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ARTICLE

Model Transfer, the Challenge of Tractability Standards, and Methodological Embedding

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Abstract

Domain-specific epistemic priorities determine which procedures for solving computational models are accepted in a given domain. Tractability assessments thus depend on how disciplines resolve epistemic trade-offs, and ignoring this domain specificity renders the notion of tractability underspecified. I argue that recognizing domain-specific tractability standards reveals an overlooked challenge to model transfer: skepticism about a model's suitability as a computational device in the new domain. Based on the case of a hybrid agent-based model in macroeconomics, I demonstrate that this challenge can sometimes be mitigated by reformulating the model's representational mode to align with the new domain's tractability standard.

1. The overlooked challenge to model transfer

Model transfer, the phenomenon that one and the same model gets reused in different domains, has recently drawn more attention from philosophers of science (see Herfeld 2024). Philosophers have studied the cross-domain use of the Lotka–Volterra model (e.g., Knuuttila and Loettgers 2017; Houkes and Zwart 2019; Chao 2023), evolutionary game-theoretic models (Kaznatcheev and Lin 2022; Grüne-Yanoff 2011), the virial theorem and the wave function (Price 2019), kinetic exchange models and Bayesian phylogeography (Bradley and Thébault 2019), the Ising model (Knuuttila and Loettgers 2014, 2016, 2023), reaction–diffusion equations (Houkes 2023), scale-free networks (Knuuttila and Loettgers 2023), rational choice models (Herfeld 2025), Malthus's model of human population (Chen and Bolduc 2025), the Chomsky hierarchy (Lin 2022), and n-person game models (Herfeld and Peruzzi, forthcoming-b).

An observation that model transfers can be challenged because tractability can be assessed differently across domains is an insight this article departs from. Tractability is the property that the literature on model transfer identifies as one of the main factors explaining the cross-domain use of a model (Humphreys 2002, 2004). Paul Humphreys, a central inspiration for this literature, has argued that model transfer is

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attractive because a model that has proven tractable in its original domain can be expected to remain tractable when reused in a target domain. Consequently, using the already tractable model in a new domain saves us the effort of evaluating a model's tractability anew in the target domain and allows us to rely on the mathematical proofs and computational techniques already established for ensuring the model's tractability in the source domain. This pragmatic advantage is seen as one of the primary motivations for model transfer.

While this might generally be plausible for some of the cases discussed in the literature so far, Humphreys's assumption that a model retains its tractability during transfer by virtue of preserving its syntactic configuration is called into question by cases of model transfer in which the model's tractability is assessed differently in the target domain than in the source domain. His assumption rests on what I call the *default view* of tractability. The default view fails to capture such cases because it relies on an underspecified notion of tractability that focuses exclusively on objective factors governing model solvability.

To overcome the limitations of the default view, tractability should be reinterpreted as solvability within the framework of an acceptable model solution. The case for revising the notion of tractability rests on two premises: first, that the acceptability of model solutions depends on how scientists in a given domain negotiate trade-offs among epistemic desiderata, and second, that the resolution of these trade-offs is itself domain-specific. From these premises it follows that the sensitivity of tractability to domain-specific epistemic priorities can be epistemically justified.

I refer to methodological commitments regarding the acceptability of model solutions, shaped by these epistemic priorities, as tractability standards—adopting a term coined by Béatrice Cherrier (2023, 41), who defines them as standards that determine "which manipulations and model solutions are considered acceptable." These standards influence how scientists in a given domain understand and define tractability, providing specific operational criteria, such as time complexity in computer science or the width of functional forms in macroeconomics (Cherrier 2023). A change in the relevant tractability standards brought about by model transfer may lead to a negative reassessment of the transferred model's solution procedures based on such domain-specific criteria, thereby undermining the pragmatic rationale for using the model in the new domain. I call the resulting challenge to model transfer the *challenge of tractability standards*.

There is, however, a strategy that can sometimes mitigate this challenge. I refer to this strategy as *methodological embedding* and argue that it involves reformulating the transferred model or its individual components to align it with the tractability standard in the new domain. In doing so, I adopt a concept analogous to Wybo Houkes's (2023, 7) "conceptual embedding." Where Houkes's conceptual embedding minimizes the distance between a transferred model and entrenched conceptions of phenomena in the target domain, methodological embedding analogously minimizes the distance between the transferred model and the relevant tractability standard. I argue that to overcome the challenge of tractability standards and thereby increase the chances of the model's adoption in the target domain, scientists should investigate the possibility of ensuring the model's tractability via methodological embedding.

To support my arguments, I draw on a case study of the transfer of agent-based models, which originated at the intersection of computer science and complex systems analysis,[1] into macroeconomics. I suggest that their transfer encountered the challenge of tractability standards and show that proponents of agent-based modeling in macroeconomics have responded to this challenge by following the strategy of methodological embedding manifest in the construction of so-called hybrid macroeconomic agent-based models.

2. Limitations of the default view of tractability and domain-specific tractability standards

The current literature in philosophy of scientific modeling has discussed model transfer largely by drawing on the so-called template-based account that originates in Paul Humphreys's work. On this account, science is characterized by widespread application of what Humphreys (2002, 2004) calls computational templates.[2] Computational templates are reusable "computationally tractable representations" (Humphreys 2011, 135), which include a syntactic structure and a set of construction assumptions.[3] Examples of computational templates that Humphreys has in mind are differential equations, such as Laplace's equation, or computational algorithms and structures, such as cellular automata and agent-based models (Humphreys 2002, 2004). Building on Humphreys's idea, model transfer can be viewed as the cross-domain application of such templates.[4] What explains their transfer is their tractability, their flexibility, and, as Tarja Knuuttila and Andrea Loettgers argue, their conceptual features (see Herfeld 2024).[5]

On Humphreys's account, construction assumptions, such as idealizations, abstractions, and approximations, ensure the tractability of templates (Humphreys 2002, 2004). It is clear that the syntactic structure underlying the template also influences tractability by shaping the range of possible numerical and analytical solutions. Moreover, the solution method is a crucial determinant of tractability. As Humphreys (2010) notes, in some cases, solution methods are distinct from templates and are incorporated only later in the process of constructing computational models from those templates. In other cases, such as agent-based models and cellular automata, the solution method is an integral part of the template itself.

Humphreys argues that computational tractability is a crucial constraint on scientific progress: "Most scientific models are specifically tailored to fit, and hence

[1] More specifically, the first applications of agent-based modeling emerged in ecology, operations research, political science, and computer science, largely within the interdisciplinary community of complex systems researchers (Axtell and Farmer 2025).

[2] Humphreys's template-based account is situated against the background of the rise of computational science and targeted at answering the question of how we can philosophically think of what computational models are and how they are constructed (Humphreys 2002, 2004).

[3] For a full list of the constituents of model templates, see Knuuttila and Loettgers (2023).

[4] The discussion has also led to developing and refining Humphreys's definition of templates (Knuuttila and Loettgers 2014, 2016, 2023; Humphreys 2019).

[5] Knuuttila and Loettgers (2014) question Humphreys's claim that tractability is the leading explanation for the widespread use of templates by emphasizing another, more significant factor. They do not, however, argue that tractability is irrelevant, nor do they challenge Humphreys's conception of tractability.

are constrained by, the available mathematics," and "it is the invention and deployment of tractable mathematics that drives much progress in the physical sciences" (Humphreys 2004, 55–56). Often, models created from scratch suffer from intractability, which motivates the search in other disciplines for computational templates potentially applicable to the problem under study, since using these templates immediately guarantees the tractability of a corresponding model. The similarity of the syntactic configuration of a model to the already used models in other disciplines becomes its advantage. In Humphreys's (2004, 68) words, "The drive for computational tractability underlies the enormous importance of a relatively small number of computational templates in the quantitatively oriented sciences."

Thus Humphreys's view presupposes that tractability amounts to the mathematical solvability of models and is determined by their syntactic configuration, and other objective computational constraints and capabilities. This view has not been challenged in the model transfer literature, and much of the philosophy of science literature also seems to presuppose such understanding, although the issue is rarely addressed explicitly. This is why I refer to it as the default view, while not claiming that it is universally accepted among philosophers of science.[6] A necessary consequence of the default view is that tractability is understood as an inherent formal property of models. To be sure, the default view does not deny that tractability is relative and depends on factors that shape our computational constraints and capabilities at a given time, such as mathematical knowledge, computational resources, and so on. However, once these relative computational constraints and capabilities are factored out, tractability becomes, on the default view, a fixed and guaranteed property: The procedure for solving an equation should not vary with the context in which it is applied.

My objection to the default view of tractability is that it leaves tractability underspecified. The concept remains vague without a clear account of what it means for a model to be "solvable." There is no universal procedure for solving a computational model or for deriving a solvable model from a given syntactic structure. In practice, multiple such procedures are often available, resulting in solutions with different properties, some of which can be considered acceptable, while others cannot. To specify the concept of tractability, we should explicitly take into account which model solutions are considered acceptable and why. To put it another way, tractability should be understood as solvability within the framework of an acceptable model solution.

Cherrier (2023) draws attention to the acceptability of model solutions by introducing the notion of "tractability standards." Based on the example of

[6] For example, when discussing Humphreys's account, Anouk Barberousse and Cyrille Imbert (2014) propose distinguishing between tractability per se (the "objective computational landscape") and known tractability (the "epistemic computational landscape"). They argue that our discussion of computational constraints in science should focus on the latter. While I agree with this suggestion, it does not resolve the problem of the view of tractability highlighted in this article, as the domain-specific nature of tractability arises not only from the lack of knowledge but also from varying epistemic priorities. For the sake of simplicity, I frame the discussion in terms of objective constraints; however, I am fully open to their epistemic formulation, and this distinction has no huge bearing on my conclusions.

economics, she shows that understandings of which model solutions count as acceptable have changed over time and vary across subdisciplines and interprets these shifts as changes in tractability standards. Both temporal and interdomain variations in such standards deserve philosophical attention, but it is interdomain differences that have a direct implication for model transfer: If the criteria for what counts as an acceptable solution shift in the course of transfer, tractability in the target domain can no longer be assumed to be preserved. Although the formal properties of a model remain constant, and, in that sense, the default view is correct, the evaluation of those properties can vary substantially across local contexts of scientific practice. If a model is not tractable according to a locally accepted standard, its tractability under an alternative standard is not necessarily relevant. This has serious implications for the success of model transfer, given that tractability is a minimally necessary property required of a model.

While differences in tractability standards may stem from the historical development of disciplines and context-specific nonepistemic considerations, such standards can be justified on epistemic grounds, if certain kinds of model solutions impede the achievement of scientists' epistemic desiderata. The procedure for solving a model depends on many factors, including the solution method and construction assumptions, such as idealizations, and, consequently, all these components can play a role in determining the acceptability of a model solution.

For example, there are multiple solution methods used in modeling, ranging from closed-form solutions to numerical approximations. The choice among these methods determines which basic tractability benchmark is adopted: analytical or numerical solvability. Already preliminary considerations suggest that the choice between them involves a trade-off among epistemic desiderata. As models become more complex, they often can only be solved using numerical methods, and the superior accuracy of the results obtained usually outweighs considerations favoring analytical solvability. Nonetheless, analytical solvability offers distinct advantages, such as greater generality of results and improved opportunities for analyzing limiting cases and asymptotic behavior. When these desiderata are especially valued, favoring analytical over numerical solvability may be epistemically justified.

The preference for certain construction assumptions, such as idealizations, and the rejection of others also depend in part on which epistemic desiderata are prioritized. In the case of so-called minimalist idealizations (Weisberg 2007; Batterman and Rice 2014), it is not only considerations of tractability that play a role. If idealizations are selected specifically for reasons of tractability, they involve inherent trade-offs concerning what must be sacrificed to achieve tractability. These sacrifices may concern not only specific representational choices but also broader epistemic values. For instance, scientists who place a high value on accuracy may resist idealization altogether and instead sacrifice scope by replacing variables in the model with empirically estimated parameters or by restricting the analysis to particular states of the target system in which solvability can be achieved without resorting to substantial idealizations. By contrast, prioritizing simplicity may motivate idealizations that not only secure solvability but also facilitate ease of deriving solutions, even at the further expense of accuracy.

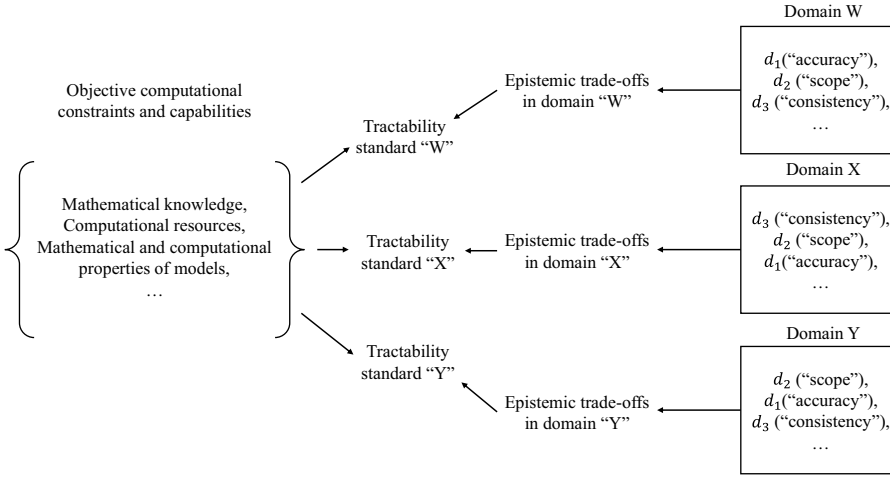


Figure 1. Factors shaping tractability standards.

Thus, when deciding how to achieve tractability, scientists confront trade-offs among competing epistemic desiderata.[7] These trade-offs do not, however, fully determine their choices: Objective computational constraints and capabilities, such as the state of mathematical knowledge and available computational resources, also play a major role. Still, tractability standards partly depend on which epistemic desiderata we aim to achieve and on their relative priority. And scientists in different domains often resolve these trade-offs in different ways. In support of this general claim, see, for example, Miles MacLeod's (2018) discussion of conceptual and methodological divides, as well as conflicts over epistemic values across disciplines.

Consequently, the domain specificity of tractability standards can be epistemically justified. Figure 1 illustrates the various factors that shape these standards. My general argument here does not depend on endorsing any specific account of how scientific disciplines are organized or how models ought to be appraised. We can remain agnostic about the precise nature of interdomain differences in epistemic desiderata, whether these are best characterized as differences in values, as famously suggested by Thomas Kuhn (1977), or, as Chiara Lisciandra (2025) has recently suggested, as differences in explanatory norms. The rankings of epistemic values identified by Kuhn are used in figure 1 for illustrative purposes only. The modest claim that such interdomain differences often exist is sufficient.

As the methodological criteria used to assess tractability, such as the computational time and memory requirements; the number of variables that a model can accommodate; and the required properties of the model solution vary

[7] Seth Bullock (2014) discusses this in a similar way in the context of modeling desiderata identified by Richard Levins, that is, precision, generality, and realism. Bullock adds that a fourth desideratum is implied in Levins's discussion, namely, tractability, which limits the extent to which the other three can be simultaneously achieved.

across domains, they may conflict with one another.[8] Such conflicts between the source and target domains can make model transfer challenging for two reasons. First, it is epistemically risky to deviate from the domain's tractability standard to accommodate a transferred model, as this deviation may result in a failure to meet domain-specific epistemic priorities. Second, it can be difficult to assess whether the potential epistemic benefits of transferring the model outweigh the risks associated with that deviation. As a result, scientists may even recognize a model's potential usefulness yet still refrain from adopting it because they are uncertain whether its benefits justify the perceived tractability-related epistemic risks.

Of course, in actual practice, there are no clear boundaries, and multiple types of modeling often coexist. Furthermore, the similarity of tractability standards in two domains should prevent the challenge of tractability standards. Nevertheless, this is not always the case, and such a challenge can arise in principle. Many instances of model transfer may fail simply because a model does not align with the target domain's tractability standard.

3. Tractability standard in macroeconomics and agent-based models

Agent-based models emerged in the 1980s at the intersection of computer science, operations research, political science, and ecology and were then transferred to various disciplines, including macroeconomics (see, e.g., Axtell and Farmer 2025). Within the template-based account, agent-based modeling can be thought of as a family of related templates grounded in shared construction assumptions. Most notably, these templates posit the existence of autonomous entities, "agents," whose behavior is defined by algorithmic, recursive rules that govern how they interact and influence one another. Leigh Tesfatsion (2023) formulated basic principles underlying the construction assumptions of agent-based models, such as agent local constructivity (an agent's action at any given time is entirely determined by its local properties at that time), agent autonomy (all agent interactions are determined by the totality of their local states), and system historicity (each subsequent event in the model world is determined by all past agent interactions). Furthermore, the assumption of agent heterogeneity has long been central to agent-based modeling, as it allows for more realistic representations of complex interacting systems.

Agent-based models come in a wide variety of forms, with many possible structures for agent interaction. In macroeconomics, the transfer at issue is not the adoption of a single template with a fixed ontology and behavioral rules; rather, it is the transfer of a general principle for generating such templates. In the case of computational templates not tied to a strict mathematical representation (such as a system of equations), transfer often seems to occur at this more abstract level, with the details of the template's structure determined during the model construction process.

Attempts to introduce agent-based modeling into macroeconomics date back to the 1990s (e.g., Lane 1993). Macroeconomic agent-based models represent the interaction patterns among consumers, firms, the government, and the central bank,

[8] See how Roberto Fumagalli (2011, 2017) and Matteo Colombo (2015) confront conflicting interpretations of tractability, stemming from different disciplinary perspectives of economics and computer science.

offering a potential alternative to established frameworks in macroeconomics, such as dynamic stochastic general equilibrium (DSGE) modeling.[9] In agent-based models, the equation-based representation common in macroeconomics is replaced by recursive algorithmic rules that specify the behavior of multiple agents. This approach enables more complex representations of firms and consumers as entities with heterogeneous properties while preserving numerical solvability.

Early attempts to construct agent-based macroeconomic models were met with skepticism from macroeconomists. Roberto Leombruni and Matteo Richiardi (2005, 105) identified two main objections: (1) agent-based models are "difficult to interpret and generalize," and (2) they are "difficult to estimate." The first objection arises from skepticism about whether a system's macrodynamics can be defined unambiguously and reliably within a simulation-based solution implemented in an agent-based model, in contrast to analytical solutions. The second concerns the excessive complexity of the functional forms employed in agent-based models. In response to these concerns, Leombruni and Richiardi argued that the issues of estimation, interpretation, and generalizability can be resolved through the construction of statistical metamodels that examine model behavior across the entire parameter space. However, this apparently proved insufficient to dispel the prevailing skepticism.

Philosophers of economics have already discussed the domain-specific desiderata in economics that, particularly, influence the disciplinary perception of simulation and network models (e.g., Lehtinen and Kuorikoski 2007, 2021; Kuorikoski and Marchionni 2014; Marchionni 2013). Their analysis boils down to the observation that economists place a particularly high value on unification, generality, and formal consistency. As Jaakko Kuorikoski and Caterina Marchionni (2014, 101) put it, it is the expectation that models should explain "many things, which were previously conceived of as being of a different kind, as manifestations of the same parsimonious set of principles."

The strong emphasis on formal consistency places additional constraints on which numerically solved models will be acceptable, as it requires an ability to investigate the theoretical structure of a model using analytical methods to a certain extent, even if its numerical results are calculated using computer simulation. Macroeconomist Manuel Santos (1999) made this position explicit in his handbook chapter on numerical solutions for dynamic models in economics. Specifically, he argued against beginning with "a numerical model (i.e., a collection of rules which could be coded as a finite set of computer instructions)" in model construction, thus "avoiding

[9] DSGE are empirical macroeconomic models of business cycles and economic growth that explain the dynamics of macroeconomic aggregates, such as output, consumption, the price level, the interest rate, and unemployment. To do this, they model the behavior of key economic agents, such as households, firms, the government, and the central bank. There are many specific types of DSGE. However, practically all DSGE models are united by a common core, which consists of several equations describing consumer demand, investment and labor supply as being determined by households that optimize the distribution of their consumption between the current and infinite future periods, and also the output, demand for labor and capital as being determined by firms maximizing their profits. In addition, the models describe the dynamics of inflation using the Phillips curve equation, linking it to the dynamics of output, the dependence of output on the expectations of economic agents using the output gap equation, and the change in the nominal interest rate by the central bank using the Taylor rule equation.

formulation of an abstract economic model" (Santos 1999, 377). According to him, although such numerical models might achieve easier solvability, introducing discreteness and round-off errors makes it significantly harder to verify essential properties of computed solutions, such as existence, stability, and monotonicity.

Moreover, the theoretical principles underlying the explanatory mechanisms used in macroeconomics largely determine the solution methods that are deemed acceptable. These methods typically rely on the notions of equilibrium, optimizing agent behavior, and rational expectations, which can at times make models harder to solve but are nonetheless maintained for the sake of theoretical consistency and explanatory power. The interplay between these theoretical desiderata and the pursuit of model solutions with certain desirable properties has led to the adoption of specific idealizations that have become deeply ingrained in macroeconomic modeling practice, particularly in DSGE models. Chief among these is the assumption of the representative agent, long regarded as useful because it enables the simultaneous achievement of multiple objectives. The representative agent is traditionally seen as providing macroeconomic models with microfoundations, that is, linking aggregate outcomes to the optimizing behavior of individual agents and thus grounding macroeconomic theory in microeconomic theory.[10] Despite ongoing controversy over whether the assumption of the representative agent adequately achieves this, the assumption has remained dominant in macroeconomic modeling, as it not only ensures formal consistency with microeconomic theory but also significantly simplifies the computation of aggregate macroeconomic equilibria, thereby enhancing solvability.

This context shapes what we can refer to as a domain-specific tractability standard in macroeconomics, which influences the choice of idealizations and other construction assumptions, as well as model-solution methods entrenched in the discipline. The tractability standard in macroeconomics differs significantly from such standard in computer science and the interdisciplinary field of complex systems analysis, both of which have exerted methodological influence on agent-based modeling (see, e.g., Anzola 2019).

Particularly, in computer science, the tractability of algorithmic solutions to computational models is evaluated according to a variety of criteria, especially time and memory requirements (e.g., Sipser 2012), but specific constraints on solution procedures that are characteristic of macroeconomics, such as the width of functional forms, receive less emphasis (see also Cherrier 2023). Moreover, David Anzola (2019) argues that methodological commitments in computer science are less concerned with the opacity of algorithmic solutions, even when such opacity substantially reduces the transparency of the solution procedure.

Furthermore, the specific construction assumptions underlying agent-based models do not align well with the procedure of model solution accepted in macroeconomics. In this regard, Tesfatsion (2023, 46) writes, "The determination of a rational expectations solution is therefore a global fixed-point problem that requires the simultaneous consideration of all modeled decision periods without regard for local constructivity, autonomy, and historical process constraints. In contrast, ACE

[10] While the rationale for microfoundations remains a topic of much debate among economists and philosophers (e.g., Ruiz and Schulz 2023; Hoover 2015), I will not explore that debate here and instead simply note the widespread commitment to microfoundations among macroeconomists.

[agent-based computational economics] permits the *open-ended* dynamic modeling of economic systems *without external imposition* of rationality, optimality, or equilibrium conditions."

This discussion shows that the concerns about the difficulty of generalizing, interpreting, and estimating agent-based models can be understood as challenges arising from their misalignment with the tractability standard in macroeconomics. One objection essentially highlights that the solution method used in agent-based models, computer simulation of agent behavior, provides less analytical control over the results than models built on simpler algebraic systems, where the mechanisms leading to specific outcomes can be more transparently traced through mathematical analysis. Another objection targets computational forms and construction assumptions typical of agent-based models, based on which complex specifications with numerous parameters are produced. This is seen as complicating empirical estimation and aggravating the underidentification problem. Specifically, the discrepancy with the tractability standard arises at the level of empirical model estimation, since economists have traditionally regarded models with large numbers of free parameters in empirical work with suspicion.[11] Thus it is the differences in acceptable model-solution procedures that resulted in the challenged transfer.

4. Methodological embedding as a mitigation strategy

Sometimes we can address the challenge of tractability standards and thereby ensure successful model transfer by modifying the transferred model so that it meets those standards. I refer to this strategy as *methodological embedding*.[12]

Literature on model transfer has already examined in detail various strategies for adapting templates at the level of conceptualization of phenomena (e.g., Price 2019, 2020; Houkes 2023). The need for this often arises from the "conceptual pressure" exerted on the transferred model, stemming from discrepancies between its conceptualizations and those entrenched in the target domain (Price 2020). In particular, Wybo Houkes (2023, 78) proposes a "conceptual embedding" strategy, which "involves deliberately minimizing the semantic distance between the (interpretation of the) template and entrenched conceptions of the phenomena in the recipient domain." In response to local pressures for a new template, scientists engaged in template transfer may offer localized justifications for the template's construction assumptions (see also Bradley and Thébault 2019). This involves not only demonstrating the reasonableness of these assumptions within a specific target system but also reformulating them through domain-specific conceptualizations.

As our discussion shows, domain-specific tractability standards can also exert pressure on the transferred template. I propose that the strategy for mitigating this

[11] Macroeconomists often invoke Robert Lucas's warning to "beware of theorists bearing free parameters" (e.g., Sargent 1993, 168).

[12] It is worth noting that modifying a model does not mean that we can no longer speak of model transfer. Models are often adapted to make them suitable for a target domain, and the literature discusses different strategies for such modifications. For instance, Catherine Herfeld and Edoardo Peruzzi (forthcoming-a, forthcoming-b) identify translation and integration as possible model transfer processes, which entail significant changes to transferred models. They explicitly note that, in such cases, the process of model transfer should be seen as a process of model construction.

pressure, namely, methodological embedding, should follow a path similar to that outlined by Houkes, that is, it can be based on minimizing the distance between the solution procedure of the transferred template and the domain-specific tractability standard, making this procedure more acceptable in the target domain given its epistemic priorities regarding model solutions.

Specific modifications that constitute methodological embedding may involve changes to the solution method and the model's idealizations. For example, a model that is solved numerically may be modified so that an analytical solution can be approximated (e.g., by introducing additional idealizations or by converting an algorithmic model into an equation-based one). These changes can affect the representational mode of the model as a whole or that of its individual components, as well as the formal languages used to describe them. In this sense, methodological embedding involves some degree of reformulation[13] and can be understood as one possible aim of what Catherine Herfeld and Edoardo Peruzzi (forthcoming-b) call "model translation," namely, the two-step process of deconstructing and reconstructing a transferred model to ensure its alignment with domain-specific features.

Of course, such reformulation is usually nontrivial. In many cases, full alignment with a local tractability standard is unachievable. Even in such situations, however, partial alignment may still be possible, and it can help address the problem of uncertainty when assessing the epistemic benefits and risks of model transfer. More specifically, methodological embedding can aim at enabling transparent comparison of the components of a model, which influence the procedure of model solution, with the tractability standard of the target domain. The comparative framework may take the form of multiple related models or a single integrated model composed of multiple independently analyzable modules.[14] It can allow identifying and reformulating key components influencing tractability, such as specific idealizations, while holding other elements of a model constant, thereby providing a clear understanding of how each factor affects the model's solution procedure.[15]

Within such a comparative framework, systematic evaluation of a transferred model's potential epistemic benefits becomes possible against the background of the corresponding tractability-related epistemic risks. First, we can reformulate it to achieve varying degrees of alignment with the local standard. Second, we can compare overall epistemic benefits and risks across these different levels of alignment. Through this process, we may uncover templates that are partially

[13] Tarja Knuuttila and Mary Morgan (2019) identify reformulation as one of the possible strategies to deidealize models. They note, however, that reformulating cross-disciplinary templates is problematic because "their application is precisely based on the tractability of their particular syntactic configurations" (Knuuttila and Morgan 2019, 651). At the same time, in the case of methodological embedding, the aim of reformulation is not to deidealize, but exactly to alter a template's tractability to render it suitable under a new tractability standard.

[14] In this case, methodological embedding bears some resemblance to what Miles MacLeod and Michiru Nagatsu (2016) describe as model coupling in interdisciplinary modeling. However, while their notion of coupling concerns the integration of models to address interdisciplinary problems, methodological embedding aims at more transparent comparison between changed constituent elements of models.

[15] Aki Lehtinen and Jaakko Kuorikoski (2021) generally emphasize the importance of this kind of comparability, as it helps to associate specific changes in the model's construction with differences in outcomes.

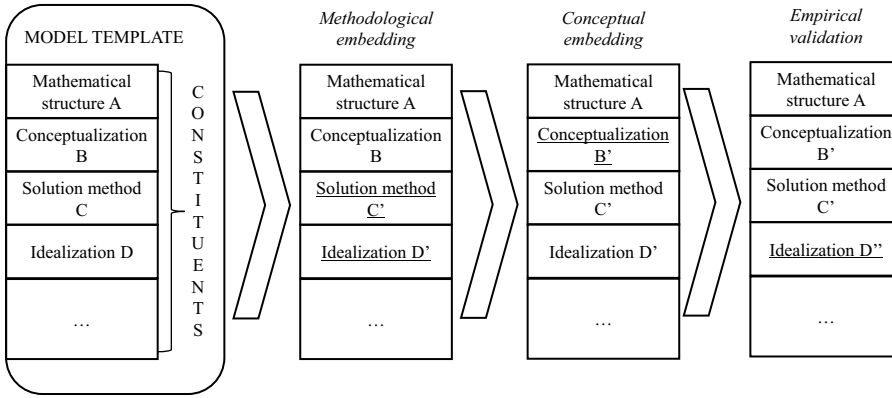


Figure 2. Stages of template adaptation during the successful model transfer process.

adapted to the target domain's tractability standard while retaining certain elements that do not fully align with it. Some of these templates may prove especially promising. Such "hybrids" may preserve the enhanced capacities for advancing our epistemic aims provided by the original template while at least partially reducing the epistemic risks entailed by misalignment with the domain's tractability standard, thereby revealing the locally relevant potential of the transferred template for initiating scientific change. In its turn, the success of constructing these hybrids may subsequently justify a relaxation of the tractability standard in the target domain.

Accordingly, methodological embedding can be defined as a strategy for ensuring successful model transfer, consisting in the reformulation of the transferred model or its individual constituents (e.g., construction assumptions) through changes in formal language and other representational means, so as to better align with the tractability standard of the target domain. Scientists engaged in model transfer, based on their understanding of the priority ranking of epistemic desiderata in the target domain, which are sometimes articulated through specific methodological guidelines like model validation criteria,[16] may alter the formal language and other means of representation they employ to enable a model solution that is better aligned with those methodological guidelines.

Methodological embedding is one component of a broader justificatory work aimed at adapting a transferred template to different domains. This work may also involve other strategies discussed in the literature, which address different challenges. These strategies can be combined and function as interrelated components of the process of model construction based on templates. If model transfer succeeds, culminating in the adoption of the model in the target domain, the overall process can be schematically described as follows (figure 2).[17] In the first stage,

[16] See Sebastiaan Tieleman's (2022) discussion of such validation criteria as factors determining the success of model transfer.

[17] In proposing this schema, I draw on the notion of the model template introduced by Knuuttila and Loettgers (2014, 2016, 2023) and related accounts of model modification. For an alternative account of such modification, based on the concept of a formal template, see Herfeld and Peruzzi (forthcoming-b).

we should assess the extent to which the template's tractability-relevant dimensions, such as its idealizations and solution method, align with the target domain's tractability standard. If this alignment is insufficient, methodological embedding is undertaken. Then, attention shifts to the template's conceptual dimensions, at which point strategies like conceptual embedding may be employed. In the final stage, we evaluate the adequacy of the methodologically and conceptually embedded template as a representational device for the target system and, if necessary, further revise its idealizations so that its resulting output representation can be empirically validated. After the initial adaptation, strategies like customization (see Houkes 2023) can be used to further demonstrate the template's usefulness within the target domain. Of course, when examining real cases from the history of science, we can observe different sequences of action. For example, at intermediate stages of model development, scientists may work with an intractable model and achieve tractability only later in the process.[18]

When methodological embedding proves feasible without significant complications, this strategy appears optimal for overcoming the challenge of tractability standards. At the same time, it is not costless and has clear limitations. Intervening in a model's representational mode can negatively affect its effectiveness in achieving various epistemic desiderata. In such cases, a dilemma arises: Methodological embedding improves the model with respect to the epistemic desiderata prioritized in the target domain, yet it simultaneously diminishes its overall effectiveness. As discussed, it is sometimes possible to resolve this tension by developing partially adapted models. However, a possible scenario is that no promising way is found to maintain the potential epistemic benefits provided by the model while satisfying the constraints of the domain's tractability standard. At this point, it may be necessary to conclude that model transfer is not possible; nevertheless, alternative strategies aimed at changing tractability standards themselves may still remain available.

5. Hybrid macroeconomic agent-based models as a case of methodological embedding

One response by proponents of macroeconomic agent-based modeling to the challenge of tractability standards has been the development of so-called hybrid agent-based models, which combine elements of agent-based and standard macroeconomic models in various ways (Baccini et al. 2025). For example, researchers "agentify" standard macroeconomic models by reformulating their algebraic construction assumptions using the algorithmic resources of agent-based modeling. This creates a unified formal framework that allows scientists to demonstrate the epistemic advantages of agent-based models while showing their capacity to replicate results from established disciplinary models (e.g., Gobbi and Grazzini 2019; Sinitskaya and Tesfatsion 2015). Another hybrid approach consists in incorporating key construction assumptions from agent-based models, such as agent heterogeneity,

[18] Furthermore, we often cannot distinguish between the various stages of template adaptation in practice. The reformulation of a construction assumption can address several objectives simultaneously, such as aligning with a tractability standard and convincingly conceptualizing the model in accordance with entrenched modeling practices in the target domain. Nonetheless, it is useful to analytically distinguish between various reasons for adaptation, as a particular reason may play a more decisive role.

bounded rationality, and learning based on heuristic forecasting rules, into DSGE models (e.g., Dilaver et al. 2018). Overall, in hybrid models, while agent-based modeling is partially adapted to the accepted solution methods and construction assumptions in macroeconomics, modelers seek to preserve certain novel assumptions regarded as especially valuable, notably the heterogeneous-agents assumption, in contrast to the representative-agent assumption that is widespread in macroeconomics.[19]

Recently, John Geanakoplos (2026), one of the leading proponents of agent-based modeling in economics, offered a methodological reflection on his use of agent-based models that, in essence, captures the rationale behind the hybrid-models strategy. Drawing on examples involving models of mortgage prepayment, monies and inflation, housing, and economic booms and busts, he argues that the most fruitful approach to constructing agent-based models in economics is to combine them with general equilibrium models that underlie economic theory. In Geanakoplos's view, the axiom-theorem foundations of general equilibrium models are advantageous because they guarantee that equilibrium solutions remain consistent with assumptions of rational behavior. At the same time, agent-based models make it possible to represent finer behavioral details and to conveniently relax assumptions of full rationality where necessary. By building agent-based models on the foundation of simpler general equilibrium models, researchers can preserve the desirable properties of equilibrium solutions while extending the model's representational accuracy beyond the inherent limitations of general equilibrium models.

Tiziana Assenza and Domenico Delli Gatti's (2019) article provides an illustrative example of a hybrid agent-based macroeconomic model. They aim to construct a model that remains as close as possible to the DSGE framework widely accepted in macroeconomic literature. At the aggregate level, the model's dynamics can be algebraically described by three standard components of DSGE models: the investment–savings (IS) curve, the Phillips curve, and the Taylor rule. Together, these equations determine the equilibrium levels of employment, the interest rate, and inflation.

While preserving this conventional aggregate structure, Assenza and Delli Gatti (2019) incorporate agent-based simulation at the micro level by introducing algorithmically simulated heterogeneous firms. A recursive rule specifies each firm's production level and its demand for capital and labor, mirroring the optimizing logic of standard macroeconomic models. When firms lack sufficient internal funds to continue production, they borrow from banks; the resulting additional interest costs constitute the external finance premium, which is determined individually for each firm.

The average external finance premium serves as the key link between the algorithmic micro and algebraic macro levels of the model. Aggregate employment, the interest rate, and inflation in period t can be expressed as functions of the average finance premium in period $t - 1$. In turn, the interest rate in period t influences the average finance premium in period $t + 1$. The average premium depends on the first

[19] At the same time, in recent years, macroeconomists outside the agent-based modeling community have also recognized the importance of developing models with heterogeneous agents (e.g., Debortoli and Galí 2025).

and second moments of the distribution of firms' net worth, and the authors approximate it using the following formula (Assenza and Delli Gatti 2019, 274):

$$f_t \approx \frac{\alpha}{A_{t-1}} + \frac{\alpha V_{t-1}}{A_{t-1}^3}$$

where α is an exogenous parameter, A_{t-1} is the cross-sectional mean of the distribution of firms' net worth in period $t - 1$, and V_{t-1} is the cross-sectional variance of the distribution of firms' net worth in period $t - 1$.

Using this formula, the authors provide an analytical account of the pattern governing the dynamics of the average external finance premium within the model and isolate the influence of different modeling assumptions. The formula separates the average premium into two components. The first, termed the RA (representative-agent) component, depends only on the cross-sectional mean and corresponds to the representative-agent benchmark. The second, the HA (heterogeneous-agents) component, depends on both the cross-sectional mean and on variance, capturing the contribution of firm heterogeneity. This decomposition makes it possible to see how incorporating heterogeneity through the agent-based framework alters the model's results. Specifically, they analytically derive the portions of fiscal, monetary, and financial shocks' effects that are independent of changes in firms' financial conditions at the micro level and then use agent-based simulations to estimate the portions attributable to changes in firms' external finance premium, distinguishing between the RA and HA terms.

Thus the model integrates new elements, namely, recursive behavioral rules and agent heterogeneity, both characteristic of agent-based modeling, into a unified formal framework alongside the common equation-based representation of aggregate structure and the representative-agent assumption. The contribution of these new elements, exemplified by the algorithmically modeled heterogeneous firms, can be quantified as a fraction of the macroeconomic equilibrium at the aggregate level.

This model nicely illustrates the strategy of methodological embedding. Assenza and Delli Gatti reformulate the assumption of heterogeneous agents in a way that maximizes its consistency with rational-agent behavior in DSGE models and preserves comparability with the representative-agent assumption; they also treat the algorithmic simulation of firm behavior as a component of the model's algebraic solution. Their model is explicitly designed to facilitate the identification of the individual contributions made by different construction assumptions and solution methods to the results, thereby enabling their systematic evaluation and, as a consequence, a more informed assessment of the necessity to adopt the transferred construction assumption and solution method.

They show that the effects introduced by firm heterogeneity are as significant as those associated with the representative agent alone, indicating that heterogeneity makes a substantial contribution to overall model dynamics. At the same time, the presence of an isolable representative-agent component makes the model's results more amenable to theoretical interpretation and more consistent with accepted model-solution procedures in macroeconomics. Deviations from the tractability standard are confined to a separate agent-based component of the model, thereby reducing the associated epistemic risks.

In this sense, Assenza and Delli Gatti's modeling strategy exemplifies both aspects of methodological embedding: minimizing the distance from the target domain's tractability standard and reducing uncertainty in assessing the epistemic benefits and risks associated with departing from this standard. The general methodological arguments advanced by Geanakoplos (2026) in favor of combining agent-based models with general equilibrium models, based on the idea of preserving the desired properties of equilibrium solutions while attaining the greater realism afforded by agent-based models, further substantiate my interpretation of hybrid macroeconomic agent-based models as instances of methodological embedding.

6. Conclusion

In this article, I argue that considerations of tractability depend not only on "objective" factors, such as the formal properties of models, computational constraints, and capabilities, but also on domain-specific priorities concerning epistemic desiderata. A fully specified notion of tractability must therefore take these priorities into account. This can be achieved by identifying tractability standards that determine which model solutions count as acceptable within a given domain.

The domain specificity of tractability standards creates a distinctive challenge for model transfer and complicates the template-based account of model transfer. In particular, it calls into question the relevance of tractability as a pragmatic motivation for transfer when the standards of the source and target domains diverge, and it helps explain why transfers in such cases may be unsuccessful. However, I argue that this challenge does not necessarily have to lead to a failure of transfer, since strategies exist that can mitigate it. As proposed in this article, methodological embedding is one such strategy, amounting to the reformulation of an entire model or selected components to ensure alignment with the tractability standard of the target domain.

When methodological embedding is not feasible, other strategies may still be available that aim at transforming the relevant standards. For example, the proponents of transfer might change the discipline's epistemic priorities through transfer itself, even though this proves extremely demanding. Some reconstructions of the history of twentieth-century economics, showing how transfers from physics played a decisive role in the deep methodological transformation that occurred in economics, can serve as an example of this strategy (e.g., Mirowski 1989). A less demanding alternative may be to bypass traditional disciplinary boundaries altogether. This approach has largely been followed by econophysics, although arguably in response to challenges other than those posed by tractability standards. As Yves Gingras and Christophe Schinckus (2012) observe, econophysics became institutionalized as a research field within physics rather than economics.

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