A}}) > u(a, \tau_{\mathcal{A}})$. Since $u_n(a_n, \tau_{\mathcal{A},n}) \geqslant u_n(a'_n, \tau_{\mathcal{A},n})$, this contradicts the convergence of the sequence $(u_n : 1, \ldots)$ to u in the supremum norm topology.

The set $\mathcal{C}_\epsilon = \beta(\mathcal{I}, \Delta^M_\epsilon, \mathcal{R}, \Delta(\mathcal{A}))$ is compact. The set $\mathcal{T}_\epsilon \subset \Delta(\mathcal{I} \times \mathcal{C}_\epsilon)$, such that, if $\tau \in \mathcal{T}_\epsilon$, then $\tau_{\mathcal{I}} = \mu$, is compact and convex.

The correspondence $\Phi_{1,\epsilon} : \Delta^M_\epsilon \times \mathcal{R} \times \mathcal{T}_\epsilon \rightarrow \mathcal{T}_\epsilon$ defined by $\Phi_{1,\epsilon}(q, R, \tau) = \{\tau' \in \mathcal{T}_\epsilon : \tau'(B(q, R, \tau)) = 1\}$ is nonempty, convex, compact valued and upper hemicontinuous.

If a sequence, $((q_n, R_n, \tau_n) : n = 1, \ldots)$, converges to (q, R, τ), and a sequence, $(\tau'_n : n = 1, \ldots)$, such that $\tau'_n \in \Phi_{1,\epsilon}(q_n, R_n, \tau_n)$, converges to τ', then $\tau' \in \Phi_{1,\epsilon}(q, R, \tau)$. If not, $\tau'(B(q, R, \tau)) < 1$ and, for an open set, U, $\tau'(U) < 1$, and $B(q, M, \tau) \subset U$. Since the correspondence B is upper hemicontinuous, there exists $\bar{n}$, such that $B(q_n, R_n, \tau_n) \subset U$, , for $n = \bar{n}, \ldots.$ Since $\tau'_n(B(q_n, R_n, \tau_n)) = 1$, while the sequence $(\tau'_n : n = 1, \ldots)$ converges weakly, $\tau'(B(q_n, R_n, \tau_n)) = 1$. But then $\tau'(U) = 1$, a contradiction.

The function $\Phi_{2,\epsilon} : \mathcal{T}_\epsilon \rightarrow \mathcal{R}$ is defined by

$$\phi_{2,\epsilon,l,m}(\tau) = \frac{\epsilon \bar{r}_{l,m} + \int_{\mathcal{I}\times\mathcal{C}} d_{l,m}(a, \tau_{\mathcal{A}})\phi_m d\tau}{\epsilon + \int_{\mathcal{I}\times\mathcal{C}} \phi_m d\tau},$$

where $\bar{R} \in \mathcal{R}$ is a fixed matrix of payoffs of contracts, and the correspondence $\Phi_{3,\epsilon} : \mathcal{T}_\epsilon \rightarrow \Delta^M_\epsilon$ by $\Phi_{3,\epsilon}(\tau) = \arg\max_{\Delta^M_\epsilon} q \int_{\mathcal{I}\times\mathcal{C}} (\theta - \phi) d\tau$.

The correspondence $\Phi_\epsilon = \Phi_{1,\epsilon} \times \Phi_{2,\epsilon} \times \Phi_{3,\epsilon} : \Delta^M_\epsilon \times \mathcal{R} \times \mathcal{T}_\epsilon \rightarrow \Delta^M_\epsilon \times \mathcal{R} \times \mathcal{T}_\epsilon$ is nonempty, convex, compact valued and upper hemicontinuous; therefore, it has a fixed point, $(q_\epsilon, R_\epsilon, \tau_\epsilon)$.

For $\epsilon = 1/n$, the sequence of fixed points is $((q_n, R_n, \tau_n) : n = M + 1, \ldots,)$.

Since Δ^M and $\mathcal{R}$ are compact, without loss of generality the sequence of prices of contracts and matrices of payoffs of contracts, $((q_n, R_n) : n = M + 1, \ldots)$. converges to (q^*, R^*).

Since $q \int_{\mathcal{I}\times\mathcal{C}} (\theta - \phi) d\tau_\epsilon \leqslant 0$, for all $q \in \Delta^M_\epsilon$, and, in particular for $q = \mathbf{1}_M(1/M)$, $\sum_{m=1}^M \int_{\mathcal{I}\times\mathcal{C}} \theta_m\, d\tau_\epsilon \leqslant \sum_{m=1}^M \int_{\mathcal{I}\times\mathcal{C}} \phi_m d\tau_\epsilon \leqslant \sum_{m=1}^M \bar{\phi}_m$. Thus there exists a compact set $\mathcal{K} \subset \mathcal{C}$, such that $\psi(u, D, q_n, R_n, \tau_{\mathcal{A},n}) \subset \mathcal{K}$, for $n = M + 1, \ldots$ and μ—almost all $(u, D) \in \mathcal{I}$. The sequence of joint distributions of characteristics and choices of individuals, $(\tau_n : n = M + 1, \ldots)$ is thus concentrated on the compact set $\mathcal{I} \times \mathcal{K}$, and, without loss of generality, it converges to $\tau^* \in \Delta(\mathcal{I} \times \mathcal{K})$.

‡If σ is a distribution on a product set, $\ldots \times \mathcal{B} \times \ldots$, then $\sigma_{\mathcal{B}}$ denotes the marginal distribution on $\mathcal{B}$.

§"1_K" denotes the column vector of 1's of dimension K.

Taking limits, $q^* \int_{\mathcal{I}\times\mathcal{C}}(\theta - \phi)d\tau^* = 0$, and $q\int_{\mathcal{I}\times\mathcal{C}}(\theta - \phi)d\tau^* \leqslant 0$, for all $q \in \cup_\epsilon \Delta_\epsilon^M = \Delta_{++}^M$. This implies that $\int_{\mathcal{I}\times\mathcal{C}}(\theta - \phi)d\tau^* \leqslant 0$. If, for some m, $\int_{\mathcal{I}\times\mathcal{C}}(\theta_m - \phi_m)d\tau^* < 0$, a modification of the demand of a nonnegligible set of individuals to $\hat{\theta} = \theta^* - \int_{\mathcal{I}\times\mathcal{C}}(\theta_m - \phi_m)d\tau^*$ ensures market clearing for contracts.

From the budget constraints of individuals, and the definition of $\Phi_{2,\epsilon}$,

$$\int_{\mathcal{I}\times\mathcal{C}} zd\tau_\epsilon = R_\epsilon \int_{\mathcal{I}\times\mathcal{C}}(\theta - \phi)d\tau_\epsilon + \epsilon\sum_{m=1}^{M}(\bar{r}_m - d_{m,\epsilon}),$$

so that, at the limit, $\int_{\mathcal{I}\times\mathcal{C}} zd\tau^* = 0$.

It remains to show that $\tau^*(B(\tau^*, q^*, R^*)) = 1$.

Take $(a^*, \theta^*, \phi^*, z^*) \in \psi(u, D, q^*, R^*, \tau_A^*)$. If $u(z) > u(z^*)$, for some $(a, \theta, \phi, z) \in \beta(u, D, q^*, R^*, \tau_A^*)$, then there exists $\eta > 0$ and (a', θ', ϕ', z') with $a' = a$, $\theta' = 0$, $\phi' = \eta\mathbf{1}_M$, $z' = R^*\theta' - D(a', \tau_A^*)\phi' = -\eta D(a, \tau_A^*)\mathbf{1}_M > \underline{z}$. By construction, $(a', \theta', \phi', z') \in \beta(u, D, q^*, R^*, \tau_A^*)$, and $q^*(\theta' - \phi') = -\eta < 0$. By taking convex combinations, and using the continuity of the utility function, u, there exists $\bar{n}$, such that this contradicts optimization at q_n, for $n = \bar{n}, \ldots$. ■

3. Remarks

The model is versatile and encompasses diverse situations; in particular, large markets under asymmetric information.

(*i*) The existence of Nash–Walras equilibria is based on the separation of the purchase from the sale of contracts and the pooling of the deliveries on contracts. This idea was introduced and developed in refs. 11 and 12 for the existence of general competitive equilibria when individuals can default on their promises; this encompasses economies with asymmetric information. Moral hazard and nonconvexities in the optimization problems of individuals lead to an analytically equivalent problem for the existence of competitive equilibria, to which separation and pooling provide a solution; this was pointed out and developed in ref. 13. Earlier references to the idea of pooling can be found in refs. 14–16.

(*ii*) Economies with adverse selection are characterized by the inability of individuals or other agents in the economy to distinguish between commodities: in ref. 6, buyers cannot distinguish good from bad cars, while insurance firms in ref. 17 cannot distinguish low from high risk individuals. Commodities are $l = 1, \ldots, L$. Associated with every individual there is a partition $\mathcal{P}$, of the set of commodities: when he trades, the individual cannot distinguish between commodities in the same cell of the partition. The meet of the partitions of individuals is $\mathcal{M}$, with cells $m = 1, \ldots, M$. To each cell of the meet there corresponds a composite commodity, or contract; only contracts are priced in the market. Each individual can exploit his ability to distinguish between commodities as a seller, but not as a buyer: $d_m = (\ldots, d_{l,m}, \ldots)$ is the $\mathcal{P}$-measurable vector of quantities delivered by the individual when selling contract m, while all individuals purchase pooled commodities described by the columns of a matrix, R, whose elements, $r_{l,m}$, give the proportions of commodities, l, in one unit of the composite commodities, m. Special features of the model allow for a simpler proof of the existence of equilibria: bounds on trades follow from the initial endowments of individuals, while the strategic choice of individuals are limited to the choice of the quantities to deliver of the commodities on which they have private information, so that no problem of nonconvexity arise.

(*iii*) Economies with moral hazard are characterized by the ability of individuals to affect, through their actions the distribution of observable outcomes which, in turn, affect the payoffs of assets, as in ref. 18. States of the world are $l = 1, \ldots, L$, with probability $\pi = (\pi_1, \ldots, \pi_L)$. There is one good per state. States of individuals are $s = 1, \ldots, S$. An action of an individual is a function $a : \{1, \ldots, l, \ldots, L\} \to \{1, \ldots, s, \ldots, S\}$ that associates with each state of the world, l, an individual state $s = a(l)$. The probability distribution over states of the world and the action of an individual determine the distribution over the states of the individual. The state of an individual is observable and can be contracted upon, though not his action. The payoffs of a contract sold by the individual, $d_{s,m}$, are conditional on the state of the individual. The matrix of deliveries of a contract sold by the individual, $D(a)$, thus varies varies with his action: $D(a)_{l,m} = d_{a(l),m}$. Separation of the purchase and sale of assets and pooling of the payoffs of assets purchased by individuals restore the existence of equilibria.

(*iv*) Ref. 19 proves the existence of competitive equilibria in a model that encompasses the well known instances of economies with adverse selection, moral hazard, signaling, monitoring, default and incomplete contracts. An individual directly chooses the matrix of deliveries on contracts: $\mathcal{A} = \mathcal{R}$ and $D(a, \nu) = a$; discretion over deliveries on contracts does not vary across individuals and, more importantly, deliveries on contracts do not vary with the distribution of actions.

Team production, as in ref. 20, and relative performance evaluation, as in ref. 21, are instances where deliveries on contracts by an individual vary with the actions of other individuals. Actions of individuals are levels of effort, $a \in \mathcal{A}$. Team output, $Y(\nu)$, varies with the distribution of effort levels; individual output, $y(a)$, varies with the effort of an individual. Output, of individuals as well as of the team, are observable and verifiable; the chosen level of effort by the individual is neither. Optimal compensation design may, then, call for the compensation, $w(y, Y)$, of an individual to vary both with his output as well as the output of the team. If individuals can sell claims, m, to their compensation, delivery on the contract is $d_m(a, \nu) = w(y(a), Y(\nu))$.

(*v*) The description of a large game or a large economy in terms of the distribution of individuals' characteristics and actions as opposed to measurable functions on a measure space of "names"is an abstraction and a generalization; it does away with any reference to individuals. For walrasian equilibria, refs. 22 and 23 developed the argument in terms of distributions and contrasted it with the argument in terms of measurable functions in ref. 24; the analogous argument for Nash equilibria was developed in ref. 25 in contrast with ref. 26. An equilibrium joint distribution of characteristics and choices of individuals, τ^* is symmetric if there is a measurable function from the set of characteristics to the set of choices of individuals, $h^* : \mathcal{I} \to \mathcal{C}$, such that $\tau^*(\text{graph}(h^*)) = 1$. For a game, ref. 25 proves that a symmetric equilibrium distribution exists if the set of actions, $\mathcal{A}$, is finite and the measure that describes the game, μ, is atomless, as in ref. 26. If the utility functions of individuals and the payoffs of assets depend only on a finite number of moments of the distribution of actions, the set of actions is a compact subset of Euclidean space, and the measure that describes the economy is atomless, symmetric Nash–Walras equilibria exist. The difficulty in extending the argument to utility functions and payoffs that depend on the distribution of actions as opposed to finitely many moments comes from the fact that the lyapunov convexity theorem for the range of vector valued measures applies to measures with a range of finite dimension.

(vi) In refs. 27 and 28, individuals choose their trades in a set $\overline{Z}$, such that, if all others choose action $\overline{a}$ that corresponds to truth telling, it is optimal for an individual to choose $\overline{a}$, as well. The formulation thus restricts arbitrarily the possible joint deviations in trades and actions.

(vii) At a Nash–Walras equilibrium, the structure of contracts at equilibrium is, in part, endogenous, since it is determined by the actions of individuals, and it may result in inefficient outcomes. The second best problem of interest in this setting is the design of contracts so as to maximize welfare at equilibrium, taking into account that individuals will then trade competitively, and, simultaneously, they will choose, strategically, actions that affect the payoffs of contracts.

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